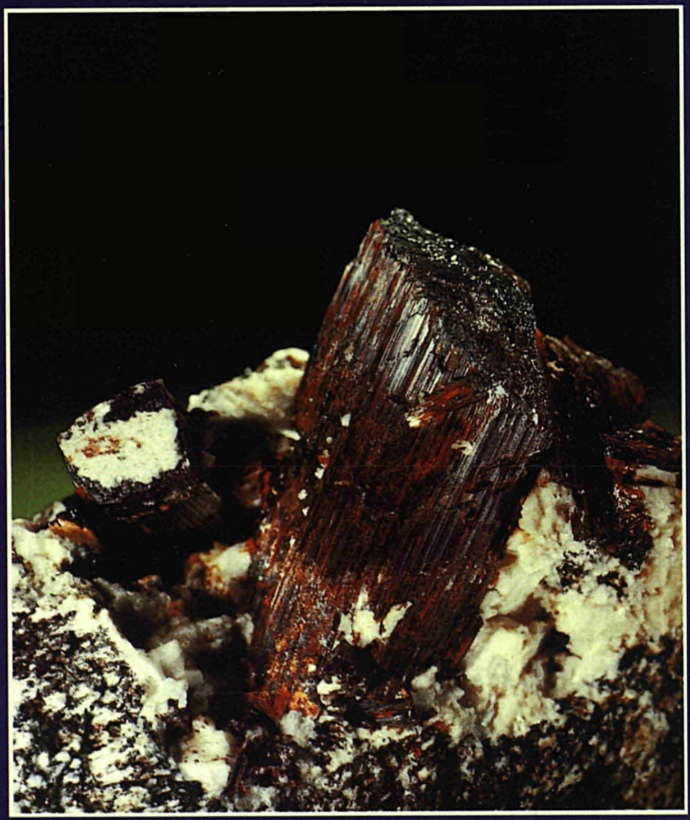
ISSN 1018-5593

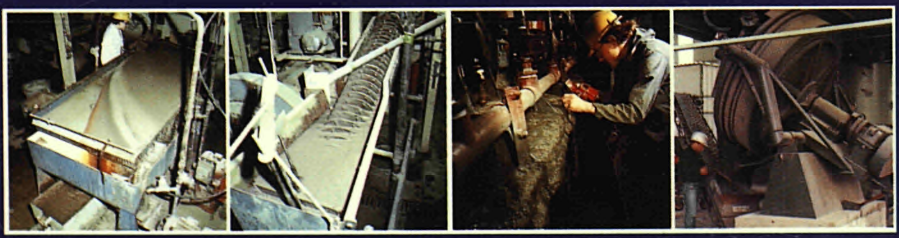
Commission of the European Communities

SUMMARY REPORTS OF THE R&D PROGRAMME

Primary raw materials (1986-89)

VOLUME 1





Report

EUR 13647/I EN

Commission of the European Communities

Summary reports of the R&D programme: Primary raw materials (1986-89) Volume I

Edited by :
M. Donato

Commission of the European Communities
200 rue de la Loi
B-1049 Brussels

Summary reports

Directorate-General
Science, Research and Development

1992

Published by the
COMMISSION OF THE EUROPEAN COMMUNITIES
Directorate-General
Telecommunications, Information Industries and Innovation
L-2920 Luxembourg

ISBN 92-826-3793-X (volumes 1-3)

Cataloguing data can be found at the end of this publication

Luxembourg: Office for Official Publications of the European Communities, 1992

ISBN 92-826-3794-8

Printed in Belgium

TABLE OF CONTENTS

	Page
FOREWORD	XXIII
PROFESSIONAL STAFF ASSIGNED TO THE MANAGEMENT OF THIS PROGRAMME	XXVII
MAJOR RESULTS OF SCIENTIFIC AND TECHNOLOGICAL VALUE	XXIX
PATENTS AND PUBLICATIONS	XXXIX
COUNCIL DECISION (10.06.86)	XLIII
CALL FOR PROPOSALS (19.06.86)	LIII
1. EXPLORATION	01
RESEARCH AREA 1.1 : ECONOMIC GEOLOGY	03
- Contract MA1M-0003-C Development of light hydrocarbon gas lithogeochemistry and its response to different styles of mineralization	05
- Contract MA1M-0004-C Ta-Nb-W-Sn-Mo mineralizations associated with acid magmatism. Links with ore-bearing hydrothermal systems	17
- Contract MA1M-0005-I Late Alpine magmatism and related W-Mo-Cu metallogenesis in the Italian Alps (examples from South Tyrol and Piedmont)	31

- Contract MA1M-0006-DK
  Factors governing concentrations of platinum group elements in layered complexes 39

- Contract MA1M-0007-E
  Optimization of electromagnetic and gravity methods of mineral exploration for the location and delineation of buried orebodies in the Iberian pyritic belt Part 1................................... 49

- Contract MA1M-0007-E
  Optimization of electromagnetic and gravity methods of mineral exploration for the location and delineation of buried orebodies in the Iberian pyritic belt Part 2................................... 57

- Contract MA1M-0008-F
  Factors governing concentrations of platinum group elements in layered complexes................................ 65

- Contract MA1M-0014-D
  Development of exploration methods for alkaline rocks rich in bastnaesite-type rare earth minerals 89

- Contract MA1M-0031-I
  Factors controlling the concentration and distribution of mineralisations rich in tungsten and associated metals in the Peloritani Mountains (NE-Sicily) 99

- Contract MA1M-0038-UK
  Comparative study of metallogeny related to granite-sediment-fluid interactions and lineaments in the Caledonides and Hercynides, Part 1. 107

- Contract MA1M-0039-D
  Comparative study of metallogeny related to granite-sediment-fluid interactions and lineaments in the Caledonides and Hercynides, Part 2................... 115

- Contract MA1M-0068-GR
  Tectonic controls on chrome ore localization in ophiolites, Greece 123

- Contract MA1M-0075-C
Platinum group element mineralisation in two basic ultrabasic complexes in northern Portugal :
(a) the platinum group elements : mineralogy and analysis
(b) structural and lithological controls on mineralisation 131

RESEARCH AREA 1.2 :
METHODS OF GEOCHEMICAL PROSPECTING............ 143

- Contracts MA1M-0027-UK and MA1M-0028-P
Hydrothermal fluid anomalies : a new strategy for geochemical exploration in Portugal 145

- Contract MA1M-0028-P
Hydrothermal fluid anomalies : a new strategy for geochemical exploration in Portugal................................. 153

- Contract MA1M-0030-F
Identification of diagnostic markers of high-grade massive sulphide deposits or of their enriched zones in France and Portugal 177

- Contract MA1M-0029-P
Identification of diagnostic markers of high-grade massive sulphide deposits or of their enriched zones in France and Portugal 191

- Contract MA1M-0032-C
Development of new multi-disciplinary techniques for mineral exploration in several areas of the Western Iberian Penisula. Part 1......................... 199

- Contract MA1M-0032-C
Development of new multi-disciplinary techniques for mineral exploration in several areas of the Western Iberian Penisula. Part 2......................... 215

RESEARCH AREA 1.3 :
METHODS OF GEOPHYSICAL PROSPECTING............ 225

- Contract MA1M-0012-I
  Development and improving of georadar system as a geophysical method for mining exploration 227

- Contract MA1M-0013-D
  UV laser prospecting - field test of Preussag's close range system 231

RESEARCH AREA 1.4 :
REMOTE SENSING. Including "integrated" studies 235

- Contract MA1M-0010-E
  Development and testing of new techniques for mineral exploration based on remote sensing, image processing methods and multivariate analysis......... 237

- Contract MA1M-0009-D
  Development and testing of new techniques for mineral exploration based on remote sensing, image processing methods and multivariate analysis, Part 1.................................. 247

- Contract MA1M-0009-D
  Development and testing of new techniques for mineral exploration based on remote sensing, image processing methods and multivariate analysis, Part 2.................................. 258

- Contract MA1M-0011-IRL
  Development and testing of new techniques for mineral exploration based on remote sensing, image processing methods and multivariate analysis, main target areas Almaden, Spain, and C. Ireland 271

- Contract MA1M-0015-DK
  Development and testing of new techniques for mineral exploration based on remote sensing, image processing methods and multivariate analysis......... 281

2. MINING TECHNOLOGY........................... 289

RESEARCH AREA 2.1 :
ROCK FRACTURING................................ 291

- Contract MA1M-0054-C
  The influence of rock properties on the efficiency of mechanized mining with reference to hard rock cutting................ 293

- Contract MA1M-0073-F
  Fractured rock mechanics and the stability of mines................................. 307

- Contract MA1M-0076-C
  Cut-and-fill mining in hard rock without the use of explosives..................... 315

RESEARCH AREA 2.2 :
ROCK MECHANICS AND STABILITY SUPPORT SYSTEMS.. 327

- Contract MA1M-0018-NL
  Cataclastic-plasto-elastic equilibria in brittle rock under triaxial differential loading conditions....................... 329

- Contract MA1M-0048-C
  Setting up of a checking system of the underground cavern evolution in mines exploited by solution technique and numerical modelling of the said process......... 345

- Contract MA1M-0055
  Stability and reinforcement of mine workings. Development of dimensioning methods based on geostatistical studies of fracturing and the key-block method. Application to cable-bolting............. 361

- Contract MA1M-0067-I
  Optimization of cemented backfill......... 375

RESEARCH AREA 2.3 & 2.4 :
APPLICATION OF ROBOTICS IN MINES.............. 401

- Contract MA1M-0016-C
Automation of trucks used in underground and open cast mines....................... 403

- Contract MA1M-0053-C
Robotics of mining machines of the road-header type to obtain selective automatic cutting................................. 415

RESEARCH AREA 2.5 :
MODELLING AND SIMULATION METHODS IN MINING OPERATION................................... 431

- Contract MA1M-0019-C
Support calculation in highly jointed rock masses.................................. 433

- Contract MA1M-0022-C
Simulations of morphologies of tectonised deposits................................ 443

- Contract MA1M-0024-C
New features of a software for simulating mining operations in open pit and development towards mining control and planning.. 451

- Contract MA1M-0025-C
Optimization of the exploitation of thin vein polymetallic sulphide deposits through mathematical modelling and rock mechanics; an application to the Molaoi mine.................................... 459

- Contract MA1M-0026-D
Computer aided design of underground metalliferous mining layouts............. 475

- Contract MA1M-0060-C
Computer aided selective production planning for complex orebodies................ 487

- Contract MA1M-0063-C
Computer aided planning of underground mining exploitations...................... 503

RESEARCH AREA 2.6 :
PROBLEMS ASSOCIATED WITH SMALL-SIZE MINES...... 515

- Contract MA1M-0050-D
  Fundamental analysis and development of small scale mining methods for in-the-ore development of small barite and fluorspar lode deposits situated near to the surface with special regard to the application of open pit mining methods with later transition to underground mining................ 517

- Contract MA1M-0056-C
  Realization of an expert software prototype on a micro-computer for the optimisation of small scale mining................ 535

- Contract MA1M-0065-C
  What equipment to develop for European small scale mines? State of the art, proposal and study of the micro-jumbo........ 545

3. MINERAL PROCESSING......................... 557

RESEARCH AREA 3.1 :
PHYSICAL SEPARATION TECHNIQUES................ 559

- Contract MA1M-0041-C
  The application of high intensity magnetic separation to the beneficiation of complex ores.................................... 561

- Contract MA1M-0046-C
  The separation of materials using selective magnetic coating................ 569

- Contract MA1M-0051-C
  A process design study for finely disseminated, partially oxidized complex sulfide ore from the Molai area, Southern Greece.. 585

- Contract MA1M-0059-C
Application of phosphoric esters to the flotation of finely divided oxidized ores. 615

- Contract MA1M-0064-C
Improvement of complex sulphide flotation using new reagent chemistry.............. 633

- Contract MA1M-0071-C
Recovery of Ta and Nb from concentrates and by-products of European ores type Echassières (France) and Golpejas and Penouta (Spain)........................... 653

RESEARCH AREA 3.2 :
HYDROMETALLURGICAL PROCESSING OF SULPHIDES AND OTHER ORES................................ 687

- Contract MA1M-0017-C
Recovery of nickel from non-sulphide sources using micro-organism assisted leaching.................................. 689

- Contract MA1M-0023-F
The use of lithium-bearing geothermal fluids for the industrial production of lithium................................ 733

- Contract MA1M-0045-C
A study of hydrometallurgical treatment of complex sulphide ores by leaching with ferrous chloride and oxygen in a highly concentrated ammonium chloride aqueous solution................................ 759

- Contract MA1M-0052-C
Iron control by hydrolytic stripping in complex ore processing, Part 1............ 781

- Contract MA1M-0052-C
Iron control by hydrolytic stripping in complex ore processing, Part 2............ 795

- Contract MA1M-0069-C
The use of novel bio oxidation techniques in the hydrometallurgical treatment of mixed sulphide ores...................... 809

RESEARCH AREA 3.3 :
PYROMETALLURGICAL PROCESSING OF SULPHIDES AND OTHER ORES.................................... 833

- Contract MA1M-0033-UK
  Simultaneous recovery of zinc, copper and lead as metals from complex sulphides in a single polymetallic smelting furnace. 835

- Contract MA1M-0074-C
  The behaviour of copper in the zinc imperial smelting furnace................. 861

RESEARCH AREA 3.4 :
TREATMENT OF MINING WASTE AND METALLURGIC RESIDUES.. 887

- Contract MA1M-0020-P
  Residual ultra fine pyrite as a raw material for non ferrous metals recovery and simultaneous sulphuric acid production 889

- Contract MA1M-0037-C
  Pyrometallurgical treatment of residues and precipitates from hydrometallurgical zinc recovery in a c.c. supplied electric arc furnace............................ 901

- Contract MA1M-0043-C
  Optimization of the Anaconda process for the electrolytic recovery of zinc from zinc sulphate solution by treating the leach residue............................ 919

RESEARCH AREA 3.5 :
MODELLING AND CONTROL IN MINERAL PROCESSING... 929

- Contract MA1M-0021-F
  Modelling of an autogenous grinding and flotation process.
  Application to the industrial processing of the Moinho complex sulphide ore........ 931

- Contract MA1M-0047-UK and MA1M-0077-UK
  Development of an integrated computer-based method for plant enhancement........ 961

- Contract MA1M-0058-C
  Development and application of a modular intelligent control system for mineral processing plants.......................... 975

RESEARCH AREA 3.6 :
CHARACTERIZATION OF ORES AND MINERAL ANALYSIS. 985

- Contract MA1M-0042-C
  Development of new sensors for on line analysis of metal and organic ions in water. Application to modelling and automatic control of flotation plants......... 987

- Contract MA1M-0061-C
  Quantitative analysis and automation of CaF_2 ore flotation via neutronic activation................................ 993

- Contract MA1M-0066
  On-line analysis of cement raw materials by prompt gamma neutron activation analysis................................. 1013

RESEARCH AREA 3.7 :
INDUSTRIAL MINERALS............................ 1021

- Contract MA1M-0035-C
  Beneficiation of talc-chlorites from Pyrenean and Valmalenco ores.............. 1023

- Contract MA1M-0070-C
  Improvement of the quality of refractory minerals such as Andalusite............... 1031

FOREWORD

This document contains the Summary Reports of cost sharing Research and Development contracts funded under the "Primary Raw Materials" subprogramme of the Commission of the European Communities. This programme was part of the research and development programme on "Raw Materials and Advanced Materials" (1986 - 1989).

The main objectives of the "Primary Raw Materials" subprogramme were to enhance the competitiveness of the European Community mining and metallurgical industries and to reduce European Community vulnerability for minerals, particularly those of critical or strategic interest.

This programme was funded with 20 MioECU for the period 1986 to 1989 of which 17 MioECU were allocated to research contracts. The balance was allocated to the management of the programme (staff, organization of contact group meetings, expert meetings, international cooperation and other costs).

The subprogramme comprised three research areas :

1. Research and Development Exploration

Economic geology, methods of geochemical and geophysical prospecting, remote sensing.

2. Mining Technology

Rock fracturing, rock mechanics, support systems, problems associated with depth, robotics, methods of modelling and simulation, problems of small-size mines.

3. Mineral Processing

Hydrometallurgy and pyrometallurgy of complex sulphide ores, oxidized ores, refractory ores, mine tailings and metallurgical residues; modelling and control in mineral processing; industrial minerals.

Iron, fossil fuels and building materials were excluded from the programme.

The breakdown of allocated funds and the number of contracts per research area was as follows : Research and Development Exploration (20 % of funds; 25 contracts), Mining Technology (40 %; 19 contracts), Mineral Processing (40%; 28 contracts). The total number of research contracts was 72. In this volume, Summary Reports for 67 contracts are presented. Summary Reports for the remaining 5 contracts will be published subsequently.

Throughout the duration of the multiannual research projects a close cooperation was maintained between the research groups and the Commission. This ensured that the research was carried out in accordance with the tasks as specified in the individual contracts.

Contractors' Seminars for Exploration, Mining Technology and Mineral Processing were organized in Paris (France), Santiago de Compostela (Spain) and Stevenage (United Kingdom) respectively to assist the Commission in managing the projects, to intensify the exchange of information between the Commission and the contractors and to further enhance international collaboration.

According to the programme's main objectives, the research was directed towards improving known technologies, development of new techniques and the discovery of new mineral resources with a strategic importance for the European Community. The immediate results are contributing to improve the competitiveness of the European Community mining and metallurgy industry; other industrial sectors will benefit from the improved availability of raw materials in the future.

This document has been compiled to facilitate and promote the rapid diffusion of the results obtained by the various research projects in accordance with Commission's policy.

The Commission acknowledges the continuous cooperation of the research contractors from industries, Universities and Research Centers including their valuable assistance in the organization of scientific seminars.

Dr. M. DONATO

Head of Unit DG XII C-5
Programme Manager

PROFESSIONAL STAFF

ASSIGNED TO THE MANAGEMENT OF THIS PROGRAMME

- Head of Unit DG XII C-5	: Dr. M. DONATO
- Scientific Officers :	
Exploration, Geochemistry	: Dr. J.-Y. CALVEZ
Exploration, Geophysics	: Dr. K. KÖGLER
Mining Technology	: Mr. G. KATALAGARIANAKIS
Mineral Processing	: Dr. A. LLOBET
Extractive Metallurgy	: Dr. A. ADJEMIAN
- Administration and Informatics	: Mr. G. HALLARD Mr. J. OLANO
- Experts	: Prof. G.F. FERRARA (part-time) Prof. G. VOUILLE (part-time) Prof. A. ARRIBAS (part-time) Dr. L. VAN WAMBEKE (retired)
- Secretariat	: Ms. D. PENNING Ms. L. MIKKELSEN Ms. F. DESMEDT Ms. A. CASE' Ms. A. ROSATI

MAJOR RESULTS OF SCIENTIFIC AND TECHNOLOGICAL VALUE

Research in the sectors of Exploration, Mining Technology and Mineral Processing has resulted in the recognition of new sources for strategic minerals and significant improvements in technologies for mineral exploration, for mining and for mineral processing.

The results obtained will contribute in the medium and long term to an improvement of the raw materials supply of the European Community and enhance the competitiveness of the European Community mining and metallurgical industries.

1. EXPLORATION

The main results of this sector were :

- In geochemical exploration techniques, the method of hydrocarbon gas lithogeochemistry for the exploration of concealed orebodies has been improved to a state where it can be employed as routine technique. Plans for commercial application are in an advanced stage and international interest to use this technique has been expressed.

  In another project, new criteria and methodologies for the exploration of concealed metal deposits were developed on the concept of "hydrothermal fluid anomalies".

- In geophysical exploration techniques, test surveys and new developments in software and hardware proved that the georadar technique can be used efficiently as a new tool. The work has contributed to an increased awareness of this method in Europe and to savings in exploration costs.

  Experimental and theoretical work on time domain and frequency domain electromagnetic techniques achieved two major results : (1) both methods can be efficiently used for the detection of deep-seated sulphide orebodies under conductive overburden; (2) a new FEM system has been developed and introduced to the market.

  A car-borne fluorosensor system for the detection of fluorescent indicator minerals has been developed and tested in the field. The "Preussag Close Range Fluorosensor" is now a fully operable system which has been patented.

- Advanced techniques of multidata analysis using a geographical information system (GIS) were employed to produce a new exploration model for gold and other hydrothermal mineralizations in Spain and Portugal. New exploration targets were identified.

Furthermore, Geographic Information Systems in conjunction with remote sensing data, ground data and automatic image analysis were successfully used in the exploration for new W-Sn occurrences in South Central Spain.

New occurrences of W-Sn mineralizations were also investigated in Northern Italy and Sicily.

Exploration criteria based on metallogenetic models were developed in several projects.

Close cooperation between several European countries resulted in improved genetic models for Hercynian and Caledonian granites and associated hydrothermal mineralization. A catalogue of criteria for the evaluation of the fertility of evolved granites was developed.

Exploration guides for massive sulphide ores in Palaeozoic volcanosedimentary belts were developed as a result of structural, geochemical and mineralogical investigations using the rich Neves Corvo and Chessy deposits as models.

Trace elements in hydrothermal muscovites and in scheelite, fluorite, and garnet as well as hydrogen isotopes in muscovites were recognized as important indicators for Ta, Nb, W, Sn, Mo mineralizations in acid magmatic rocks.

Research in the area of strategic metals was a main topic of this programme.

Tectonic investigations of ophiolites in Greece have significantly improved the understanding of tectonic parameters necessary for the formation of economic chrome ores inside and outside Europe.

Mapping, structural and geochemical investigations in the Bragança ultrabasic complex in Portugal have contributed to the understanding of geographical variations in PGE and chromite occurrences. The commercial potential which was indicated by this work is now followed-up by exploration companies.

Identification and investigation of a new type of PGE mineralization (in Madagascar) led to the determination of a new occurrence with excellent economic potential. New exploration procedures for this specific type of mineralization were developed.

Experimental petrology and mineralogy on the system PGE-S-As have significantly improved the understanding of the geological transport and concentration of PGE. The new mineralogical results are also applicable to certain technological processes, e.g. performance and degradation of PGE catalysts.

- Detailed geological and geochemical investigation of the bastnaesite occurrences at Kızılçaören (Turkey) have confirmed that this is a rare-earth element deposit of significant grade and tonnage. The project has identified the small grain-size of the ore as the main obstacle to economic exploitation.

2. MINING TECHNOLOGY

The main results of this sector were :

- The development of a software package for modelling the operation of opencast mines. This package permits decision-making for optimum short and medium term planning.

- A Computer Aided Design programme was developed for underground metalliferous mines. It is an integrated tool permitting the use of existing knowledge and techniques in the fields of geostatistics, rock mechanics and mining engineering for optimum design of mine layouts.

- A Computer Aided planning for underground mining exploitation was developed for PC users. It integrates the simulation of the different mine phases into one single workstation which can be used in different mines as a decision making tool.

- A checking system has been developed for monitoring the evolution of cavities in mines exploited by the solution technique. This system allows for better safety conditions and for avoiding damage to the mine and its environment by preventing subsidence and sinkhole phenomena.

- A geostatistical analysis method for the study of ore-deposits formed by tectonic processes has been developed. It can be used for the study of ore deposits quite difficult to assess by conventional methods.

- In the field of mechanical cutting of hard rock important progress has been achieved for understanding the mechanism of rock cutting by mechanical means.

  An extensive study was also completed for the design of mining systems in hard rocks without the use of explosives. This study was based on the Curraghinalt gold mine in Ireland.

- In the field of rock mechanics progress has been achieved both in the theoretical and the practical approach. This has led to better understanding of the rockmass behaviour under stress and especially how discontinuities influence their mechanical behaviour. A direct result is better design of underground excavations and their required support.

- In one mine research has given valuable results for the successful application of backfilling techniques adapted to the specific situations of the mine. This will result in higher productivity, improved safety and working conditions and higher selectivity of ore extraction and hence less environmental impact.

- Automation of mine trucks and robotization of the roadheaders for selective mining is another research item where significant progress has been achieved. These automation systems which will require reasonable investment from the exploitants are expected to improve mining conditions in many mines.
  Specific drilling equipment has been designed according to the needs of European small mines in an effort to provide this sector with well adapted equipment at a reasonable price.

3. MINERAL PROCESSING

The main results of this sector were :

- In physical separation techniques, new developments and improvements have been obtained on magnetic separation and flotation techniques.

  High intensity magnetic separation techniques have been developed for the separation of minerals having small differences in magnetic susceptibility.

  A new separation method based on ferromagnetic selective mineral surface coating has also been successfully developed.

  New collector reagents have been tested for the selective flotation of complex sulphides from Spain and Greece and for the flotation of rare earth bearing minerals.

- In hydrometallurgical processes, a novel ammonium chloride treatment for the Iberian complex sulphide ores has been designed and patented. This treatment has a high potential for commercial exploitation which is currently being considered by the Value programme (DG XIII).

New processes for the removing of iron from aqueous leach liquors have been developed in order to avoid the problems of residue disposal of the jarosite and/or goethite processes.

Production of lithium from geothermal fluids in French and Italian aquifers has been studied. Furthermore new schemes for Ta and Nb beneficiation have been designed and investigated.

- Innovative research in biohydrometallurgical processes has provided new insights into the biological oxidation of nickel and gold ores from Greece.

- In pyrometallurgical processes, research has been focused on the simultaneous recovery of Zn, Cu and Pb from complex sulphides in a single pilot polymetallic furnace.

  Research has also been directed torwards the problems related to the copper content increases in the Pb and Zn concentrates feeds for the Imperial Smelting Furnaces.

- New process routes for the recovery of metallurgical residues have been designed and developed. They include the treatment of ultrafines from pyrite ores, the optimization of the Anaconda process and the treatment of residues form hydrometallurgical zinc winning.

- In modelling and control, new information technologies have been specifically applied to mineral processing operations (autogeneous grinding modelling, process control and management, new sensors for monitoring and controlling flotation units, neutron activation on-line analysis).

- Research in the area of industrial minerals has been performed for talc and andalusite.

  Two new routes are considered to improve the direct beneficiation of talcs from the Pyrenees (France, Spain) and from Valmalenco (Italy) comprising wet micronisation and heat treatment.

  A new process to treat andalusite residues has been successfully developed and implemented. As a result higher quality andalusite is obtained and the plant productivity increased. Both direct and inverse andalusite flotation processes have been patented.

PATENTS AND PUBLICATIONS

The following is a preliminary list of patents and publications that has emerged as a result of the research work performed by the contractors under the cost-shared subprogramme on Primary Raw Materials (1986-1989).

PUBLICATIONS

Contract MA1M - 0047

- "Computer optimisation of a shaking table".
  P. Tucker, K.A. Lewis and D. Wood
  Submitted to the International Symposium on Gravity Separation Technology. Camborne School of Mines, Sept 1990.

- "A mathematical model of the duplex concentrator".
  M. Pearl, K.A. Lewis and P. Tucker
  Submitted to the International Symposium on Gravity Separation Technology. Camborne School of Mines, Sept. 1990.

- "Expert system supervisory control of the Wheal and Jane tin concentrator".
  K.A. Lewis, P. Tucker, A. Wells and G. Le Jeune
  Submitted to the 2nd Symposium on Personal Computers and Industrial Control.

Contract MA1M-0018

- "True axial compression experiments on Felser sandstone".
  M.J. Cockram, W. Kamp
  Accepted at the conference for "Fracture processes in brittle disordered materials (concrete, rock, ceramics)" June 1991 Noordwijk.

Contrat MA1M-0066

- "Some Comparisons of Spectral Responses of Neutron-Gamma logging Tools between the MOCA Monte Carlo Code and Experimental Results".
  J.L. Pinault
  Nucl. Geophys vol 4 n° 4 pp 443-453, 1990.

PATENTS

Contracts n. MAIM-0016

- French patent n. 8908459 of June 26th, 1989.
  "Procédé d'assistance à la conduite d'engins de transport dans une mine ou analogue et installation pour sa mise en oeuvre".

Contract MA1M-0035

European patent extended to Chile, USA, Canada, Zaire and Zambia.
"Processo per la flottazione selettiva dei minerali metallici utilizzando derivati del 2-mercaptotiazolo".

Contract n. MA1M-0045

- Spanish patent n. 8902487 (Priority July 13th, 1989).
  "Procedimiento para la recuperacion de cinc, cobre y plomo de minerales oxidados y/o sylfurados".

- European and world-wide patent (Canada, USA, Mexico, Australia), pending.
  "Process for the recovery of zinc, copper and lead from sulphided and/or oxidized materials and ores".

Contract MA1M-0070

- French patent n. 8718125 of June 30th, 1989, pending to Australia, Canada, USA and South Africa.
  "Procédé d'enrichissement de l'andalousite".

- European patent pending.
  "Procédé d'enrichissement de l'andalousite".

- Patent pending.
  "Flottation inverse de l'andalousite".

COUNCIL DECISION

of 10 June 1986

adopting a research programme on materials (raw materials and advanced materials) (1986 to 1989)

(86/235/EEC)

THE COUNCIL OF THE EUROPEAN COMMUNITIES,

Having regard to the Treaty establishing the European Economic Community and in particular Article 235 thereof,

Having regard to the proposal from the Commission,

Having regard to the opinion of the European Parliament [1],

Having regard to the opinion of the Economic and Social Committee [2],

Whereas Article 2 of the Treaty assigns to the Community the task, *inter alia,* of promoting throughout the Community a harmonious development of economic activities, a continuous and balanced expansion and an accelerated raising of the standard of living;

Whereas, in its resolution of 14 January 1974 on an initial outline programme of the European Communities in the field of science and technology [3], the Council stated that the whole range of available ways and means should be used as appropriate;

Whereas, in its resolution of 25 July 1983 [4], the Council adopted a first framework programme (1984 to 1987) for Community research, development and demonstration activities, two of the principal objectives of which are met by the proposed research, namely industrial competitiveness and improvement of management of raw materials;

Whereas the economic availability of raw materials and advanced materials is indispensable to maintaining the industrial competitiveness of the Community;

Whereas the programme on recycling of urban and industrial waste adopted by Decision 79/968/EEC [5], as last amended by Decision 83/634/EEC [6], and the programme in the field of raw materials, which includes subprogrammes on metals and mineral substances, wood as a renewable raw material, recycling of non-ferrous metals and substitution and materials technology, adopted by Decision 82/402/EEC [7], have produced encouraging results and opened up promising prospects, relative to the objectives sought;

Whereas, by Decision 84/197/EEC [8], the Council adopted a concerted-action project of the European Economic Community on the use of lignocellulose-containing by-products and other plant residues for animal feeding;

Whereas the Treaty has not provided the specific powers necessary for the adoption of this Decision;

Whereas the Scientific and Technical Research Committee (CREST) has given its opinion on the Commission's proposal,

HAS DECIDED AS FOLLOWS:

Article 1

1. The Community shall implement, over a period of four years from 1 January 1986, a research programme in the materials sector (raw materials and advanced materials), as described in the Annex.

2. The work shall be carried out as shared-costs contract research, coordination and training activities, and one concerted action, as described in the Annex.

Article 2

1. The amount estimated as necessary to carry out the programme shall be 70 million ECU, including expenditure for a staff of 23.

The breakdown of this amount by subprogramme is given in the Annex by way of indication only.

2. In the light of the experience gained in the course of implementing the programme and after receiving the opinion of the Committee referred to in Article 3, the Commission shall be authorized to transfer funds from one subprogramme to another, provided that the final appropriation for any subprogramme does not differ, upwards or downwards, by more than 15 % from the original appropriation as set out in the Annex for each subprogramme.

Article 3

The Commission shall be responsible for the execution of the programme. It shall be assisted in its task by the Management and Coordination Advisory Committee on Raw Materials and Other Materials set up by Council Decision 84/338/Euratom, ECSC, EEC [9].

(1) OJ No C 68, 24. 3. 1986, p. 76.
(2) OJ No C 354, 31. 12. 1985, p. 6.
(3) OJ No C 7, 29. 1. 1974, p. 6.
(4) OJ No C 208, 4. 8. 1983, p. 1.
(5) OJ No L 293, 20. 11. 1979, p. 19.
(6) OJ No L 357, 21. 12. 1983, p. 33.
(7) OJ No L 174, 21. 6. 1982, p. 23.
(8) OJ No L 103, 16. 4. 1984, p. 23.

(9) OJ No L 177, 4. 7. 1984, p. 25.

Article 4

The programme shall be reviewed at the end of the second year. In the light of this review the Commission may, through the appropriate procedures, present to the Council a proposal for a new four-year programme which would supersede the current programme at the beginning of the third year.

Article 5

1. With regard to the concerted actions, the participating Member States and the Community shall, in accordance with a procedure to be laid down by the Commission, after having consulted the Committee referred to in Article 3, regularly exchange all useful information concerning the execution of the research covered by such activities.

The participating Member States shall provide the Commission with all information relevant for coordination purposes. They shall also endeavour to provide the Commission with information on similar research planned or carried out by bodies which are not under their authority. Any information shall be treated as confidential if so requested by the Member State which provides it.

2. Following completion of the programme, the Commission shall, after having consulted the Committee referred to in Article 3, send to the Member States and the European Parliament a summary report on the implementation and results of the concerted actions.

It shall publish the report referred to in the first subparagraph six months after it has been sent to the Member States, unless a Member State objects. Should a Member State object, the report shall be distributed, in agreement with the Committee referred to in Article 3, only to those institutions and undertakings which request it and whose research or production activities justify access to the results of the research arising from the concerted actions. The Commission shall make the necessary arrangements for the report to remain confidential and not to be divulged to third parties.

Article 6

1. In accordance with Article 228 of the Treaty, the Council may conclude agreements with third States, in particular those involved in European cooperation in the field of scientific and technical research (COST), with a view to associating them wholly or partly with this programme.

2. The Commission is hereby authorized to negotiate the agreements referred to in paragraph 1.

Done at Luxembourg, 10 June 1986.

For the Council

The President

G. M. V. van AARDENNE

ANNEX

I. PRIMARY RAW MATERIALS (MINERALS)

A sum amounting to 20 million ECU shall be allocated to this subprogramme.

The subprogramme shall cover the following research ares:

1. **Exploration**

1.1. Economic geology.

1.2. Methods of geochemical prospecting.

1.3. Methods of geophysical prospecting.

1.4. Remote sensing.

2. **Mining technology**

2.1. Rock fracturing.

2.2. Rock mechanics and stability in underground and open-cast mines.

2.3. Application of robotics in mines.

2.4. Problems associated with depth.

2.5. Modelling of mining operations.

3. **Mineral processing**

3.1. Development of processing routes for treating indigenous and non-indigenous resources: complex and low-grade ores.

3.2. Metallurgical processes (pyro and hydro).

3.3. Modelling and control in mineral processing.

3.4. Industrial minerals.

II. SECONDARY RAW MATERIALS

A sum amounting to 10 million ECU shall be allocated to this subprogramme.

This amount includes a sum of 250 000 ECU for the extension of the concerted action (COST 84a) under item 2.4 below.

The subprogramme shall cover the following research areas:

1. **Recycling of non-ferrous metals**

1.1. Physico-chemical characterization of metals and alloys in scraps and residues.

1.2. Improvement of physical separation processes.

1.3. Development of advance technologies and improved pyrometallurgical and hydro-metallurgical processes.

1.4. Development of improved refining techniques for secondary metals and alloys.

1.5. Upgrading the characteristics of secondary alloys to the level of primary alloys.

1.6. Manufacturing semi-product alloys from waste materials containing titanium, tungsten, molybdenum, aluminium, etc.

2. **Recycling and utilization of waste**

2.1. Modelling of waste arisings, sampling and analysis (coordination activities).

2.2. Recycling technologies:

— recovery and separation processes,
— upgrading and use of reclaimed products.

2.3. Integrated technologies for the utilization of wastes:

— anaerobic digestion, composting and other aerobic treatments (coordination activities),
— production of chemicals - thermal treatment of waste (mostly coordination, with shared-cost contracts for special projects).

2.4. Use of lignocellulose-containing by-products and other plant residues for animal feeding (concerted action COST 84a).

III. WOOD, INCLUDING CORK, AS A RENEWABLE RAW MATERIAL

A sum amounting to 10 million ECU shall be allocated to this subprogramme.

The subprogramme shall cover the following research areas:

1. **Wood production**

1.1. Forest-tree breeding and gene resource conservation.

1.2. Protection against damage from biotic and abiotic agents and fire.

1.3. Better use of land resources (coordination action only).

1.4. Forest inventory (coordination action only).

2. **Wood harvest, storage and transport**

2.1. Organization of harvesting operations and development of harvesting machinery.

2.2. Harvesting, treatment, storage and transport.

3. **Wood as a material**

3.1. Properties, protection and improvement of wood and wood-based panels.

3.2. Development of testing and grading procedures.

4. **Mechanical wood processing and use of finished wood products**

4.1. Mechanical conversion and manufacturing processes.

4.2. Drying processes.

4.3. Use of wood and wood-based materials in construction.

4.4. Other uses of finished products made of wood.

5. **Pulp and paper manufacturing and processing and wood chemicals**

5.3. The physical and organic chemistry of wood defibring.

5.2. Chemi-mechanical pulping (high-yield pulping).

5.3. Pulping processes with low-grade wood.

5.4. Substitutes for wood fibres and material additives.

5.5. Fibre recycling.

5.6. The process of manufacture of paper and board.

5.7. Products derived from wood as a source of chemicals.

IV. ADVANCED MATERIALS (EURAM)

A sum amounting to 30 million ECU shall be allocated to this subprogramme.

The subprogramme shall cover the following research areas:

1. Metallic materials

1.1. Light aluminium-based alloys.

1.2. Light magnesium-based alloys.

1.3. Light titanium-based alloys.

1.4. Electronic and electrical-contact materials.

1.5. High-performance magnetic materials.

1.6. Materials for surface coating for machine-tool and cutting equipment.

1.7. Thin-walled castings.

2. Engineering ceramics

2.1. Optimization of engineering ceramics.

2.2. Study of metal/ceramic interface: cermets.

2.3. Ceramic composites with fibres and whiskers.

2.4. High-temperature behaviour of engineering ceramics.

3. Composite materials

3.1. Organic-matrix composites.

3.2. Metallic-matrix composites.

3.3. Ceramic-matrix composites.

3.4. Other specific advanced materials.

The aim of research carried out under the subprogramme shall be to provide the basis for a Community policy for supporting research and development in the advanced materials sector and for coordinating national programmes.

To this end, every two years:

— an assessment shall be made of European research and development capacity in the advanced materials sector, by area, Member State and in the Community as a whole, by comparison with the technological capacity of Japan and the United States,

— a medium-term analysis and estimate shall be made of requirements in the various sectors of the European industry in relation, if necessary, with other Community programmes related to materials.

B-Brussels: research action programme on materials

RESEARCH ACTION PROGRAMME ON MATERIALS (¹)

(1986 to 1989)

Call for research proposals on primary raw materials

The Commission of the European Communities is implementing a multi-annual research and development programme on primary raw materials with a total budget of 20 million ECU.

The main objectives of the programme are to enhance the competitiveness of the European Community mining and metallurgical industries and to reduce European Community vulnerability for mineral raw materials, particularly those of critical or strategic interest.

The programme covers three research areas:

1. *Research and development exploration*

   Economic geology, methods of geochemical and geophysical prospecting, remote sensing.

2. *Mining technology*

   Rock fracturing, rock mechanics, support systems, problems associated with depth, robotics, methods of modelling and simulation, problems of small-size mines.

3. *Mineral processing*

   Hydrometallurgy and pyrometallurgy of complex sulphide ores, oxidized ores, refractory ores, mine tailings and metallurgical residues; modelling and control in mineral processing; industrial minerals.

Iron, fossil fuels and buildings materials are excluded from the programme.

The programme will be carried out principally by means of cost-shared research contracts where the European Community contribution will in general be 50 % of the overall cost. The main part of the budget will be allocated to research areas 2 and 3.

The Commission invites proposals for participation in the programme. Proposals will be treated in strictest confidence. They may be submitted by any natural or legal person, by public or private bodies, established within the territory of a Community Member State.

The duration of contracts will not exceed 36 months. The deadline for the submission of proposal is 10. 10. 1986.

The proposals will be judged on their value to the Community, their scientific merit, their innovative approach, and their potential for industrial application. Preference will be given to joint projects associating organizations of at least two Member States. Approximately 90 % of the funds for contracts will be allocated to projects which require a minimum annual European Community contribution of 80 000 ECU.

Please contact the Commission at the address below for a detailed description of objectives and research topics of the programme on primary raw materials, and for proposal forms.

Address: Commission of the European Communities,
200, rue de la Loi,
B-1049 Brussels,
DG XII/G — Materials Research Programme.

Tel: (2) 235 70 62 (General information),
(2) 235 84 37 (Technical information).

Telex: 21877 COMEU B.

Telecopy: (2) 235 01 45.

4835-86COM

(¹) OJ No L 159, 14. 6. 1986. Council Decision 86/235/EEC of 10. 6. 1986

1. EXPLORATION

RESEARCH AREA 1.1

ECONOMIC GEOLOGY

DEVELOPMENT OF LIGHT HYDROCARBON GAS LITHOGEOCHEMISTRY AND ITS RESPONSE TO DIFFERENT STYLES OF MINERALIZATION

Project Leaders : P.C.D. CAZALET
Mercury Hydrocarbons Ltd, Limerick, Ireland

and

J-R DISNAR
Centre National de la Recherche Scientifique et
Bureau de Recherches Géologiques et Minières (BRGM), Orléans, France

Contract MA1M-0003-C

1. INTRODUCTION

The fortuitous discovery of anomalously high amounts of methane in rocks adjacent to mineralization in the Northern Pennines Orefield led to the examination of a new lithogeochemical exploration tool for hidden base metal deposits. The method, based on the chromatographic analysis of the volatile organic compounds released by heating the rocks in sealed tubes (210°C; 2h 30) was first tested on the site of the initial findings and later on deposits in Ireland and in other European countries. The work frequently led to the detection of methane and/or other organic compounds in the vicinity of mineralization but left questions unsolved, the main problems being :

1. the significance of results from the heat extraction procedure, questioned by the production, together with alkanes, of high amounts of compounds not usually observed in rocks (alkenes, oxygen-containing compounds);

2. the difficulty of obtaining precise results compared to other lithogeochemical methods such as trace metal analysis;

3. the relationship between hydrocarbon gases, trace metals and ore genesis.

2. RESULTS OF THE FRENCH TEAM

The French team was composed of J.R. Disnar, D. Defoix and M. Helleisen.

2.1 LABORATORY STUDIES

In addition to methane and other alkanes which are normal components of sedimentary rocks, the heat extraction procedure produces high proportions of alkenes and oxygenated organic compounds such as methanol, ethanol and acetaldehyde. Thus, it had to be established if these unusual compounds really occur in rocks or if they are artifacts of the heat extraction technique. Information about this point was obtained by a comparison of various methods of extraction (grinding, vacuum extraction, heating at variable temperatures and with various devices). The results of this study and general considerations led us to conclude that only sorbed species are capable of fulfilling the two opposite properties required for the exploration of concealed orebodies :

1. to escape slowly from their formation site at depth and

2. to remain a long time in outcropping rocks in sufficient amounts to enable their detection.

Basically, sorbed species can be extracted by pumping or heating. Laboratory tests have demonstrated that the first method is difficult to apply and gives no meaningful results.

On the other hand, heat extraction, used up to now for exploration tests, has proven its usefulness for the routine analysis of a large number of samples. Experiments of stepwise heating of rock samples in sealed vessels and other experimental conditions, have shown that the release of gases appears to take place in two successive stages. With the samples studied, containing low mature organic matter, the first stage, observed from ambient temperature to about 200°C is thought to result from the release of sorbed compounds, no thermal cracking of the organic matter contained in the sample being expected at such low temperatures. The thermal cracking could be responsible for the second gas emission stage observed at higher temperatures (>200°C). Sorbed gases released by heating up to about 200°C, contain high proportions of alkenes and other unusual organic compounds which are not observed in the free gases, initially contained in the pores of freshly drilled cores, which are almost uniquely composed of saturated hydrocarbons. The ability of organic matter and minerals, to a lesser extent, to absorb hydrocarbons has been verified in the laboratory. The higher adsorption efficiency of alkenes relative to their saturated homologues, due to the presence of carbon-carbon double bonds, may explain why they are released only by heating.

These observations support the idea that alkenes and oxygenated volatile compounds observed when heating the rocks at moderate temperatures (<200°C approx.) are normal components of sedimentary formations which are not released by other extraction procedures.

2.2 FIELD STUDIES

Two different field studies have been carried out to determine the relation between volatile organic compounds and mineralization. The first one deals with the analysis of 81 outcrop samples taken from various mineralized and unmineralized areas in Liassic rocks along the eastern margin of the Causses Basin (France).

Previous geochemical studies on the Treves Zn-Pb-Ba deposit and on various other locations of the region, led to the conclusion that mineral occurrences in Liassic terranes of the whole area probably resulted from a unique low temperature hydrothermal event which was also responsible for the dolomitization of the host carbonate formations. Sulfide formation resulted very likely from biological activity developed where warm hydrothermal solutions met with cold surface waters. The inorganic analyses showed that eight of ten localities investigated are mineralized (i.e. individual samples containing more than 30,000 ppm Zn and/or 3,500 ppm Ba). All the mineralized samples are dolomitized (Mg/Ca>0.33), and all generally contain high concentrations of Hg (between 50 and 230 ppb for individual samples). The dolomitized samples, mineralized and barren, display a hydrocarbon gas composition (C1 to C4) with a tendancy towards pure methane ("dry gas"), whereas calcarenites contain relatively high proportions of C_2-C_4 alkanes and alkenes ("wet gas"). This thermal maturity relationship is confirmed by Rock-Eval pyrolysis data, which show parallel increases in the values of the Tmax maturity parameter and the proportions of methane in gas fractions from the corresponding samples. The Rock-Eval method also reveals migrated oils or bitumens in many samples exhibiting a mature gas composition. These compounds were very likely brought in by the hydrothermal fluids responsible for the abnormal maturity, dolomitization, and ore deposition of the corresponding samples. These results clearly demonstrate the possibilities offered by the analysis of volatile organic compounds to detect paleo(hydro)-thermal events with which mineralization may have been associated.

The second approach was to try to get a better insight into the origin of gas signatures through a comparison with detailed analytical results on the other organic compounds contained in the corresponding samples, and amenable to classical geochemical studies (Rock-Eval pyrolysis; bitumen extraction and fractionation; analysis of the saturated and aromatic hydrocarbons by gas chromatography (GC) and GC-mass spectrometry (GC-MS)). The work was undertaken on samples from the Les Malines mine (Gard, France). Les Malines is an unconformity type Zn-Pb deposit which comprises various types of mineral occurrences (veins, massive bodies, ore minerals breccia cements) in the Georgian dolomitic basement, Triassic marls and conglomerates and Bathonian dolomites.

Analyses have been performed on 19 samples representing most of the mineralized and barren facies encountered in the mine and taken from five different workings : Ratonneau, Vieille Mine, Espérance (4 samples each), Mondardier (6 samples) and Sanguinade (1 sample).

Organic carbon contents, rarely exceeding 1 % TOC, are due to autochtonous and/or allochtonous material. Autochtonous organic matter is, as expected, very mature in the metamorphosed basement, but only slightly mature in Triassic marls (beginning of the oil window). Except a low mature oil impregnating the old basement at Mondardier, the allochtonous materials is represented by (pyro) bitumens associated with barite, precipitated in fractures and voids, by hydrothermal fluids (300°C; Ramboz and Charef, 1988). Warm water circulations are certainly responsible for strong alteration of the saturated hydrocarbon signatures produced by the corresponding samples, as the result of various phenomena : water-washing, molecular "chromatographic" segregation and thermal cracking. Despite the extent of this alteration, Rock-Eval pyrolysis of the solid pyrobitumens, reveals that they also seem to have undergone thermal maturation caused by burial diagenesis. This observation indicates that oil and bitumens migration and emplacement very certainly occurred early during the deposition history of the sedimentary cover.

Because of low organic matter contents, low maturity and absence of any signs of change in composition of the associated hydrocarbons, the Triassic marls, sole rocks to have some oil potential in the mine area, can hardly be regarded as the source of the allochtonous carbonaceous substances. Increasing amounts of these latter products, from E to W, may indicate that they were expelled from sedimentary (Triassic?) formations of the Languedoc basin. The mineralizing character of the oil-bearing brines is suggested by the general association between migrated oil/bitumen and ore, both accumulated in paleo-reservoirs and likely conduits (conglomerates, faults and fractures). The ore metals may have precipitated as the result of bacterial sulfate-reducing activity involving organic matter from the Triassic marls and adjacent formations (and not at the expense of hydrocarbons as hypothesized in a previous study; Connan and Orgeval, 1977). The part played by hydrothermal fluids (Ramboz and Charef, 1988 and other references in the text) in the ore deposition is almost impossible to appreciate. However, the general low maturity of autochtonous organic materials indicates that the circulation of warm solutions has certainly been restricted to faults and other particularly favourable conduits.

Variations in hydrocarbon gas signatures between mine samples can be explained by the mixing of dry gas (CH_4) originating from the metamorphosed basement, with wet gas (CH_4 an higher homologues) produced by autochtonous and allochtonous Triassic organic materials. The upward migration of components from the latter source may be responsible for a surface anomaly previously delineated to the SW of the mine, in the Causses basin (Disnar et al., 1986). However, the real significance of this anomaly for metal exploration is questioned by the possibility, mentioned here and above, that the mineralizing fluids may have originated to the SE.

3. RESULTS OF THE IRISH TEAM

3.1 LABORATORY STUDIES

The fist stage of the project concentrated on a re-examination of the analytical method to try to identify and eliminate the sources of poor precision. These were found to be due mainly to poor sealing of the sample vials during the heat extraction process, and to varying amounts of residual contaminants as the result of inadequate cleaning of the vials between extractions.
The lower blank values resulting from this improvement in hygiene revealed that some batches of silicone rubber discs used to seal the sample vials were also a major source of contamination.

Three limestone samples used as standards were run at intervals throughout the analytical campaign, which lasted intermittently from 1988 - 1990. Two of these showed good agreement, with standard deviations better than 30 % for most components. The third sample showed much higher variation for most components even though the mean results were similar. The reasons for this are not understood, but it is clear that the consistency of release may vary even between samples of similar lithology.

3.2 FIELD STUDIES

Field studies were completed in Ireland, United Kingdom and Belgium, with samples being submitted from other projects, such as Almaden (Spain), Rhodope (Greece), Rittsteig (Germany), and from a number of Carboniferous areas by the British Geological Survey (BGS, UK).

Most of the fieldwork was concentrated in Ireland, which has current and former mines (Tynagh, Silvermines, Gortdrum, Navan), as well as the highly prospective Galmoy-Lisheen area, and numerous minor mineral projects and occurrences. Samples were collected at an average density of 1 sample per 9 km^2 (2500 samples), the location of sample sites being determined by exposures marked on 1 : 63360 geological maps in the Geological Survey of Ireland.

455 samples were collected from UK Carboniferous areas in the Southern and Northern Pennines, on 1 sample per km^2 grids.

90 samples were collected from the Belgian Carboniferous of the Dinant basin, and another 100 pulps from previous trace metal work studies were analysed.

In addition to samples collected as part of this project, samples submitted from other projects were also analysed. These included 200 samples submitted by the BGS, 238 samples by Minas de Almaden, 86 samples from a base-metal prospect in Bavaria (Rittsteig), and 20 samples from Greece

(Rhodope). Altogether about 3,700 samples were analysed for hydrocarbons. The 2500 Irish samples were also analysed for Cu, Pb, Zn, Mn, Fe, Ca, Mg, insoluble residues and total organic carbon (TOC).

3.3 ANALYTICAL RESULTS

3.3.1 Ireland

If the hydrocarbon approach is to be genuinely useful, it has to be able to cover large areas at low density, preferably using only the available outcrops. This meant starting a fresh evaluation from scratch, using all twelve hydrocarbon species or groups identified by the heat extraction procedure, and either confirming the previous conclusions or deriving a new set of diagnostic parameters. This was achieved in three stages by taking increasingly large areas in Ireland and seeing how the hydrocarbon signatures responded to the mineralization encountered, or to lithological variations, and eliminating those that showed no correlation.

Silvermines basin

The first area selected, the Kilmastulla syncline in the Silvermines basin, contains the erstwhile Silvermines deposit. The 44 samples collected from the 60 km^2 area showed traces of the original propyne anomaly close to the mine itself and the suggestion of C4 enrichment to the north of it. However, a methane envelope was not detected. There were indications of lithological influences too : the lower (subreef) shaly lithologies appeared to have higher amounts of many components than the reef itself.

1:126720 Sheet 18

The next stage was to look at a complete 1:126720 sheet, Sheet 18, with a total area of about 5000 km^2 of which about 65 % was Carboniferous limestone. 286 samples collected from this sheet represent about 1 sample per 11.5 km^2 of Carboniferous terrain. All hydrocarbons were examined along with a suite of trace and major elements.

The results showed large variations in the absolute amounts of all hydrocarbon compounds, many of them at least partly related to TOC content. The reasons are debatable : more TOC may mean more sorption sites available for attachment of hydrocarbons passing e.g. in solution, or it may mean more sidechains remaining from the original organic matter which are available for release by the heat extraction process. Use of ratios (percentages) very much reduced the obvious TOC-related effects such as higher values occurring in shaly lithologies at the base or top of the Dinantian succession.

As with the Silvermines deposit, these results did not indicate anomalous methane round mineral deposits. However, associated with some of them (Carrickittle-Gortdrum, Galmoy-Lisheen) were methane lows due to enhanced amounts of propyne and/or C4 compounds. Silvermines itself does not show up, although most of the samples from the Silvermines basin are anomalous fro propyne. Other methane lows, mainly due to C4 compounds, were present mainly in the S and SE of the area, either at the top or at the base of the Dinantian succession. The Aherlow deposit lies close to one of these, but most of them are of doubtful significance from a mineral exploration point of view.

In the case of the major and trace elements, lead and zinc highlight the Silvermines syncline, as well as the propyne anomaly associated with Carrickittle and Gortdrum and the methane low in the Galmoy-Lisheen area. A magnesium anomaly is also associated with this zone, where dolomite is extensive.

All Irish results

The final stage of the Irish assessment programme was to examine the hydrocarbon and trace metal data for all 2500 samples collected from the Irish Carboniferous, concentrating on the main parameters suggested from the orientation studies above, to have possible diagnostic value.

Propyne is the only hydrocarbon which defines the main base metal mines (Navan, Tynagh, Silvermines) and the increasingly important Galmoy-Lisheen zone at the low sample densities used. Methane is the only other hydrocarbon which highlights even two of the four. Lead, zinc and iron are all anomalous for three out of the four deposits, but not the same three.

Taking the 23 deposits/prospects on the most recent geological map within about 1 km of a sample point, methane, copper and iron pick out about half of them (11,12), and propyne and zinc slightly less than half (9,8). The low degree of correlation with C4 compounds confirms the earlier suspicion that C4 anomalies are not generally related to mineralization. The "wet gas" signature shows no correlation either, but its inclusion (along with the saturated/total C4 parameter) was to look for evidence in the hydrocarbon composition of lower regional temperatures in the N. of the country. This is clearly indicated.

The total response of the above parameters to mineralization hides what may be important differences between the north and south of the Irish study area. Most of the methane-linked deposits (eight out of 10) lie in the south as do most of the iron-associated ones (7). In the north, copper is the best marker (eight out of 13).

Regionally there are therefore two distinguishable marker groups :

North : THC, methane, propyne, copper, manganese, iron

South : Methane, propyne, zinc, iron and magnesium

It can be seen that the THC and methane link is at least partly related to organic maturity - THC being more important than methane in the "cooler" north and the converse in the "hotter" south.

3.3.2 United Kingdom

The 455 United Kingdom samples were collected from the S. Pennines Orefield (120 samples), the Trough of Bowland (Clitheroe) area (125 samples) and the N. Pennines, including the N. Pennines Orefield (210 samples). These samples were only analysed for hydrocarbons.

Vein-type mineralization in the S. Pennines only shows a weak link with propyne anomalies in a small part of the area, even using a sample density double that in Ireland to compensate to some extent for the smaller size of deposit. Many anomalous "wet gas", Total C4 and sat. C4 results are from samples close to veins.

Neither is there any obvious hydrocarbon response to similar mineralization in the N. Pennines. "Wet gas" anomalies there only occur in the interblock troughs (shalier lithologies, lower temperatures). Acetaldehyde often correlated with the "wet gas" and associated responses in both the Northern and Southern Pennines.

Clastic sediments (sandstones and siltstones) invariably have much higher methane and propyne levels than limestones. Use of percentages reduces the affects of this, but comparison of limestone with sandstone data has been deliberately avoided.

Drill core samples submitted by BGS from the Southern and Northern Pennines show a completely different response to surface samples - much more propyne, acetaldehyde, C4 and C5+ compounds.

3.3.3 Belgium

In the limited Belgian sampling, La Calamine gives a weak response but vein systems elsewhere show no response. Rock material finely pulverised for several years apparently loses C4 compounds but gains propyne compared to freshly collected coarsely crushed material.

3.3.4 Spain (Almaden)

Surface quartzite samples round the Almaden deposit show high methane levels (cf. English sandstones), but there is no obvious response to the mercury mineralization there. Underground samples contain about 80 % less methane and ten times more propyne than the surface samples. Different lithology is suspected.

3.3.5 Germany (Rittsteig)

Outcrop samples from a lead-silver occurrence in Bavaria showed a methane low associated with a moderate soil anomaly, but no propyne high was associated. The methane low appeared to be due to slightly higher amounts of several hydrocarbons, especially ethene and propene, rather than to a particular species, and as such it resembles the C4 anomalies found in Ireland of doubtful diagnostic value.

3.3.6 Greece (Rhodope)

The few samples submitted by IGME from this project in Greece showed nothing of interest with respect to this study.

3.4 SURFACE vs. UNDERGROUND SAMPLES

Discrepant results from surface and underground samples have been encountered twice during this project :

- the contrast between BGS core samples and surface samples collected by us from similar areas;
- the contrast between surface and underground samples collected by Minas de Almaden staff.

In the BGS case, far more core samples contained detectable propyne and amounts of acetaldehyde which would normally be regarded as indicating contamination, than in surface samples.

At Almaden, there was no difference in acetaldehyde levels, but methane was much lower and propyne much higher in underground samples. Similar differences have been suspected before (at Navan, and at the Bidjovagge deposit in Norway).

The fact that the underground samples usually have higher contents of one or more compounds suggests that exposed rock loses hydrocarbons. This could explain the United Kingdom observations, but not the Almaden ones, where underground samples contain more propyne but less methane that outcrop.

Suffice it to say that hydrocarbon results from surface and subsurface samples may not be directly comparable. Additional research is required.

4. CONCLUSIONS

4.1 THE HEAT EXTRACTION PROCESS

Laboratory observations by the French team strongly support the idea that volatile compounds can be strongly held in rocks, under the sorbed state. A comparison of the results provided by various techniques reveals that heating is certainly the most appropriate way (probably the only one) to release them effectively. Sorption is also the only process which permits the compounds to remain in the rocks for long periods of time, and also allows them sufficient mobility to migrate form concealed orebodies.

4.2 IMPROVEMENTS IN THE ANALYTICAL TECHNIQUE

Studies by the Irish team improved the reliability of their version of the heat extraction process, but the precision of the analytical results did not increase as much as expected. They conclude that there is inherent variation in 1-4 mm rock fractions which cannot be easily reduced. It would be consistent with irregular distribution of organic matter, which the French team suggests provide the majority of hydrocarbon sorption sites.

4.3 THE RELATIONSHIP BETWEEN HYDROCABON GASES, TRACE METALS AND ORE GENESIS

Field studies by the French team demonstrate variations in gas signatures in response to mineralizing events, leading to the possibility of detecting corresponding variations in surface rocks. In Liassic sediments of low thermal maturity, higher trace metal levels tend to be associated with increasing proportions of methane ("drier" hydrocarbons; higher fluid temperatures).

In addition, organic geochemical studies carried out on samples from the Les Malines mine, suggest new genetic hypotheses, supplementing or contradicting previous interpretations.

Studies by the Irish team in Carboniferous areas of very high thermal maturity, also point to a strong correlation between some hydrocabon species (propyne) and mineralization, be it with known mineral deposits, or with trace metal anomalies, or both. Although the relationship between hydrocarbons and trace metals was not examined in the UK or Belgian studies, there does not seem to be any obvious hydrocarbon response to the predominantly vein type mineralization in the Carboniferous rocks of these countries. This difference in response is mainly thought to be a function of deposit size, and could have considerable exploration significance.

Both teams have therefore established a direct link between hydrocarbon gases and base metal mineralization.

5. ORAL COMMUNICATION AND PUBLICATION

DISNAR J.R., 1990. Volatile hydrocarbons in Ba-Zn-Pb ore genesis: analysis and use in mineral exploration. J. Geochem. Explor., 38, 205-224.

DISNAR J.R. et DEFOIX D., 1990. Use of volatile hydrocarbons held in rocks for mineral exploration. CIGG: colloque International sur Géochimie des Gaz, Mons, Belgique, 3-6 Octobre 1990. Résumé no. 12, p. 4.

Ta-Nb-W-Sn-Mo MINERALIZATIONS ASSOCIATED WITH ACID MAGMATISM. LINKS WITH ORE-BEARING HYDROTHERMAL SYSTEMS

Project Leader: J. VERKAEREN
J. Salemink
Université Catholique de Louvain (U.C.L.), Laboratoire de Minéralogie Appliquée, Belgique

D. Garcia and L. Raimbault
ARMINES, Ecole des Mines, Saint Etienne, France

Contract MA1M-0004-C

1. OBJECTIVE AND INTRODUCTION

This contribution to the development of geochemical methods in mineral exploration focuses on granite-related mineralizations. Earlier studies evidenced the importance of a magmatic contribution in W-bearing skarns (GUY and VERKAEREN, 1988) and the genetic similarities between skarns and other types of W-bearing ores (veins, greisens). The present study enlarges the scope of our previous investigations in two main directions :

- It concerns a wider range of metallic associations which are related to acid magmatism, namely the Fe-(Cu)-W, W-Mo, W-Sn (Nb, Li) or Ta-W (Nb) associations;

- It provides a deeper insight into the nature of the associated magmatism and the differentiation processes which concentrate the ore elements; in particular, magmatic rocks have been studied not only for themselves (chemistry, internal evolution, ore potential), but also as elements of magmatic suites that reflect more deep-seated differentiation processes, a task which often led us to develop our geochemical investigations on a regional scale.

This emphasis on magmatic processes is deliberate, not only because they are thought to concentrate ore metals, but also- and more pragmatically - because they offer an almost unique possibility of predictive modelling and hence they may provide quantitative methods to check the economic interest of a given prospect.

Hydrothermal processes are of course not neglected and one of our main goal is to demonstrate the necessary superposition of a magmatic enrichment of ore elements combined with a redistribution and reconcentration by hydrothermal fluids of distinctive origins.

2. MATERIALS AND METHODS

We report here the main geochemical results of a comparative study on 13 ore-bearing systems whose locations are shown on figures 1 and 2. These examples have been selected in order to cover the large range of geological situations of interest in mineral exploration. Our area of expertise allows some general features of magmatic-hydrothermal systems to be evidenced and some classification made; perhaps more than a typology of granite-related ores, it offers a representative spectrum of examples within a continuum of geological processes that lead to the formation of economic deposits.

2.1. MAGMATIC UNITS AND EVOLUTION PROCESSES

In each area of expertise, geochemical methods were used primarily in order to identify the exposed suite(s) of magmatic rocks. We combined the analysis of several isotopic ratios ($^{87}Sr/^{86}Sr$, $\delta^{18}O$, D) in whole rocks and minerals with the determination of major and trace element concentrations by complementary techniques (XRF, ICPAES, NAA).

The great variety of elements analyzed in each case allowed us to identify in the observed suites some compatible elements (e.g. Mg, Co, Ni, Ti almost systematically) as well as the hygromagmaphile ones despite the scarcity of this latter kind of elements in felsic systems (Ta, Nb, W, Sn in most cases, sometimes Th). The nature of the evolution processes was thus inferred from the geometry of selected bivariate concentration diagrams; as an example, a pair of elements of contrasting behaviour such as Ti and Ta may be used to discriminate fractional crystallization from batch melting; on the other hand, element pairs which exhibit close similarities (Nb-Ta, Zr-Hf, REE) were extensively used in this study. Quantitative modelling of the magmatic processes was performed whenever possible in order to predict the metallic content of successive melts within a given suite, a necessary step towards the evaluation of the ore potential of the magmatic-hydrothermal systems in the course of mineral exploration.

2.2 HYDROTHERMAL SYSTEMS

Hydrothermally derived materials include replacement bodies (skarns, greisenised areas) as well as vein fillings. Stable isotopes (H, C, O, S) and/or selected trace element ratios in hydrothermal minerals were used to constrain the fluid sources and the geometry of hydrothermal circulations. The use of radiogenic isotopes as fluid tracers was tested on the Traversella skarn deposit (Italy) with encouraging results (Rb-Sr system).

Special attention was paid to the element ratios which are sensitive to the degree of differentiation of magmatic systems (REE patterns, Nb/Ta); such parameters were extensively used in the precise identification of the magmatic parents of the observed mineralizations. In order to increase the applicability of this method we investigated the partitioning of REE between minerals and fluids in some favourable cases, and the previous database was extended to include new minerals (garnet, helvite, beryl and tourmaline).

3. ANALYSIS OF RESULTS

Our database is considerably enlarged by hundreds of analyses. We choose to discuss here some selected examples which clearly enhance the understanding of the main geochemical processes investigated in this research project.

3.1 MAGMATIC PROCESSES

Pairs of incompatible elements like Nb-Ta may be used :

(1) To distinguish between fractional crystallization and partial melting.

(2) To show the extend of magmatic preconcentration of ore elements.

(3) To show the influence of the initial magmatic composition on the relative preconcentration of ore elements.

Fig. 3 is an illustration of these statements. It concerns the Dajishan (China) and the Echassières (France) magmatic suites (Figures 1 and 2). The Dashisjan deposit is of wolframite vein type. These veins however are related to a garnet-bearing granite cupola which hosts W and Ta disseminated ores. Echassières is a Sn-Ta-Li deposit of disseminated ore in a granite cupola. Both granites are distinctly peraluminous with A.S.I. (alumina saturation index) of 1.24 for Dajishan and 1.43 for Echassières. The main differences lie in Si and P contents: high Si and low P at Dajishan and low Si and high P at Echassières (RAIMBAULT et al., 1989). In a bilogarithmic Nb-Ta diagram (fig.3) both magmatic suites lie on nearly parallel straight lines indicating a magmatic evolution by fractional crystallization. Nb and especially Ta are distinctly enriched during this evolution. The initial distinct Nb/Ta values for the least evolved liquids are clearly related to the differences in ASI values. Magmatic evolution plays thus a fundamental role in determining ore element preconcentration. As it can be seen on fig. 3, some of the most evolved granites, which are ore bearing, plot on incurved trends indicated by an arrow, with a marked enrichment in Nb. This is interpreted as the result of hydrothermal reworkings by late magmatic fluids.

Other pairs of elements are extensively used in the framework of this project. For example the Zr-Hf pair is a very useful tool to distinguish between partial melting and fractional crystallization. In this context, some particularly clear results have also been obtained using pairs of compatible versus incompatible elements like Ti-Nb, Ti-Ta, Ti-Rb etc as it is emphasized by granitic suites in southern and northern Vosges (France).

3.2. HYDROTHERMAL PROCESSES

Although a significant magmatic enrichment of the ore metals was reported in many cases, hydrothermal reworking proved to be necessary to form economic ores, even in the disseminated Ta-Nb bodies. As we showed in the previous studies, most of the hydrothermal systems involved two or more sources for the fluids. Mixing and/or superposition of fluids from different origin are common, particularly in well mineralized areas. None of the mineralized solutions was found to be free from a granitic contribution.

We summarize hereafter the main geochemical results obtained on the Traversella Fe-W-(Cu) skarn deposit (Italy) which provides a particularly clear example of such complex processes.

At Traversella, the oxygen isotope composition ($\delta^{18}O$) of water in equilibrium with the diorite is 8.0°/₀₀. At 600°C, the water in equilibrium with the early stage of skarn formation ranges from 8.3 to 8.9°/₀₀. At the beginning of the first hydroxylation stage, the fluid's $\delta^{18}O$ remains in the same range as above but it decreases at the end of this stage to 5.0°/₀₀. During the sulfidation stage, the $\delta^{18}O$ of the fluid decreases more gradually from 5.0 to 3°/₀₀.

The strontium isotope composition of the early silicates ranges from the values observed in the dolomitic marbles (0.70874 to 0.70971) to that of the intrusion (0.70947 to 0.71064). During the secondary stage, there is a progressive increase up to 0.71372.

In conclusion, both stable and radiogenic isotopes suggest that the early high-temperature metasomatic fluid was equilibrated with the dioritic intrusion. This fluid was either exsolved from the intrusion (magmatic fluid) or equilibrated with the intrusion (metamorphic fluid). During the secondary stage, the replacement of early anhydrous phases by hydrated ones was accompanied by a decrease of ^{18}O and an increase of the initial strontium isotope ratio, indicating a progressive mixing with a fluid of a meteoric origin. This mixing was responsible for the formation of the major ore bodies (magnetite+scheelite+minor Cu sulfides).

Many other geochemical tools (especially REE in minerals) may be used to further support these conclusions (this report).

Furthermore, differential mobility of ore elements during magmatic and hydrothermal processes appears to exist. The results especially from the Vosgian granitoids, clearly reveal the existence of an order of mobility upon hydrothermal alteration among the elements Ta, Nb, Sn, W, Mo. The two hygromagmaphile elements Ta and Nb appear to be the most strongly enriched upon fractional magmatic crystallization, and the least susceptible to hydrothermal-metasomatic mobilization, whereas Mo is virtually unaffected by magmatic specialization, and predominantly mobilized by hydrothermal-metasomatic actions. Sn and W are magmatically enriched by fractional crystallization, and they are strongly mobilized by hydrothermal activities.

In the Soultzbach cupola (Vosges, France), the distributions of Cu, Pb, and Zn within the leucogranite were used as patterns fingerprinting the channel ways of the hydrothermal fluids.

3.3. GEOCHEMICAL VARIATIONS WITHIN ORES

Changes in the nature of the chemistry of ore minerals within hydrothermal systems have received a lot of attention from economic geologists, because of direct applications to the search for ore extensions. Our insight into this problem is by no means complete because each area of study has its sampling limitations. Nevertheless, the geochemical variations within ores are definitely not random and some of the studied parameters may provide useful tools in mineral exploration.

Efficient tools are :

(1) Trace elements (Ta, Nb, Sn, Ga) in hydrothermal muscovites.

(2) Trace-elements in Ca-bearing minerals as Ta in scheelite, fluorite, and garnet.

(3) H isotope composition of hydrothermal muscovites.

3.4. ESTIMATING GRANITE PRODUCTIVITY

In granitic systems, loss of metals occurs during magmatic degassing and/or hydrothermal reworking by externally derived fluids.

Quantitative modelling of the metal extraction has been performed using mass-balance calculations in the wolframite-vein system of Dajishan (China) and in the Sn-W veins associated with the Vale das Gates granite (Northern Portugal). These models may lead to quantitative estimates of ore reserves in a given deposit. The basal prerequisite to perform them is that one has to know the mode of differentiation of associated granitic rocks.

4. CONCLUSIONS

In order to prospect Ta-Nb-W-Sn-Mo, both magmatic and hydrothermal processes have to be taken under careful examination.

Only magmatic suites linked by fractional crystallization are to be selected in a given region, and those exhibiting large ranges of evolution seem to be the most promising ones. Preconcentration of the ore elements during evolution seems to be a prerequisite for further concentration processes. The nature of magmatism also plays a role in the level of the magmatic concentrations. Efficient geochemical tools to distinguish fluid sources are the combination of O and Sr isotopic compositions and REE distribution in magmatic and hydrothermal minerals.

Reconstitution of hydrothermal events and fluid channelways are very important in exploration especially in the search of extensions of known ore bodies. Adequate tools are H isotopic composition and trace element composition (Ta-Nb-Sn-Ga) in hydrothermal muscovites and Ca-bearing hydrothermal minerals, and distribution contours of some trace elements (Nb, Rb, Sn, W, P, Zn) mapped in small granitic cupolas.

Finally ore reserves may be evaluated in some favourable cases using mass balance calculations between parent liquids and lixiviated rocks, given the knowledge of the mode of magmatic differentiation.

5. BIBLIOGRAPHY

1. Demange M., Derré C., Fonteilles M., Guy B., Krier-Schellen A.D., Soler P., Verkaeren J., and Zahm A.
   THE SCHEELITE SKARN DEPOSIT OF SALAU (ARIEGE, FRENCH PYRENEES)
   Econ. Geol.,84, 1172-1209, 1989

2. Desmedt A., and Sonnet Ph.
   GENESIS OF SCHEELITE-BEARING CALCSILICATE GNEISSES IN THE TANNERON MASSIF (VAR, FRANCE). MONOGRAPH SERIES IN MINERAL DEPOSITS N°6.
   Ed. J. Boissonnas and P. Omenetto, Springer-Verlag, pp. 160-178, 1988

3. Dubru M., Vander Auwera J., Van Marcke de Lummen G., and Verkaeren J.
DISTRIBUTION OF SCHEELITE IN MAGNESIAN SKARNS AT TRAVERSELLA (PEIMONTESE ALPS, ITALY) AND COSTABONNE (EASTERN PYRENEES, FRANCE) : NATURE OF THE ASSOCIATED MAGMATISM AND INFLUENCE OF FLUID COMPOSITION.
Monograph series in mineral deposits, n° 6, J. Boissonnas and Omenetto, Springer-Verlag, pp. 117-134, 1988

4. Garcia D.
IMPORTANCE DE LA FRACTION CUMULATIQUE DANS LES GRANITOÏDES PRODUITS PAR CRISTALLISATION FRACTIONNEE ; EXEMPLE DES GRANITES DE LA REGION DE VILA REAL (NORD PORTUGAL).
C.R. Acad.Sci.Paris, 307, série II, 1879-1885, 1988

5. Garcia D. and Vilela de Matos A.
DIVERSITE DES SOURCES DES FLUIDES ET DES METAUX DANS LES GITES A Sn-W; EXEMPLES DES GREISENS DE VILA, NORD PORTUGAL
In Gisements métallifères dans leur contexte géologique : condition de formation des minéralisations à Sn-W.
Doc. BRGM, n° 158, vol. I, 59-77, 1988

6. Guy, B. and Verkaeren, J.
Tungsten and associated metals ore deposits in western Europe: development of a geochemical tool of general validity in mineral exploration. In Donato M. and Van Wambeke L. (eds.)
SUMMARY REPORTS OF THE SUBPROGRAMME : METALS AND MINERAL SUBSTANCES (1982-1985), Vol. 1, pp. 103-114. Luxembourg Office for Official Publications of the European Communities, 1988.

7. Raimbault L.
THE RECORDING OF FLUID PHASES THROUGH REE CONTENTS IN HYDROTHERMAL MINERALS. A CASE STUDY : APATITES FROM THE MEYMAC TUNGSTEN DISTRICT (FRENCH MASSIF CENTRAL)
Mineral deposits within the European Community,
J. Boissonnas and P. Omenetto eds., Springer 151-159

8. Raimbault L., Azencott Cl., Joron J.L., Gruffat J.J., Moutte J., Ouin M.C.
ANALYSE DE 129 ECHANTILLONS DU MASSIF GRANITIQUE D'ECHASSIERES (MASSIF CENTRAL FRANCAIS), DONT 67 ECHANTILLONS DU SONDAGE GPF. LE FORAGE SCIENTIFIQUE D'ECHASSIERES (ALLIER)
Données analytiques recueillies de 1985 à 1987, Doc. BRGM, 124, 369-418, 1988

9. Raimbault L., Kaelin J.L.
PETROGRAPHIE ET GEOCHIMIE DE LA GRANODIORITE DE LA FOURQUE (GISEMENT DE SCHEELITE DE SALAU, PYRENEES, FRANCE).
Bull. Minéral. 110, 633-644, 1989

10. Raimbault L., Meyer G., Treuil M.
COMPORTEMENTS DIFFERENCIES DE W, Sn, U, Ta, Nb dans quelques complexes granitiques du Massif Central Français
Bull. Minéral. 110, 591-601, 1987

11. Schellen A.D. and Dubessy J.
THE GEOBAROMETER FLUID-PYRRHOTITE : APPLICATION TO THE SALAU W DEPOSIT.
Geochem. Cosmochim. Acta

12. Vander Auwera J.
MINERALOGICAL AND CHEMICAL COMPOSITION OF SKARNS DVELOPED IN MICASCHISTS AT TRAVERSELLA (SESIA-LANZO ZONE, ITALY)
Abstract. Miner. Soc. Bull. 72, 7, 1986

13. Vander Auwera J. and André J.
O, C AND Sr ISOTOPES AS TRACERS OF THE METASOMATIC FLUIDS : APPLICATION TO THE SKARN DEPOSIT (Fe, Cu, W) OF TRAVERSELLA (IVREA, ITALY)
Accepted for publication in Geochim. Cosmochim. Acta, 1988

14. Van Marcke de Lummen G. and Vander Auwera J.
PETROGENESIS TO THE TRAVERSELLA DIORITE (PIEMONTE, ITALY) : A MAJOR, TRACE ELEMENT AND ISOTOPIC (O, Sr) MODELLING
Lithos, 24, 121-136

Ph. D. Theses

15. Croze V.
ETUDE DU SKARN A TUNGSTENE DE LONGOBUCCO (CALABRE, ITALIE) DANS SON ENVIRONMENT GRANITIQUE.
Pétrographie et géochimie,
254 p., 1989

16. Desmedt A.
ETUDE PETROGENETIQUE ET METALLOGENIQUE DES MINERALISATIONS EN TUNGSTENE DU MASSIF GNEISSIQUE DE TANNERON (VAR, FRANCE). RECHERCHE D'UN LIEN GENETIQUE AVEC LE METAMORPHISME REGIONAL, L'ANATEXIE ET LA GRANITISATION
1990

17. Schellen A.D.
ETUDE MICROTHERMOMETRIQUE PAR INCLUSIONS FLUIDES DES PARAGENESES MINERALES DU GISEMENT DE SCHEELITE (TUNGSTENE) DE SALAU (PYRENEES, FRANCE)
1988

18. Teissier B.
MISE EN PLACE, PETROGRAPHIE, GEOCHIMIE ET MINERALOGIE DES GRANITES ASSOCIES AUX SKARNS MINERALISES EN TUNGSTENE DE FUMADE (TARN, FRANCE)
348 p., 1989

19. Vander Auwera J.
PETROLOGIE ET GEOCHIMIE DES SKARNS FERRIFERES ET TUNGSTIFERES DE TRAVERSELLA (PIEMONT, ITALIE)
1988

Oral communications

20. Fonteilles M., Raimbault L., Fouillac A.M.
MAGMATIC HISTORY AND GEOCHEMICAL CHARACTERISTICS OF GRANITES ASSOCIATED WITH DAJISHAN TUNGSTEN DEPOSIT.
International symposium on petrogenesis and mineralization of granitoids, Guangzhou, 7-10/12/87, 78-79

21. Garcia D. and Raimbault L.
Ta-Nb-W-Sn-Mo MINERALIZATIONS ASSOCIATED WITH ACID MAGMATISM : CHEMICAL EVOLUTION OF GRANITIC MAGMAS AND CHARACTERISTICS OF THE ASSOCIATED HYDROTHERMAL DEPOSITS.
Contact group, Padova, Sept. 1988

22. Raimbault L., Autran A., Cuney M., Fonteilles M., Rossi Ph.
EVOLUTIONS MINERALOGIQUES ET GEOCHIMIQUES EN CONTINU DANS UN APEX GRANITIQUE (ECHASSIERES)
Réunion SGF-GPF "Forages scientifiques continentaux", Paris, 24/04/89, 1989

23. Raimbault L., Croze V., Teissier B.
Ta-Nb-W-Sn-Mo MINERALIZATIONS ASSOCIATED WITH ACID MAGMATISM. GEOCHEMICAL CHARACTERISTICS OF GRANITIC MAGMATISM. LINKS WITH ORE-BEARING HYDROTHERMAL SYSTEMS.
Extended abstract of the St Etienne team contribution, Contact group, Paris, 21-23/11/89

24. Raimbault L., Fonteilles M., Fouillac A.M.
REE PATTERN EVOLUTION IN THE FLUID PHASE AND VEIN MINERAL COMPOSITION IN DAJISHAN TUNGSTEN DEPOSIT.
International symposium on petrogenesis and mineralization of granitoids, Guangzhou, 7-10/12/87, 250-251

25. Salemink J. and Verkaeren J.
Ta-Nb-W-Sn-MO MINERALIZATIONS ASSOCIATED WITH ACID MAGMATISM. GEOCHEMICAL CHARACTERISTICS OF GRANITIC MAGMATISM. LINKS WITH ORE-BEARING HYDROTHERMAL SYSTEMS : APPLICATIONS ON VOSGIAN LEUCOGRANITES.
Contact group, Paris, November 1989

26. Vander Auwera J. and Verkaeren J.
Ta-Nb-W-Sn-Mo MINERALIZATIONS ASSOCIATED WITH ACID MAGMATISM. GEOCHEMICAL CHARACTERISTICS OF GRANITIC MAGMATISM. LINKS WITH ORE-BEARING HYDROTHERMAL SYSTEMS.
Contact group, Padova, september 1988

27. Donato M. and Van Wambeke L.
SUMMARY REPORTS OF THE SUBPROGRAMME : METALS AND MINERAL SUBSTANCES (1982-1985)
Vol. 1, 1989

Fig. 1: DaJIshan W deposit - locatlon map

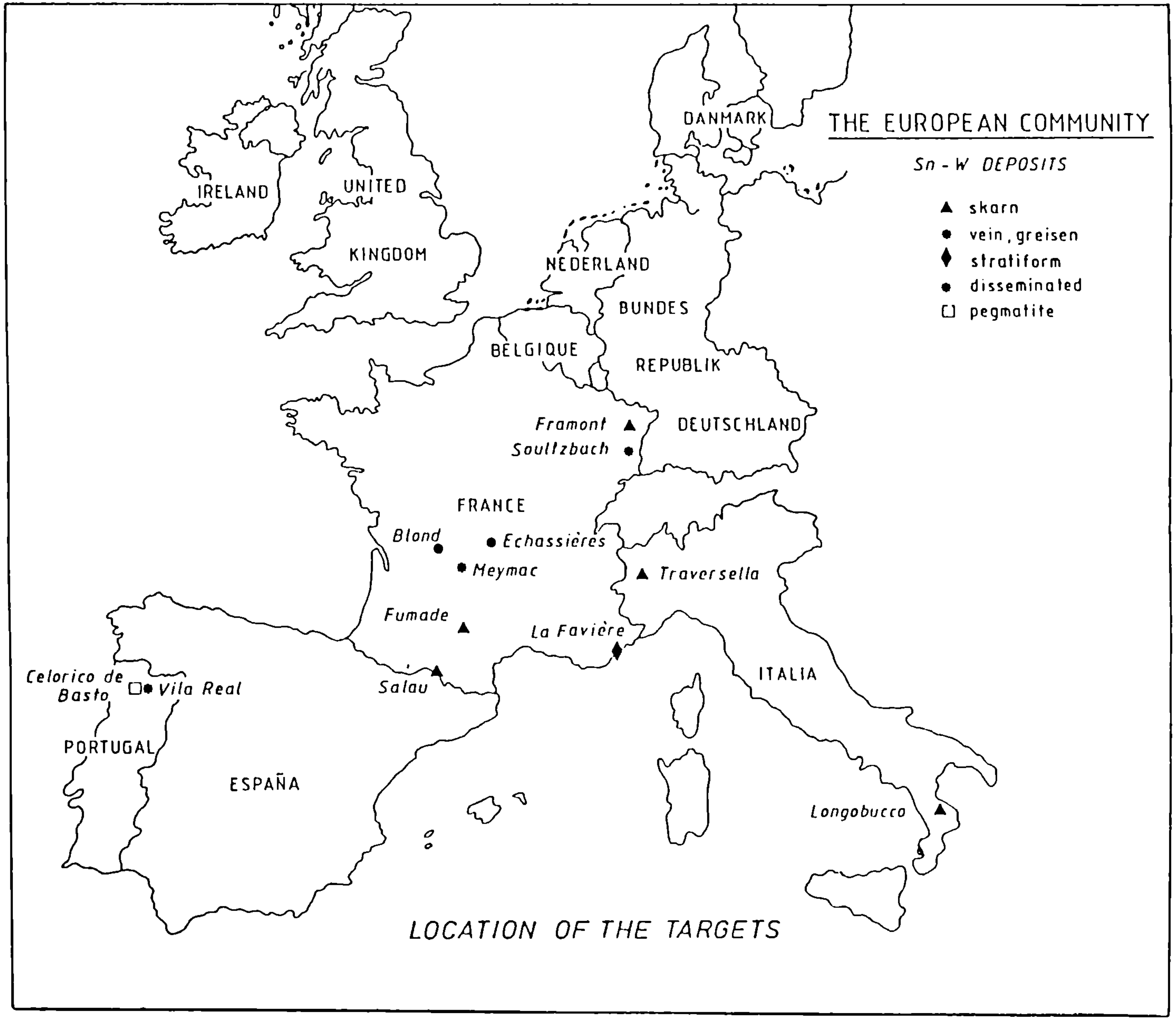


Fig. 2: Sn-W deposits of the EC - location map

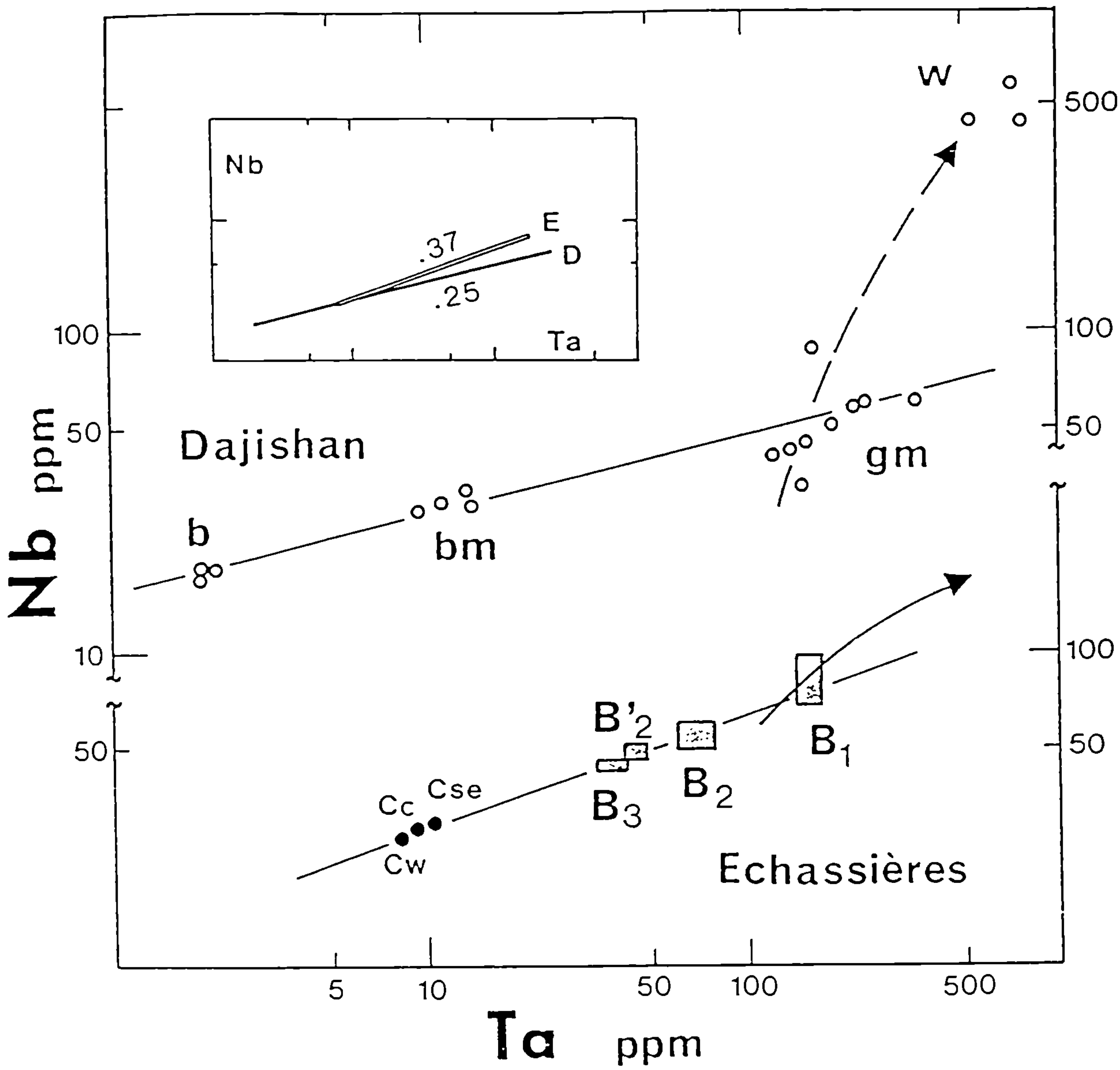


Fig. 3: Comparison of Nb/Ta relationships at Echassières and Dajishan.
The magmatic and hydrothermal late-magmatic stages are indicated by straight lines and arrows respectively. Comparison of the slopes of the straight lines is shown in inset. At Echassières, the arrow indicative of the hydrothermal stage is actually the envelope of ca.50 analytical data, not shown individually.

LATE ALPINE MAGMATISM AND RELATED W-Mo-Cu METALLOGENESIS IN THE ITALIAN ALPS (EXAMPLES FROM SOUTH TYROL AND PIEDMONT)

Project Leader: A. DELLA GIUSTA (*)
Dipartimento di Mineralogia e Petrologia
dell'Universita' degli Studi di Padova, Italia

Contract MA1M-0005-I

1. OBJECTIVES

The report presents the results of the comparative analysis of two Austroalpine areas of the Italian Alps (Fig. 1), where new discovered W-Mo(Cu-Au) showings lie in connection with shallow-level intrusions and dykes of Oligocene age: the Lago Verde-Lago Nero zone in the high Ultimo Valley (Ultental, South Tyrol) and the Cervo Valley near Biella (Piedmont). In terms of mineralization type and size, the economic significance of the stockwork ores spatially related to magmatic intrusions is low (Cervo Valley, W-Cu-Mo showings in the innermost monzogranitic core(1) to very low (Ultimo Valley, predominantly scheelite). Let us discuss here some significant aspects, from the geochemical viewpoint, of these "anomalous" magmatic lithologies (Fig. 2), to be considered - in our opinion - at least as interesting protoliths of an aborted economic ore-forming process.

2. INTRODUCTION

Selected example is the less and mostly tungsten-mineralized Lago Verde area. 27 samples (4 granites, 2 tonalites, 5 granodiorites, 7 monzonites, 1 quartz-diorite, 5 porphyrites, 3 mafic enclaves) have been analyzed for 38 major, minor and rare earth elements; 7 samples also for Sn, W, Mo, U. Globally, all the rocks plot in the calc-alkaline field (the intermediate types have the SiO_2 content interval between 53% and 62% of orogenic andesitic magmatism; GILL 1981) Fig. 3. In the HARKER's diagrams, (Al, Fe(tot), Mn, Mg, Ca, Na, K, P, Ti, Ba, Zr, Th, Cr, Ni, Sc and Nb-oxide content vs. SiO_2), along with the "normal" variations to be assigned to magmatic differentiation, we observe a

(*) Research coordinator (replaced by F.P. Sassi since November 1, 1987). Scientific-technical results are also due to M. Chiaradia, V. Meggiolaro, P. Omenetto, s. Primon / D. Visonà.

(1) The Cervo Valley-Tavagnasco-Brosso-Traversella district in Piedmont has been recently explored in the framework of the Italian Ministry of Industry activities. No practical interest resulted for the skarn ores linked to Traversella and Brosso intrusions. Some importance show only the veins parallel to the Canavese lineament, locally showing good scheelite and gold contents, in our opinion mostly governed by the lineament activity.

noticeable dispersion of the Na_2O and K_2O, due to the enrichment of these elements in the final interstitial melt. Noteworthy is also the compositional gap between the intermediate rocks and the granite dykes, and the appertainance of the mafic enclaves to two distinct groups (Fig. 4a, b, c). It is also possible to predict a consanguinity relationship between enclaves and related host rock.

Comparing the diagrams of the REE-normalized content of the "intermediate" intrusives, mafic enclaves, porphyrite ("andesitic") dykes and granites, three pattern types are recognizable:

- pattern A (granitic dykes): REE contents much lower than the other lithologies, no (or slightly positive) Eu anomaly, convex pattern. The granites do not seem consanguineous with the other magmatites;

- pattern B: the porphyritic dykes and "intermediate" rocks (except monzonite IS 4) show significant LREE fractioning, flat HREE pattern and practically absent Eu anomaly. The differences are consistent with slight fractioning of plagioclase and amphibole;

- pattern C: the mafic enclaves show distinct patterns with common low LREE fractioning. As indicated by major element chemistry, two groups of enclaves are recognizable: a) similar to pattern B, with possible plagioclase fractioning connection between enclaves and host rocks; b) the pattern C s.s., with high contents (and related low fractioning) of HREE and pronounced Eu anomaly, also typical of the "monzonite IS 4" sample.

We can therefore conclude that the granitic dykes (pattern A) do not derive by magmatic differentiation from the lithologies of patterns B and C. In turn, B and C lithologies are suggestive of two different sources, as it is also confirmed by the evolution trends shown by hygromagmaphile elements (Fig. 4d).

Scheelite distribution results as follows. In the majority of cases, the mineral represents a normal (and often very scarce) accessory component of the main "intermediate" lithologies B and C. Positive correlation W-Mo in scheelite is evident. Paragenetically, scheelite is associated with accessory sphene and apatite, with aggregates of biotite flakes+sulfides, and with chlorite and quartz filling self-sealing cavities in porphyrites. Relative scheelite enrichments are found, very likely bound to the main tectonic trend (N-S/NW-SE) intersections, in the form of stockworks of quartz + K-feldspar (plagioclase) veinlets in the intrusives corresponding to the main monzonitic types (included the "monzonite IS 4" sample with its peculiar magmatic trend). Granitic dykes are completely barren: on the contrary, typical are the Cu-Mo-W anomalies of the inner granitic core of the Valle del Cervo pluton, co-magmatic with the outer monzonites and syenites. Molybdenite in the Lago Verde area is practically absent, except in two cases, both connected with porphyritic veins.

3. REFERENCES AND ORAL COMMUNICATIONS

First Meeting of the Contact Group: "GEOCHEMICAL METHODS IN EXPLORATION", Padova, September 15-16, 1988.

E.C. Seminar on Exploration, Paris, November 21-23, 1989.

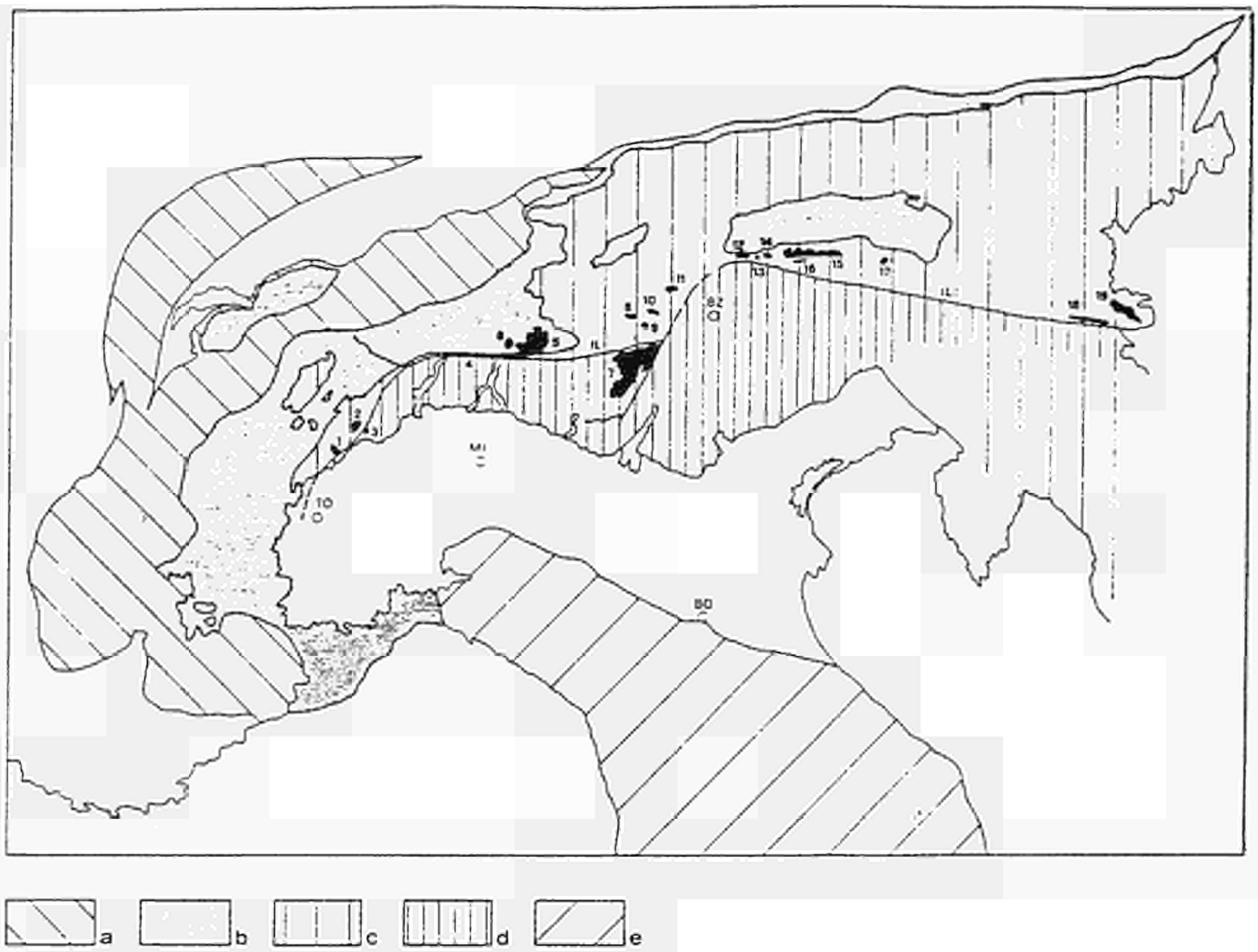


Fig. 1 - Location map. Legend: a) Paleoeuropean Helvetic - Dauphinois zone and Jura; b) Paleoeuropean Pennine Zone including ophiolite units; c) Paleoafrican Austroalpine units; d) Southern Alps; e) Northern Apennines; IL = Insubric Lineament. Periadriatic magmatism: 1) Traversella; 2) Biella; 3) Miagliano; 4) Iorio; 5) Valmasino - Bregaglia; 6) Novate - San Fedelino; 7) Adamello ; 8) Passo della Bottiglia - Pale Rosse; 9) Tof di Malè - Malga Mare; 10) Lago Verde - Lago Nero (Val d'Ultimo); 11) Val d'Ultimo - Val Venosta; 12) Rensen; 13) M. Alto; 14) Rio Vena; 15) Vedrette di Ries; 16) Cima di Vila; 17) Wölltratten; 18) Karawanken; 19) Pohorje.

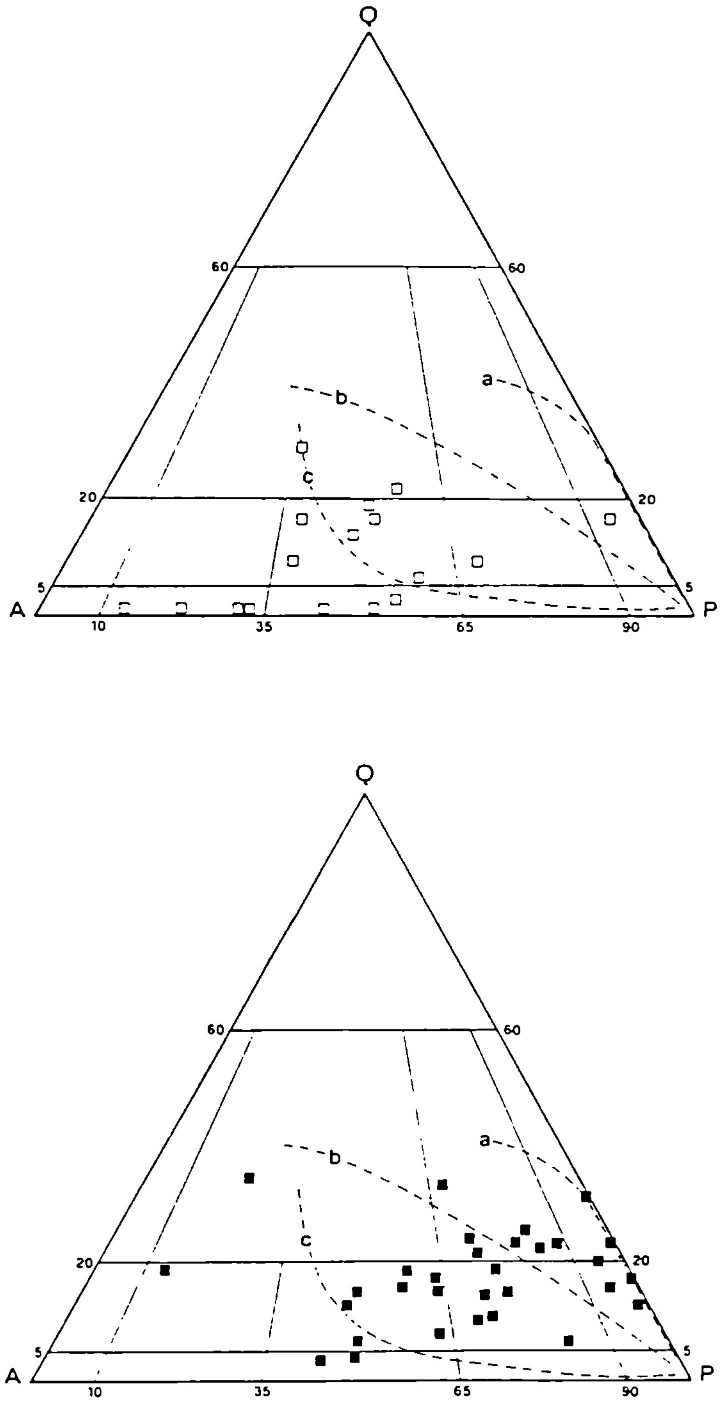


Fig. 2 - QAP diagrams of Valle del Cervo (□) and Lago Verde (■) magmatites (after Lameyre & Bowden, 1982). Magmatites plot according to a bimodal trend: the first one has high-K calcalkaline affinity (trend c), the second one has a normal calcalkaline affinity (trend b).

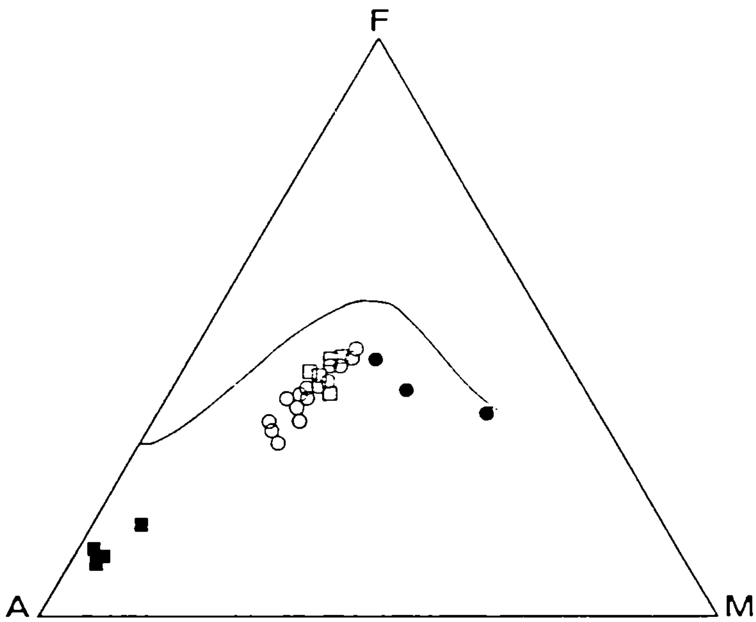


Fig. 3 - AFM diagram. The line separates the calcalkaline - alkaline field (lower) from the tholeiitic one (upper), according to Irvine & Baragar (1971).

Legend:
- ○ magmatites
- ● mafic enclaves
- □ porphiritic dykes
- ■ granitic dykes

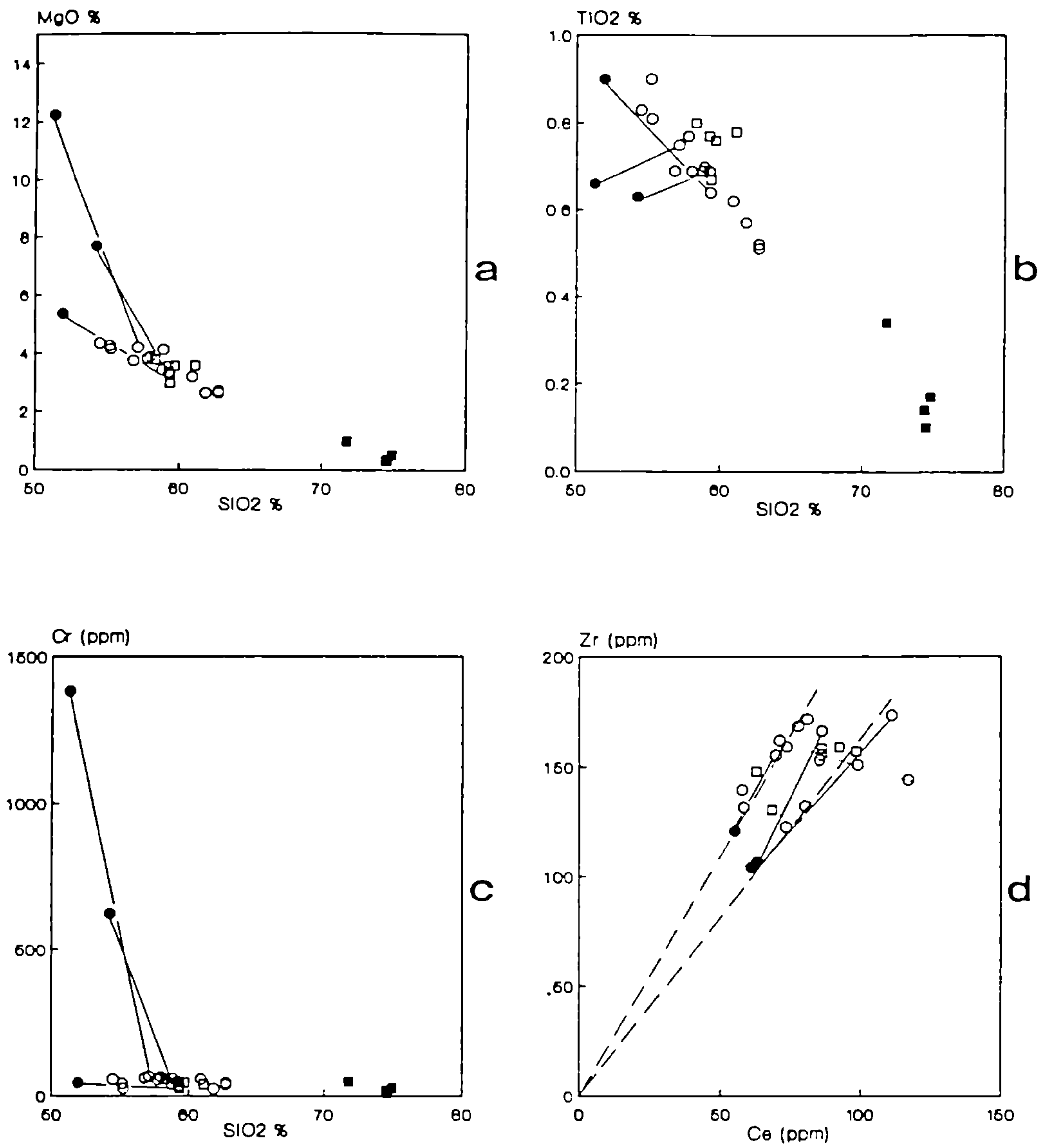


Fig. 4 - HARKER's diagrams (a, b, c) and Zr vs Ce diagram (d). Symbols as in Fig. 3.

FACTORS GOVERNING CONCENTRATIONS OF PLATINUM GROUP ELEMENTS IN LAYERED COMPLEXES

Project Leaders: E. MAKOVICKY and J. ROSE-HANSEN
The University of Copenhagen, Institutes for Petrology
and Mineralogy, Copenhagen, Denmark

Contract MA1M-0006-DK

1. OBJECTIVES

Platinum group elements (PGE) represent important strategic commodities that are at present essentially supplied only by two countries, RSA and USSR. Therefore a broadening of the supply base of PGE for the EEC, preferably within its borders or in associated countries, has been considered one of the important tasks of the just completed European research programme on the primary raw materials, under the common heading "Factors governing concentrations of PGE in layered complexes".

The Danish participants of this research programme have specialized in the mineralogical phase studies of the phase systems Fe-Ni-Pd-S and Pt-Pd-Fe-As-S that are of primary importance for the understanding, exploration and beneficiation of the PGE deposits studied by the associated groups, as well as for nearly all PGE deposits of economic importance world-wide. Such theoretical basis has been largely missing; the existing works (including the previous research of the present group) mostly specialized in simpler, binary and ternary phase systems. The present research represents therefore a decisive step towards more exact modelling of the ore-forming processes in PGE deposits. Apart from this, it is directly applicable to technological processes that involve PGE, for example the performance and degradation of PGE catalysts in the presence of aggressive admixtures at high temperatures.

The phase systems Fe-Ni-Pd-S and Pt-Pd-Fe-As-S are important for PGE deposits in layered intrusions, Sudbury and Norilsk-type deposits, those in komatiites and for a number of Alaskan-type deposits and the Shetland PGE occurrences. The system Fe-Ni-Pd-S contains important carriers, pentlandite and pyrrhotite. The system Pt-Pd-Fe-As-S involves the problems of Pt/Pd partitioning among sulphides, arsenides and alloys, the solubility of Pt or Pd in base metal sulphides/arsenides or in the respective melts as well as the stability of Pd and Pt minerals in various associations of iron sulphides, sulpharsenides and arsenides. In this quinary system, the portions Pt-As-S, Pt-Fe-As-S and Pt-Pd-As-S were investigated.

2. MATERIALS AND METHODS

In all experiments, dry condensed sulphide systems were studied. The investigated assemblages were prepared by reacting weighed mixtures of analytical grade pure elements sealed in evacuated silica glass tubes. "Specpure" and "high purity" materials have been used.

After prereacting at 300°C the charges were reacted at the reaction temperature for several weeks, reground and homogenized, refilled, and again annealed in evacuated silica glass tubes for several additional weeks. After quenching and polishing, the charges were examined in reflected light and by means of detailed microprobe analyses. The instrument used was JEOL Superprobe 733 with on-line correction programs. The wavelength dispersive mode and sulphide, arsenide as well as PGE metal standards were employed. Regularly interspersed measurements on standards allowed to renormalize the microprobe results when necessary. The average composition of sulphide or arsenide melts was obtained by microprobe scanning of appropriately large areas of crystallized melts.

At elevated temperatures reaction kinetics are good and reactivity problems are small. Below 500°C however, reactions are sluggish, difficult and often incomplete. Reaction products are very fine-grained making microprobe analyses very difficult. In the As-containing systems additional complications are caused by high-temperature corrosion of silica glass by As-containing vapours during which porous, As-containing cristobalite is produced far below its lower temperature stability limits.

3. ANALYSIS OF RESULTS

In the phase system Pd-Fe-Ni-S, four isothermal sections, at 900°, 725°, 550° and 400°C were investigated. At higher temperatures (900° and 725°C) the sulphide melt occurs for the majority of metal ratios, at ~30-40 at % S. From the sulphur-poor compositions of this sulphide magma Pd-Ni-Fe alloys crystallize during its entire cooling history, with the alloy enriched in Pd for all but Pd-poorest and Pd-richest compositions. For the latter compositions, the sulphide melt represents the Pd-richer phase. For the majority of compositions, the Fe/Ni ratio in the alloy changes little from that in the sulphide melt. These relationships have been quantified as the melt/alloy distribution coefficients and allow to chart the fractionation of Pd in the course of development of the ore deposit, using the alloys precipitated. In sulphur-rich portions, <u>mss</u> (i.e., the 'pyrrhotite' solid solution, $Fe_{1-x}S-Ni_{1-x}S$) and PdS crystallize from the melt. At and above 900°C braggite and <u>mss</u> cannot coexist so that the geologically relevant amounts of Pd will be distributed between mss (pyrrhotite) and the sulphide melt. Only at about 725°C mss and PdS coexist with each other so that for the geological concentrations of Pd in sulphide magmas, PdS will be a relatively late mineral, far later than PtS that coexists freely with pyrrhotite already above 1000°C.

PdS dissolves appreciable amounts of Ni and small amounts of Fe at all temperatures. This solubility increases with decreasing temperature, reaching 11.5 at % Ni at 400°C. Review of published analyses of braggite/vysotskite proved unambiguously for the first time that these (and the associated) palladium minerals formed down to such low temperatures as 400°C, i.e. within the confines of solid ore/rock.

The phase studies show that in the association with low-Pd alloys, pyrrhotite-$Ni_{1-x}S$ and pentlandite dissolve only negligible amounts of Pd; alloys scavenge Pd from the deposit in this case. Pentlandite associated with the high-Pd alloy, or pyrrhotite at high sulphur fugacities, dissolve several percent of Pd; in its range of existence the high-temperature phase $Ni_{3\pm x}S_2$ dissolves considerable amounts of Pd as well. Another important indicator for PGE deposits is the mutual exclusivity of PdS and Pd-Fe-Ni alloys; they do not coexist at any of the examined temperatures. Pyrite does not concentrate Pd but $(Ni,Fe)S_2$ is an important palladium concentrator at higher temperatures.

In the phase system Pd-Pt-Fe-As-S, at 850°C there are several sulphide or arsenide melts, all of potential interest for ore formation. Except for the melt (S,As), barren at 850°C and 470°C the As-based melts dissolve only several percent of S and vice versa, i.e. the sulphide and arsenide melts are essentially immiscible at 850°C. All may represent potential ore-bearing liquids. The broad arsenide melt based on the ~Pt_7As_3 - ~Pd_7As_3 join is in the case of the Pt-Fe-As-S subsystem at 850°C replaced by two melts: an essentially S- and Fe-free Pt-As melt and a ~Fe_3As melt that dissolves important amount of Pt and some sulphur.

The Pd-S based melt dissolved important amounts of Pt and some As as well. At 850°C nearly all Pd arsenides are replaced by Pd-As melt that shows only low solubility for Pt, except for its ~Pt_7As_3 region. Hence, Pt and Pd will separate in the As-rich arsenide melts whereas they will follow the same transport paths in the As-poor arsenide melts. Arsenide ore magma is known for Pd occurrences in Spain and Morocco, albeit it is mostly Ni-based. Therefore, the activity of arsenide magmas in PGE ore occurrences is a potentially important geological factor. The phase systems Pt-Fe-As-S and Pt-Pd-As-S are dominated at both temperatures by the extensive solid solution of sperrylite, $PtAs_2$, that can dissolve up to 25.3 at % S at 850°C and only somewhat less at 470°C. From the S-poor to the S-richest compositions of sperrylite, sulphur fugacity changes by a factor of several hundred. Solubility of Fe in sperrylite is low for its entire temperature and composition range; that of palladium, however, increases with the increasing sulphur contents until it reaches the composition of palladium platarsite at 850°C. Solubility of Pd in pure $PtAs_2$ is unexpectedly low; the same holds for the solubility of Pt in Pd arsenides, including $PdAs_2$. This again suggests separation of Pt and Pd during their crystallization (probably as $PtAs_2$ and Pd-rich fluids).

The addition of As to the system Pt-Fe-S changes profoundly the role of (Pt,Fe) alloys in the phase relationships with PtS. Makovicky et al. (1988) showed that the geologically very important association pyrrhotite-PtS-isoferroplatinum ($Pt_{72.5}Fe_{27.5}$) exists in the As-free system between 1000°C and at least 500°C. Addition of As at 850°C leads to the association pyrrhotite-PtS-$PtAs_2$-tetraferroplatinum (~$Pt_{45}Fe_{55}$). The latter plays a role also in other geologically interesting associations. However, at 470°C it again is the isoferroplatinum that partakes in the potentially most important ore associations Pt_3Fe-$PtAs_2$-PtS-pyrrhotite and Pt_3Fe-$PtAs_2$-FeAs-pyrrhotite. At this temperature, tetraferroplatinum is involved only in the Fe-richest associations. These features were all found in the Alaskan-type of Pt deposits by our colleagues (Johan et al. 1989).

The slightly arsenoan pyrrhotite dissolves up to 0.5 at % Pt at 850°C but only traces of Pt at 500°C. Towards the troilite compositions the solubility of Pt drops to zero. Loellingite and westerveldite represent potential Pt-bearing minerals at high temperatures. Arsenopyrite is not a platinum collector.

4. CONCLUSIONS

The present research investigated behaviour of two important platinum group elements, Pt and Pd, at magmatic and postmagmatic temperatures in the important element associations Pd-Fe-Ni-S and Pt-Pd-Fe-As-S.

In the first of these two systems the extent and crystallization products of the central, extensive Pd-Fe-Ni-sulphide melt were determined. Distribution coefficients for the melt/alloy association were determined for Pd and other metals. Solubility of Pd in the following sulphides achieves practically important levels, at different temperatures and different S concentrations: pyrrhotite, pentlandite, $Ni_{3\pm x}S_2$ and $(Ni,Fe)S_2$. Solubility of Ni and Fe in Pd sulphides can be used as a geothermometer.

In the second system, sperrylite $Pt(As,S)_2$ represents the most important phase that coexists with the majority of other phases present. Alone, it is not a geothermometer. At 850°C separate arsenide and sulphide melts exist that represent potential transport agents for Pt and Pd; they are immiscible at this temperature. Pd and Pt are strongly separated in arsenides and for the As-rich portions of the Pd-As melt. Only in the metal-rich arsenide melt they can coexist at all ratios. Pd is strongly soluble in platarsite. These facts offer a number of possibilities for separation of Pt and Pd in mineral deposits. In the (Pd,Pt)S series this separation is much less pronounced. $FeAs_2$ and FeAs are Pt collectors at high temperatures; FeAsS is not a collector of platinum. Arsenic alters profoundly the role of different Pt-Fe alloys in the geologically important ore assemblages.

Therefore, the present research allows to define:

(a) the role of different sulphide and arsenide melts in the geological transport and deposition of Pt and Pd;
(b) the role of different concentrator minerals for these metals;
(c) potential geothermometers, either based on solid solubilities or on profound changes in phase associations; and
(d) the influence of As on the PGE-combining phase associations

Number of such phenomena, observed in the present laboratory research, were found in the ore deposits by our colleagues, (see contract MA1M-0008-F, this volume).

Project participants: Emil Makovicky*, John Rose-Hansen*, Sven Karup-Møller**, Milota Makovicky*.

* University of Copenhagen
** Danish Technical University

5. PUBLICATIONS

Johan Z., Ohnenstetter M., Slansky, E., Barron, LM., Suppel, D. 1989: Platinum mineralization in the Alaskan-type intrusive complexes near Fifield, New South Wales, Australia. Part I. Platinum-group minerals in clinopyroxenites of the Kelvin Grove Prospect, Owendale intrusion. Mineralogy and Petrology 40 : 289-309.

Makovicky, M., Makovicky, E., Rose-Hansen, J. 1988: Experimental evidence on the formation and mineralogy of platinum and palladium ore deposits. In: Boissonas J., Omenetto P. (eds) Mineral deposits within the European Community. Springer, Berlin, Heidelberg, New York, Tokyo, pp 303-317.

Makovicky, E., Karup-Møller, S., Makovicky, M. & Rose-Hansen, J. 1990: Experimental Studies on the Phase Systems Fe-Ni-Pd-S and Fe-Pt-Pd-As-S applied to PGE Deposits. Miner. Petrology 42, 307-319.

Papers nearly completed:
The phase system Pd-Ni-S at 900°C, 725°C, 550°C and 400°C.
The phase system Pd-Fe-Ni-S at 900°C, 725°C, 500°C and 400°C.
The phase system Pt-Fe-As-S at 850°C and 470°C.
The phase system Pt-Pd-As-S at 850°C and 470°C.
The phase system Pd-Fe-S at 900°C, 725°C, 550°C and 400°C.
The phase system Pt-As-S at 850°C and 470°C.

6. ORAL PRESENTATION

Karup-Møller, S. and Makovicky, E. 1987: The phase system Pd-Ni-S at 900°C, 725°C, 550°C and 400°C. Abstr. 5th Magmatic Sulphide Field Conference, Zimbabwe.

Makovicky, E., Karup-Møller, S., Makovicky, M. and Rose-Hansen, J. 1989: Phase systems Fe-Ni-Pd-S and Pt-Pd-Fe-As-S and their application to PGE deposits. IAGOD Commission on ore deposits in Mafic and Ultramafic Rocks. Bull. Geol. Soc. Finland, 61,1.

Makovicky, E., Karup-Møller, S., Makovicky, M and Rose-Hansen, J. 1990: Experimental studies on phase systems related to the mineralogy of platinum-group deposits. Abstr. of the 15th General Meeting of the International Mineralogical Association, Beijing, China.

Karup-Møller, S. and Makovicky, E. 1991: The phase system Pd-Fe-S at 900°C, 725°C, 550°C and 400°C. The 6th International Platinum Meeting, Perth, Australia.

7. FIGURE CAPTIONS

Fig. 1. Phase system Pt-As-S at 850°C; sp denotes sperrylite, $Pt(As,S)_2$.

Fig. 2. Phase system Pt-Fe-As-S at 850°C; sp denotes sperrylite; the width of compositional fields was adjusted to ensure clarity of presentation.

Fig. 3. Phase system Pt-Pd-As-S at 850°C; the principal phase associations. sp denotes sperrylite $(Pt,Pd)(As,S)_2$.

Fig. 4. Phase system Pd-Ni-Fe-S at 900°C. Selected tielines between the sulphide melt and alloy, as well as between $(Fe,Ni)_{1-x}S$ and the sulphide melt are indicated.

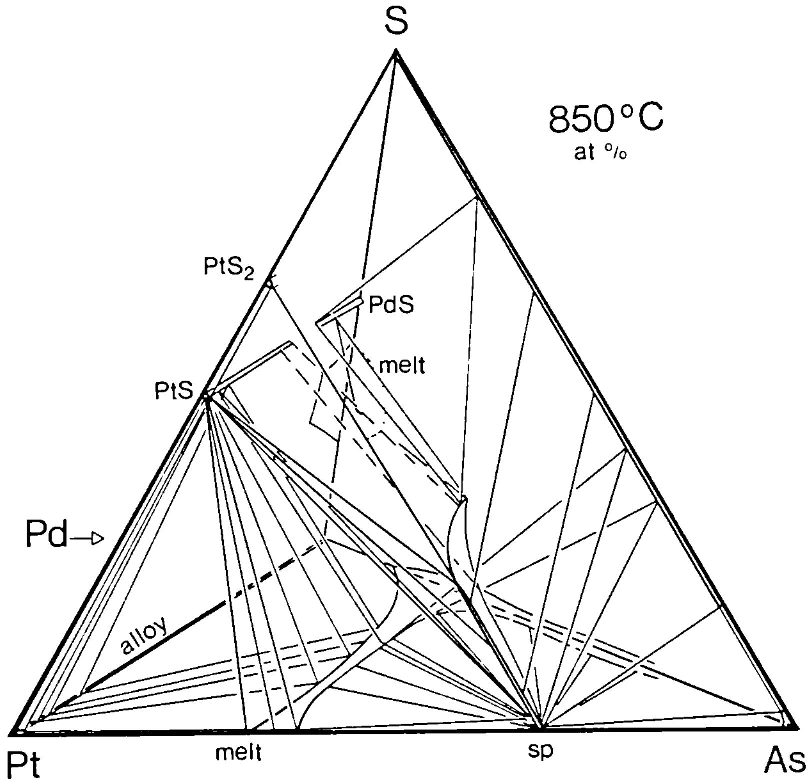

S
850°C
at %
PtS2
PdS
melt
PtS
Pd
alloy
Pt
melt
sp
As

Fig. 1

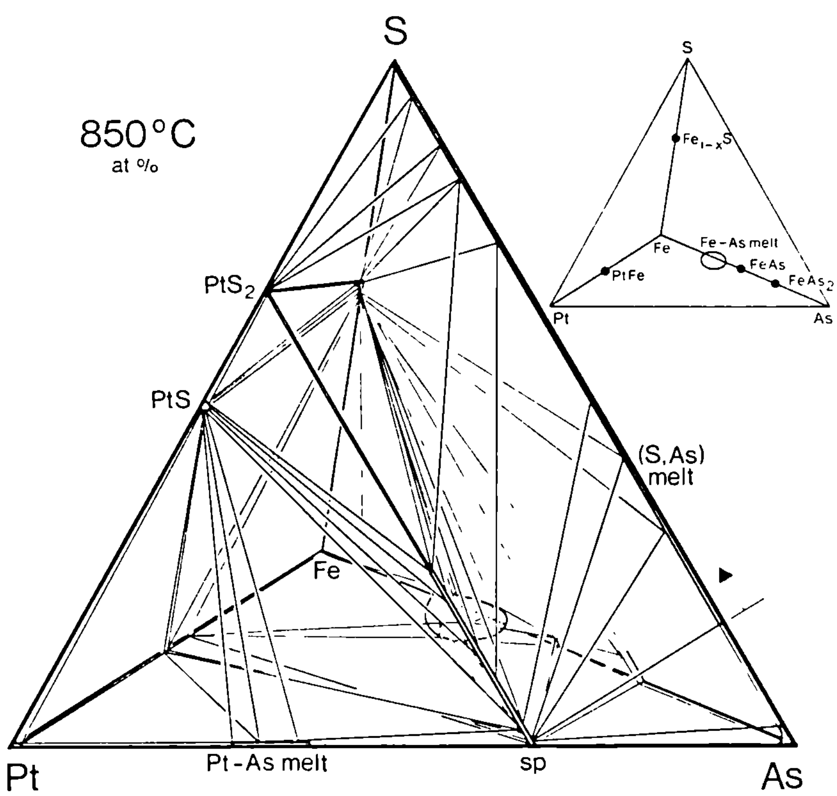
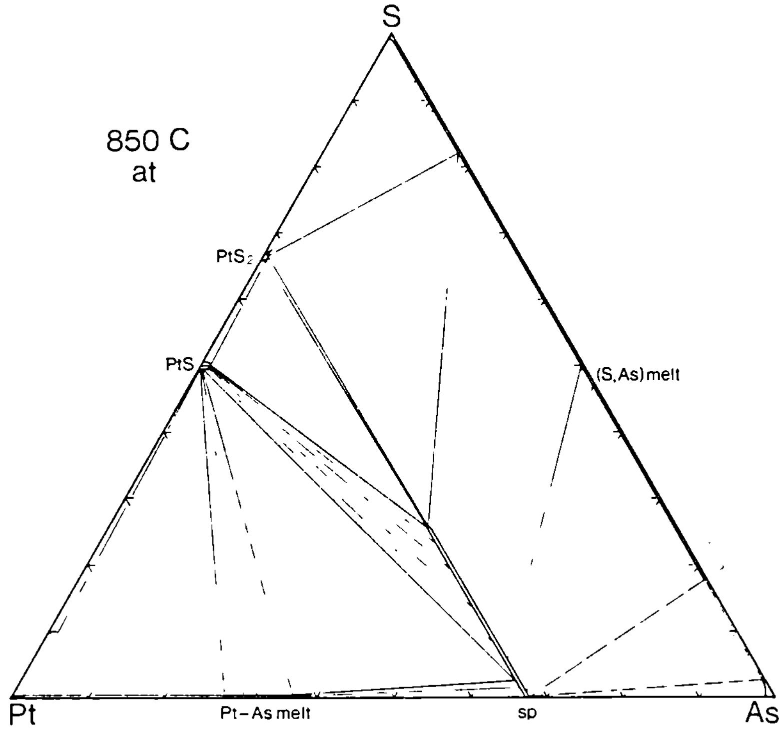
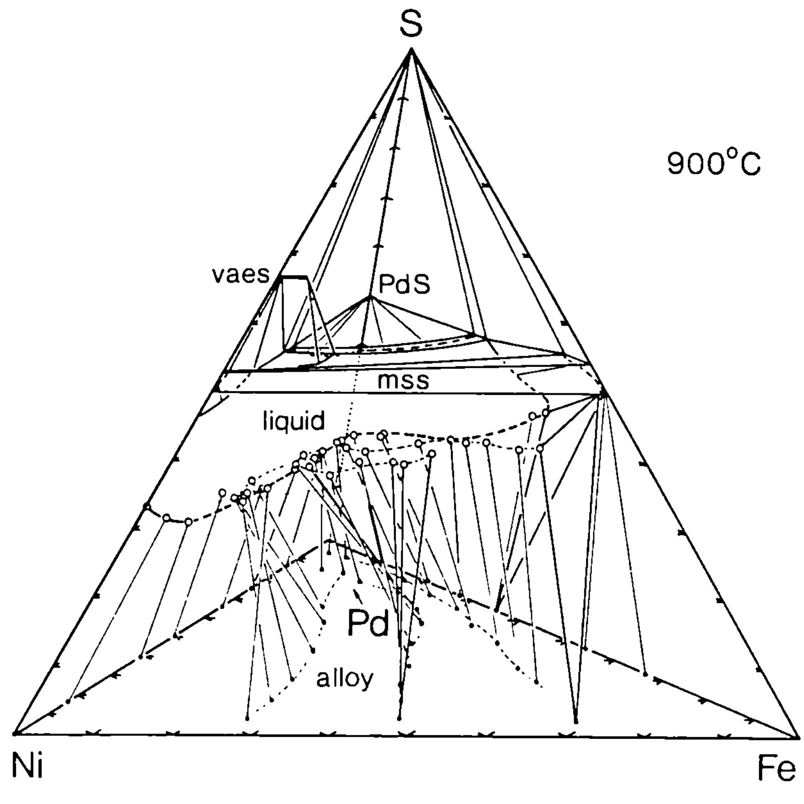

S
850°C
at %
PtS2
PtS
(S,As)
melt
Fe
Pt
Pt-As melt
sp
As
S
Fe1-xS
Fe
Fe-As melt
PtFe
FeAs
FeAs2
Pt
As

Fig. 2


S
850 C
at
PtS2
PtS
(S,As)melt
Pt
Pt-As melt
sp
As

F I g . 3


S
900°C
vaes
PdS
mss
liquid
Pd
alloy
Ni
Fe

F I g . 4

OPTIMIZATION OF ELECTROMAGNETIC AND GRAVITY METHODS OF MINERAL EXPLORATION, FOR THE LOCATION AND DELINEATION OF BURIED OREBODIES IN THE IBERIAN PYRITIC BELT (PART 1)

Projet Leader: S. GREINWALD
G.-U. Sandmann, R. Koch
Bundesanstalt für Geowissenschaften und Rohstoffe (BGR),
Hannover, Germany

Contract MA1M-0007-E

PREFACE

This research contract was part of a joint research project conducted by the five partners Enadimsa (Spain), BRGM (France), University College of Wales (UK), Resonance Geophysics (UK) and BGR (Germany). This report deals with the work of BGR within this project.

1. OBJECTIVES OF THE RESEARCH

The overall objective of research project MA1M-0007-E was to further strengthen the effectiveness of electromagnetic methods for mineral exploration. BGR's efforts were concentrated on the use of Transient Electro Magnetics (TEM). Two goals were considered of main importance :

- to test the depth of exploration and the resolving power under the geological conditions in the Iberian pyritic belt;
- to develop a new receiver, which allows a wider time range of measurement channels and provides better possibilities for noise suppression and data processing.

2. MATERIALS AND METHODS - ANALYSIS OF THE RESULTS

2.1 EQUIPMENT FOR FIELD WORK

The receiver coil is a small rigid coil connected to a Sirotem-IIe (Geoex, Australia). The Sirotem receiver provides a time range from 50 microseconds to 168 milliseconds in two ranges, each covering 32 logarithmically spaced time channels.

For borehole measurements the Sirotem borehole probe is used. It reads the component parallel to the borehole axis.

The transmitter (TAP, Braunschweig) can handle up to 100 A at a maximum voltage of 200 V. All transmitter coils are square loops with a side length of 400 m.

The following different coil configurations are used :

- coincident;
- inloop;
- fixed transmitter profiling.

2.2 FIELD MEASUREMENTS AND RESULTS

2.2.1 Geological background

The area investigated is covered by a thick layer of Culm formation with a specific resistivity of more than 400 Ohmmeters. Within the lower part of the Culm, layers containing graphite and pyrite with a thickness of up to 60 m have been found. These layers show resistivity values down to 2 Ohmmeters and have a conductance between 3 and 4 Siemens. They screen all geological units below for high frequency electromagnetic systems. Beneath this Culm formation lies the volcanic sedimentary complex, in which all of the generally lens shaped orebodies have been found.

The ore itself is highly conductive with a total conductance of more than 100 Siemens. It is this contrast between the conductance of the ore and the layers atop of it, which allows an effective use of low frequency or late time transient electromagnetic methods in this area.

In the year 1986 Enadimsa and Penarroya drilled a hole in the centre of a gravity anomaly in the Autonomia Area of Andaluzia and hit 96 m of massive pyrite at a depth between 434 and 530 m. More holes have been added during the duration of this research project and lined out a major pyritic body. On this site BGR carried out TEM field measurements in 1987-1989 using the newly found body as a test object.

2.2.2 Fixed transmitter profiling

Most of the measurements were done with the fixed transmitter setup. The large transmitter loop and a transmitter current of 25 - 30 A gave good data with sufficient signal to noise ratio. This allowed the recording of more than 20 time channels in the Sirotem standard time mode and corresponds to a time window of approximately 28 ms starting 0.48 ms after the beginning of the switch off of the transmitter current. Three components of the secondary magnetic field were regularly recorded, the vertical, the radial (parallel to the profile) and the tangential (perpendicular to the profile).

A total of five profiles was measured with fixed transmitters. The most impressive results were found along profile 600E crossing the ore close to the hole A1, the discovery hole. On this profile the transmitter loop was layed out with its midpoint about 400 m south of the centre of the anomaly. Fig. 1 shows the amplitudes of the vertical component in logarithmic scaling.

An interesting feature is the change of location of the maximum amplitude. While the first channel shows a maximum at the centre of the transmitter loop as expected from a horizontally layered structure, the maximum at late channels is shifted 400 m to the north. This indicated that the early channels with little depth penetration see a one-dimensional resistivity distribution. At late times when the response from the less conductive parts of the ground has already decayed and the current system has penetrated deeper into the ground, the remaining response is caused by currents flowing in the best conducting geological units which coincide with the orebody.

The position of the maximum response at late times will therefore depend solely on the position, strike and dip of the conductor with the slowest decaying current system and will shift the anomaly accordingly. A similar shift of the crossover, indicating the position of the good conductor, can be seen in the radial component (fig. 2).

The profiles over the deeper parts of the orebody further to the west show a much smaller response from the ore. However, on each profile a clearly visible anomaly indicates the position of the orebody.

2.2.3 Soundings

Each of the transmitter loops laid out for the profiling work was used for soundings as well. Soundings allow a better interpretation of the data and give a detailed picture of the resistivity distribution below the location of the coils. To improve the effectiveness, each transmitter loop was used for several soundings : in addition to the inloop setup the receiver coil was moved to 4 locations, parallel or perpendicular to the profile, at a distance from the centre of the transmitter loop equal to the sidelength of the loop (multi sounding array).

At all locations the apparent resistivity curves show a minimum. Over the shallower parts of the orebody this minimum indicates very well the highly conductive ore and separates it from the response of the conductive layers in the Culm formation. Over the deeper parts of the orebody such a clear separation between the ore and the conductive horizons is not always possible. The results from a one dimensional inversion of the data indicate a depth somewhat larger than the depth found from drilling. This observation is common knowledge for the results of a one dimensional inversion in a more dimensional situation.

2.2.4 Borehole measurements

To test the additional advantage of borehole measurements two holes over the shallowest parts of the ore were logged. The holes selected were A2, passing the ore at a certain lateral distance, and A3 which went through the ore. It was not possible to survey other holes because BGR's borehole equipment is limited to a depth range of 500 m.

Due to the vertical separation of the conducting layers of black shale from the ore and the strongly different conductance of both geological units, the data allow a separation of the response of each unit. While the ore indications in the data of hole A2 are weak indicating some distance from the pyrite body, hole A3 shows a very strong response from the ore down to the last channel (fig. 3).

Forward modelling of the data recorded in hole A3 with the model of a layered halfspace shows that a conductivity of more than 5 S/m for the good conductor is necessary to reach an acceptable agreement between the calculated and the measured data sets. This demonstrates that borehole measurements can contribute to improve the interpretation of other kinds of TEM surveys.

2.3 DEVELOPMENT OF A NEW RECEIVER

Commercially available receivers have one major drawback : the memory installed is too small to store each reading as a separate value. The values of all the stacks for one channel are continuously added up to the final average reading. This reduces the possibilities of a more sophisticated processing of the data, e.g. selective stacking, and eliminates the possibility to determine exact error boundaries for the readings of each channel.

To overcome these deficiencies BGR started the development of a new receiver. This receiver is based on a laptop computer as a controller, combined with a fast analogue to digital converter. The maximum conversion speed is 300,000 readings per second, the dynamic range 120 dB.

With this new receiver large amounts of data up to 100 kBytes per measurement are collected. First successes in processing have been achieved in low-pass filtering followed by reduction of data into logarithmically equally spaced channels.

Any of the important processing steps to reduce low frequency noise caused by interference from powerlines have not yet been applied. First results from measurements with only 14 stacks and a transmitter current of only 4 A show smooth decay curves for the time range between 0.15 - 17.8 milliseconds (fig. 4). The reason that no earlier time channels have been recorded is the lack of a transmitter with a fast current turn-off and an appropriate high frequency receiver coil.

3. CONCLUSIONS

The measurements with the TEM system in the Iberian pyritic belt demonstrated the excellent capabilities of the method very clearly. After these tests the use of the method can be recommended despite the difficult geological setup in this area.

The following facts have been proven within this research project :

- TEM can detect massive sulfide orebodies below conducting layers with a conductivity of several Siemens down to a depth of 600 m below surface.

- Soundings allow to determine the vertical resistivity distribution beneath the coil array with a high lateral resolution.

- Borehole measurements can be used to locate ore even if the orebody itself has been missed by the hole. From borehole data a more accurate value for the conductivity of the ore can be found and help to improve the interpretation of other TEM data.

- TEM measurements, especially fixed transmitter profiling, can be performed fast and are practically unaffected by topographic features. This is a tremendous advantage in areas with a strong topographic relief.

This allows to recommend TEM as a very effective geophysical method in this area in addition to gravity.

Besides the above mentioned field tests with commercially available instrumentation research has been undertaken to overcome some of the problems found in such units. This lead to the construction of a new receiver with a high digitizing frequency. The data sets collected provide a strongly improved processing capability. Further research in data processing is necessary to extract the full information from the data, especially to reduce the signal to noise ratio at low frequencies. This noise contribution stems mainly from cultural interference.

4. COMMUNICATIONS AND REFERENCES

Greinwald, S.: Bericht über "Erprobung von neuentwickelten TEM Meß- und Interpretationstechniken über verschiedenen Largerstätten Europas"; BGR report no. 103 310, Hannover, 1987.

Greinwald, S., Sandmann, G.-U:, Koch, R.: Optimization of Electromagnetic and Gravity methods of mineral exploration, especially buried orebodies in the Iberian pyritic belt; BGR report no. 108 320, Hannover, 1991.

Greinwald, S., Sinha, A.K.: Case histories on the application of two ground transient electromagnetic systems for sounding and profiling; Geol. Jahrb. E 45, Hannover, 1991.

Rodemann, H., Weidelt, P.: Zweidimensionale Modellrechnungen nach der Oberflächen-Integral-Methode zum TEM-Verfahren; BGR report no. 98731, Hannover, 1985.

Weidelt, P.: Inversion transient-elektromagnetischer Messungen über geschichtetem Untergrund; BGR report no. 96720, Hannover 1984.

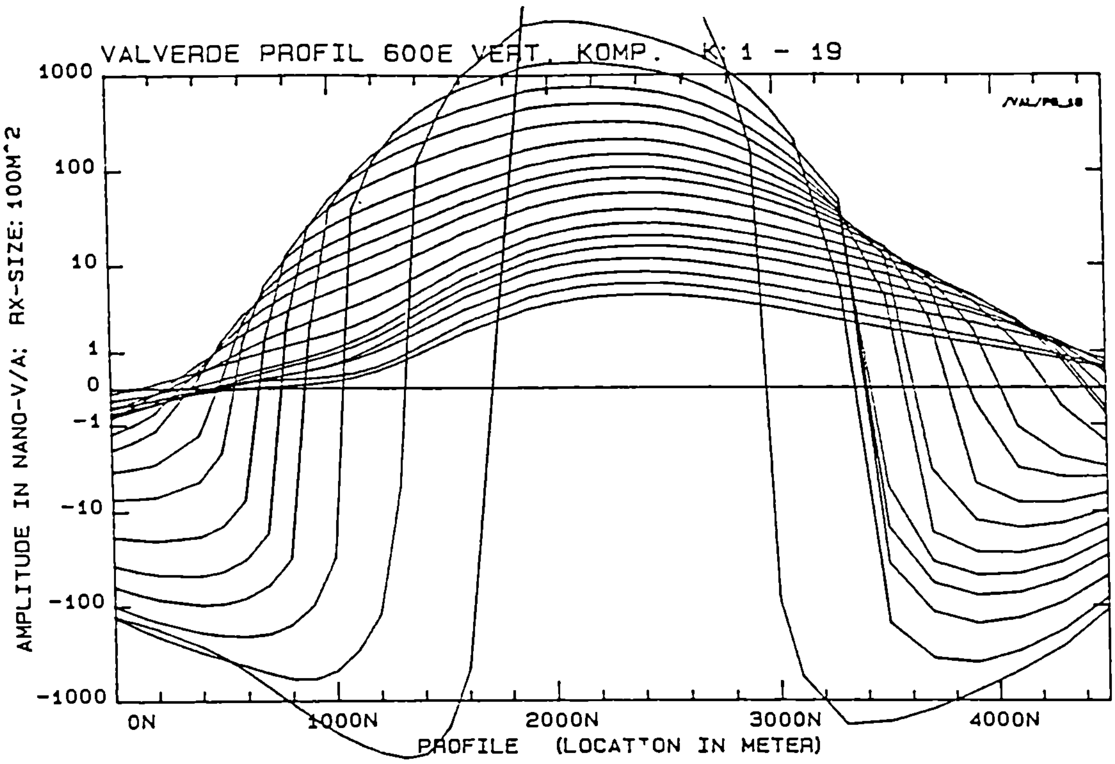
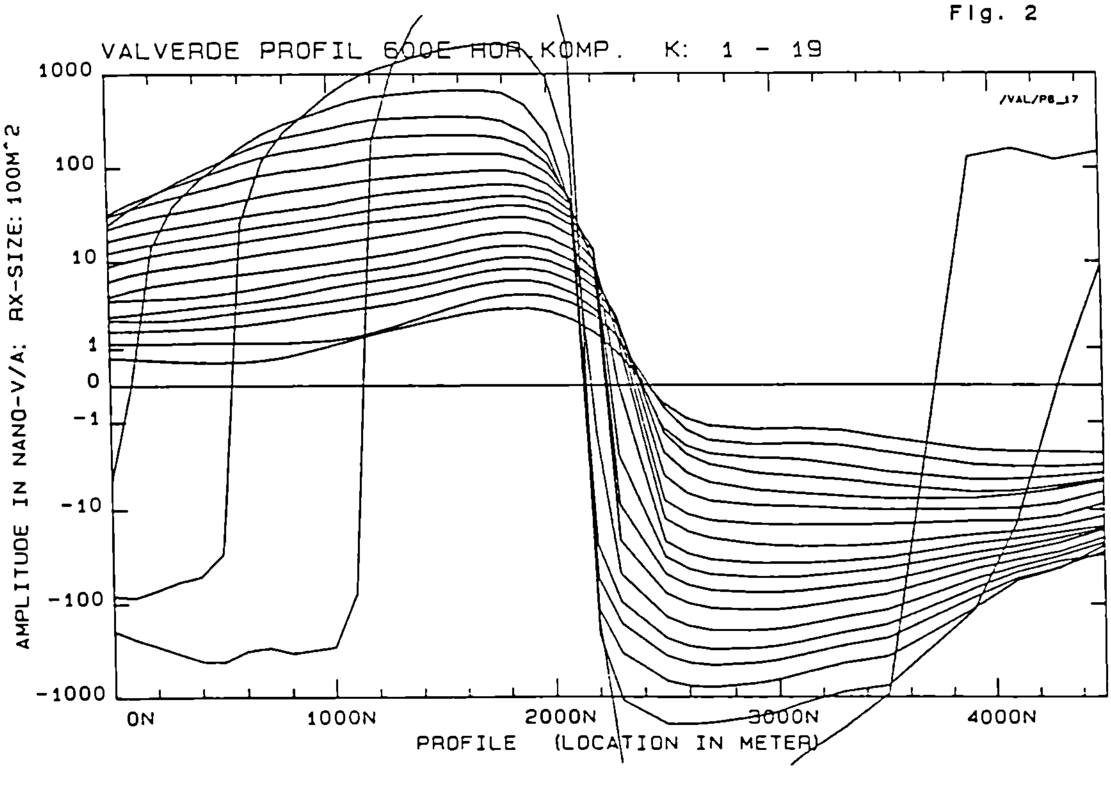

VALVERDE PROFIL 600E VERT. KOMP. K: 1 - 19
/VAL/P6_18
AMPLITUDE IN NANO-V/A; RX-SIZE: 100M^2
1000
100
10
1
0
-1
-10
-100
-1000
0N
1000N
2000N
3000N
4000N
PROFILE (LOCATION IN METER)

Fig. 1

Fig. 2


VALVERDE PROFIL 600E HOR.KOMP. K: 1 - 19
/VAL/P6_17
AMPLITUDE IN NANO-V/A; RX-SIZE: 100M^2
1000
100
10
1
0
-1
-10
-100
-1000
0N
1000N
2000N
3000N
4000N
PROFILE (LOCATION IN METER)

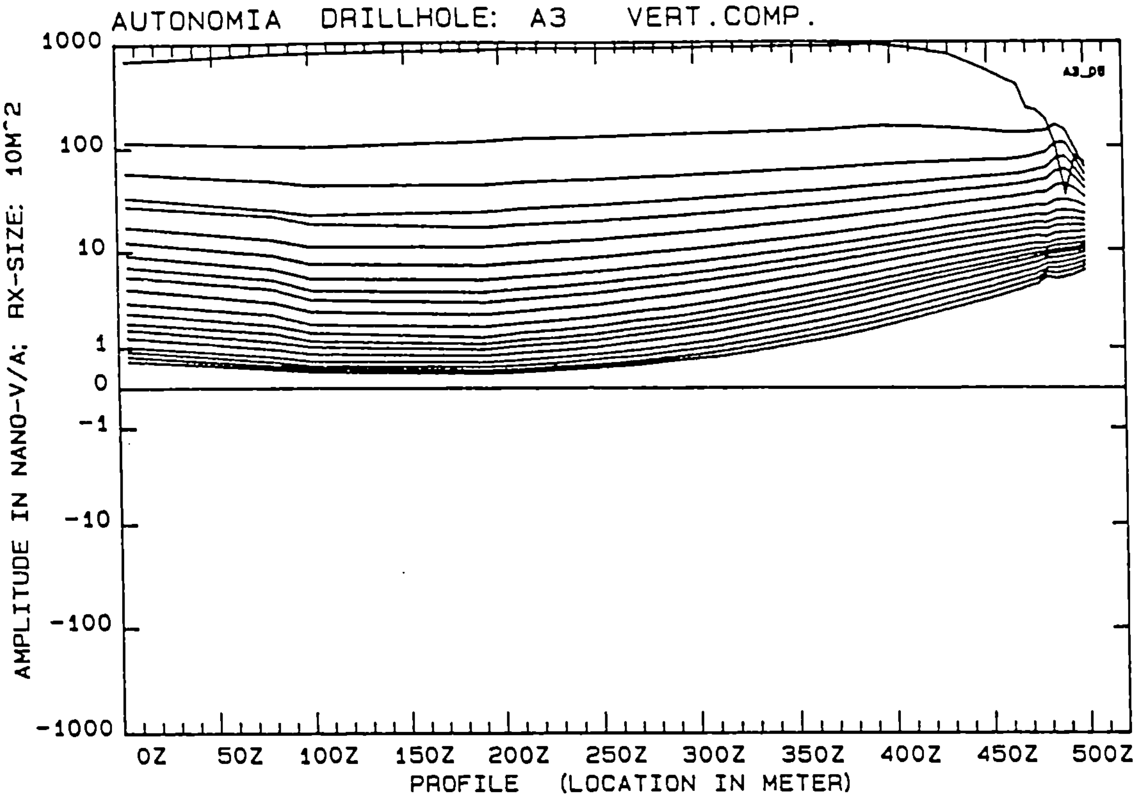

AUTONOMIA DRILLHOLE: A3 VERT.COMP.
1000
100
10
1
0
-1
-10
-100
-1000
AMPLITUDE IN NANO-V/A; RX-SIZE: 10M^2
0Z 50Z 100Z 150Z 200Z 250Z 300Z 350Z 400Z 450Z 500Z
PROFILE (LOCATION IN METER)

Fig. 3

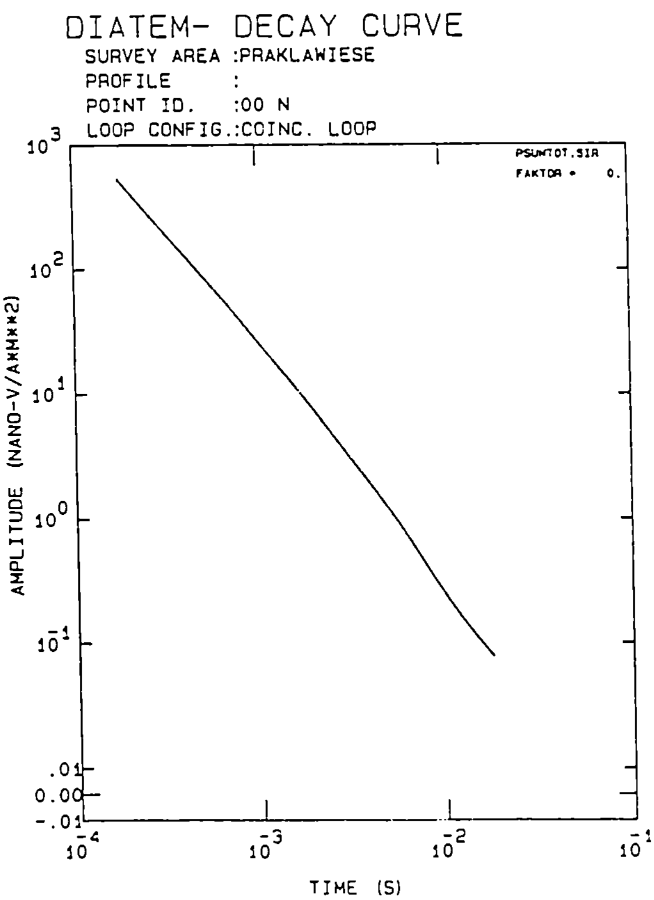

DIATEM- DECAY CURVE
SURVEY AREA :PRAKLAWIESE
PROFILE :
POINT ID. :00 N
LOOP CONFIG.:COINC. LOOP
AMPLITUDE (NANO-V/A*M**2)
TIME (S)

Fig. 4

OPTIMIZATION OF ELECTROMAGNETIC AND GRAVITY METHODS OF MINERAL EXPLORATION FOR THE LOCATION AND DELINEATION OF BURIED OREBODIES IN THE IBERIAN PYRITIC BELT (PART 2)

Project Leaders: P. VALLA and B. BOURGEOIS
BRGM, Geophysics Dept., Orléans, France

Contract MA1M-0007-E

PREFACE

Contract MA1M-0007 was a joint research project carried out under the coordination of ENADIMSA-PENARROYA (Spain) with participation from Bundesanstalt für Geowissenschaften und Rohstoffe-BGR (Germany), BRGM (France), Resonance Geophysics (Ireland) and the University of Wales (United Kingdom).

The present report concerns the contribution by BRGM.

1. OBJECTIVE OF THE RESEARCH

In an area such as Europe where minerals have been sought for many centuries, base metal resources have more and more to be looked for as hidden or deeply buried massive sulphide deposits. For such targets, geophysical tools are a necessary and important component of a successful exploration programme.

This is especially the case in the South-Iberian pyrite belt. As for geophysics, the exploration methodology is based on the one hand upon gravity prospecting to locate anomalies hopefully due to orebodies, and on the other hand upon geoelectrical methods to crosscheck and perform a more detailed study of such anomalies. However for deep targets, geoelectrical methods, and more specifically electromagnetic techniques, must be optimized in order to gain as much quantitative information as possible.

The Geophysics department of BRGM has focused its work on frequency domain electromagnetic (FEM) techniques both for surface and borehole measurements. The objectives of the research performed within the framework of the "Metals and Mineral Substances" 1986-1989 subprogramme were twofold:

1. To develop a methodology for measuring and interpreting results obtained by the various FEM techniques and systems devised at BRGM (MELIS, a surface-to-surface multifrequency EM system, REMI, a surface-to-borehole one-axis EM receiver probe, and ARLETT, a surface-to-borehole three-axis EM system under development).

2. To assess their ability to detect and characterize conductive deposits in terms of location, depth, thickness, conductance and limits.

2. MATERIALS AND METHODS

2.1 THE MELIS SYSTEM

Frequency EM methods such as MELIS use the EM field created by a transmitting loop (300 m x 300 m) laid out on the ground, in which the transmitter maintains a sinusoidal alternating current. The total magnetic field at the surface of the earth is the vector sum of the empty-space primary field and of the secondary fields created by the various induction currents existing within the conductive bodies. The MELIS system measures the quadrature component of the radial magnetic field with respect to the vertical field; from the ratio of these two quantities, an apparent resistivity is obtained for each station and each frequency (f). The MELIS data can be represented as soundings (graphs of apparent resistivity versus pseudo-depth $f^{-0.5}$ for the various stations), profiles (variation of apparent resistivity along the stations at given frequencies) or pseudo-sections (resistivity "map" where the X-axis represents the stations and the Y-axis represents the pseudo-depth $f^{-0.5}$).

2.2 THE REMI AND ARLETT PROBES

The REMI probe is a one-axis sensor used to perform measurements of the axial magnetic field in a borehole. The aim is to locate conductive bodies missed by the hole. The fundamental parameter given by REMI is the phase of the axial field by reference to the surface field at the well head. A REMI recording is represented as a profile of phase versus depth along the borehole (i.e. a phase log).

The ARLETT probe is a three-axis sensor still under development which will provide direct directional information about conductors in the vicinity of the hole.

2.3 MODELLING AND INTERPRETATION SOFTWARE

MELIS soundings are modelled on a horizontally layered earth hypothesis (1D interpretation) using the FREMIS software which performs synthetic data computation and data inversion through a Marquardt fitting algorithm. Modelling of a REMI log can be made using a derived software.

For 2D interpretation, the BIEFEM software is used. It is based on the finite element method using quadratic interpolation and permits the computation of MELIS resistivity or REMI phase profiles for a given two-dimensional polygonal model, including topography. The model is progressively modified until a good fit with the field results is obtained.

2.4 THE VALVERDE TEST SITE

A massive polymetallic orebody was discovered in June 1986, by an Enadimsa-Penarroya joint venture, near Valverde (Huelva, Andalusia) in the Iberian pyrite belt, as a result of a gravity survey. The ore lies at about 450 m depth, and is some 100 m thick. It is located beneath a thick series of Culm slates. From an electrical point of view, the Culm is fairly resistive (± 700 ohmmeters) providing good EM wave penetration, though its base is more conductive (± 80 ohmmeters over some tens of meters). The barren volcanic rocks are also resistive (± 1000 ohmmeters). The massive deposit itself is very conductive (< 1 ohmmeter); so is the associated mineralised stockwork (< 10 ohmmeters).

3. ANALYSIS OF RESULTS

3.1 PRELIMINARY 2D MELIS MODELLING

In order to predict the MELIS response that should be observed in the presence of a deep conductive orebody, preliminary 2D modelling has been performed on two simple models adapted to the Valverde setting. For a resistive host rock with no deep conductive body, apparent resistivity profiles and pseudo-sections show no distinctive response. By adding a laterally limited deep conductive body (depth 450 m, thickness 100 m, width 200 m, resistivity 5 ohmmeters, a conductive response is seen at low frequency (< 10 Hz) and a resistive one at medium frequency (± 200 Hz). This dual response is the MELIS signature of a deep, laterally limited, conductive body: it is characterized by a conductive-resistive bipolar image on the pseudo-section, and a spindle image on the profile diagram.

3.2 RESULTS OF THE MELIS SURVEY AT VALVERDE

A MELIS survey was carried out at Valverde during two field campaigns, in the autumns of 1987 and 1988. It involved 102 frequency soundings on six profiles with three loop positions. In a methodological perspective, one profile was recorded with two symmetrical loop positions at each end and with a third loop position away from the profile.

The interpretation of these measurements was made first on a qualitative basis in the field, then on a quantitative basis using 1D and 2D modelling.

It showed:

- An extension of the orebody 400 m northwestward (fig. 1), which was confirmed by a latter drillhole; a further extension of another 400 m northward, probably deeper, which has not yet been confirmed by drilling (this second extension would increase the length of the orebody to 1300 m).

- A greater width of the orebody (average width of 300 m); a pronounced increase in width is seen to the north on the central profile using the northern loop position; this widening is interpreted as being due either to a shallower lobe of mineralization or to a thrust slice of the ore horizon to the north.

- A second deep conductive body to the west of the main body, that could be massive sulphide or a stockwork, or possibly a fault.

- A negative result on the neighbouring site of La Bomba (fig. 2), which was confirmed by later drilling.

This study, as an actual example, shows that the MELIS method is able to locate deep conductive bodies at depth greater than 500 m. The method of interpretation developed under this contract has proved to yield valuable quantitative information for the delineation of orebodies.

3.3 PRELIMINARY 1D AND 2D REMI MODELLING

1D modelling has shown that in a horizontally layered medium, the phase measured by the REMI probe decreases almost linearly with depth, by sections whose boundaries correspond closely to those of the geoelectrical layers. The rate of decrease varies as the signal frequency and the conductivity of the host layer.

Numerous 2D synthetic REMI logs have been computed with the BIEFEM software, for a frequency of 1800 Hz which happened to give the measurements of best quality. The study has shown that two kinds of REMI response are possible when a drillhole has missed a conductive target:

- If the transmitting loop is located above the mass, or on the opposite side of the drillhole from the mass, the response is a phase maximum; it is perceptible up to 100 m away from the mass.

- If the loop is located on the same side of the mass as the hole, the response is a phase minimum; it is perceptible up to 50 m away from the mass.

3.4 RESULTS OF REMI LOGS AT VALVERDE

A total of eight REMI recordings have been made at Valverde, in five drillholes with one or two of four loop positions. The two types of responses (minimum or maximum) have been observed.

In one barren borehole, a pronounced phase minimum suggests that the gap in the mineralization is too small to be sensed by REMI.

In another hole, an asymmetrical phase maximum (fig. 3) shows that the mineralization is probably less than 50 m away from the hole, to the west of it.

So the REMI survey yields information that complements that of drillholes and MELIS. More accurate directional information will be obtained only with a three-axis EM probe such as ARLETT, presently undergoing development.

4. CONCLUSIONS

The methodological study of frequency-domain EM methods, used from surface and boreholes, made by the Geophysics department of BRGM as part of a project aimed at the "Optimization of Electromagnetic and Gravity Methods of Mineral Exploration" has reached its main intended objectives.

For the two EM methods studied (surface-to-surface MELIS, and surface-to-borehole REMI), the measurement procedures have been optimized and a method of interpretation has been developed using 2D modelling. Subsequently, the measurements made at Valverde were successfully interpreted. The two methods are now operational and ready to be marketed, thanks in large measure to the experience acquired in the course of this contract. Instrument sales have already been made in Canada.

Compared to classical CSAMT, measurements of magnetic only components, such as performed with MELIS, are less sensitive to superficial inhomogeneities.

Compared to time domain methods (TEM), such as the one studied on the same site by BGR, FEM is easier in terms of field operation (stronger signal to noise ratio, lighter equipment) and of numerical modelling for interpretation. Although its depth of investigation is limited by the transmitter to receiver distance, the MELIS system appears to be one of the most efficient technique for deep massive sulphide exploration.

It has been possible to study the borehole 3-axis EM method only briefly (the ARLETT probe is still being developed). The modelling achieved on this method has shown the direction for continuing research. Such a research should lead to a promising tool, in view of the good results already obtained with the single axis REMI probe.

5. COMMUNICATIONS

In addition to internal communications made at meetings of CEC contact groups, three external communications were made during this contract:

J. BERNARD, B. BOURGEOIS, P. VALLA, 1989 - Application of MELIS frequency EM method in the detection of a deeply buried orebody (Spain). Paper read at the 51st meeting of EAEG. Berlin. June 1989.

J. BERNARD, B. BOURGEOIS, P. VALLA, 1989 - Application of a loop source multifrequency EM method in the detection of a deep massive sulphide orebody (Spain). Poster presented at the 59th meeting of the SEG. Dallas. November 1989.

B. BOURGEOIS, 1989 - Detection of deep conductive orebodies by frequency domain electromagnetism. Paper read at the combined BRGM and Société géologique de France Geophysics meeting. Paris. November 1989.

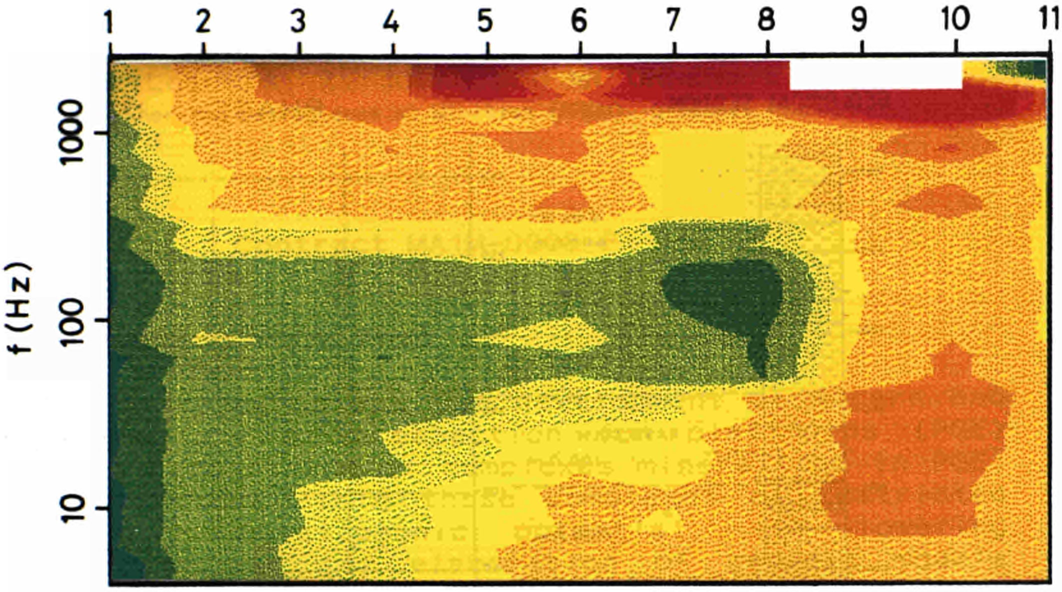


Figure 1 : MELIS apparent resistivity pseudo-section showing a bipolar anomaly (below stations 7 to 10) due to a deep conductive body

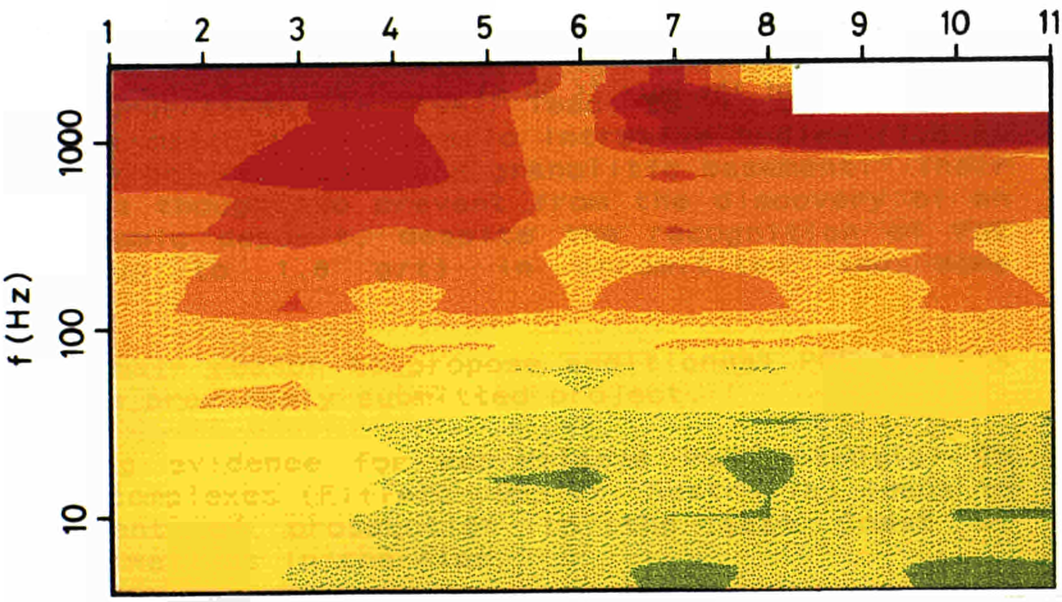


Figure 2 : MELIS apparent resistivity pseudo-section showing no conductive anomaly at depth on the site of La Bomba

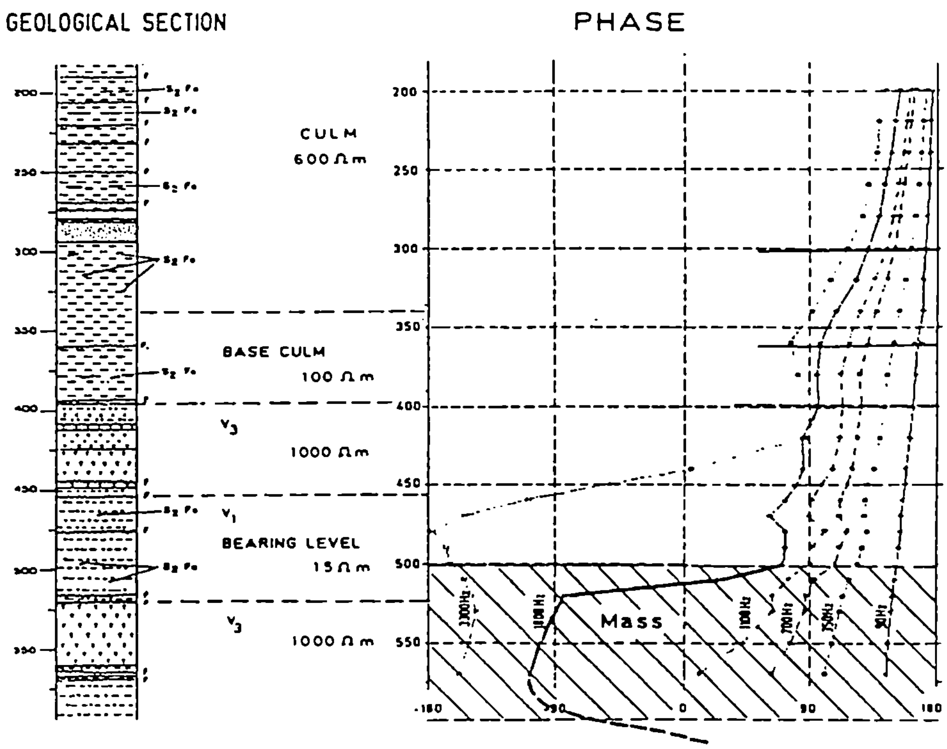


Figure 3 : REMI phase log showing an anomaly in a barren drillhole ; the massive ore is inferred to be in the close vicinity of the hole (< 50 m)

FACTORS GOVERNING CONCENTRATIONS OF PLATINUM GROUP ELEMENTS IN LAYERED COMPLEXES

Project Leaders: Z. JOHAN and M. OHNENSTETTER
Bureau de Recherches Géologiques et Minières (BRGM), Orléans, France

Contract MA1M-0008-F

1. OBJECTIVES AND INTRODUCTION

The aim of this research was the development of modern and reliable methodology of prospection for platinoids (PGE) allowing : (1) recognition of complexes mineralized in PGE, (2) characterization within these complexes of restricted zones with high metallogenic potential, (3) lowering prospection costs and (4) elaboration of genetic models based on field and laboratory experiments. To realize this project, a multidisciplinary approach was engaged in the area of Andriamena, Madagascar. This area was selected because of : (1) the existence of abundant alluvial sperrylites; (2) it is a large, folded, basic-ultrabasic complex extending over an area of 170 km x 160 km and carrying chromite deposits and, locally, Fe and Ni sulphide concentrations; (3) the Archean age of the Andriamena complex is thought to be a possible equivalent of the Bushveld type complexes.

Field work undertaken in 1987 lead to recognition of numerous small mafic to ultramafic intrusive bodies (1.5 km long to 1 km wide) emplaced in a granulitic basement. Their small size was thought to prevent from the discovery of an extended economic deposit, despite the recognition of PGE enrichment (up to 1.8 g/t) in chromitites and some pyroxenites.

This was the main reason to propose additionnal PGE targets in 1989 to the previously submitted project.

The increasing evidence for appreciable PGE potential in alaskan-type complexes (Fifield complex, Australia) leads to the development of prospection in the East Coast of Madagascar as well as in the Alps.

2. MATERIALS AND METHODS

This project which proposed to find new prospection tools and to explain the origin of PGE-ore mineralization involving a multidisciplinary approach both in the field and in the laboratory. At the beginning of the project, the generally accepted hypothesis was that in layered complexes, PGE concentration is mainly controlled by chromite and/or sulphide deposition with magma mixing and/or the action of fluids as the main mechanisms for the formation of a PGE-enriched reef.

In the Andriamena area, where no PGE concentration was previously known, field studies were developed independently of, but coordinated with, stream sediment and alluvial prospection engaged by BRGM on its own budget resources.

Field work in Madagascar was realized by a multidisciplinary team, after previous field reconnaissance by T. Augé (1 month in 1986) : (1) in 1987 with T. Augé (5 months), Z Johan (5 weeks), J. Le Metour (1 month) and M. Ohnenstetter (2 months); (2) in 1988 with T. Augé (5 months); (3) in 1989 with M. Ohnenstetter (2 months) and (4) in 1990 with M. Ohnenstetter (6 weeks). Prospecting was assumed by B. Martel-Jantin from BRGM (Exploration Department) since 1987, except in 1989.

In the investigated Andriamena area (100km x 50km), field studies began up-stream in sectors with a high recovery of alluvial sperrylites. Representative rocks of the ultramafic complexes were sampled for Pt and Pd analyses and for petrological and geochemical investigations. Soil was prospected for auger drilling in 1987 through 1990; trenches were dug in 1989 and drilling carried out in 1990. Field work on the East Coast of Madagascar began in 1989, concomitantly with those in the Andriamena area. Sampling was done both in the field and at the core library in Antananarivo.

Detailed mapping as well as structural analysis were done locally to define the internal geometry of the complexes as well as their relationship with the enclosing rocks and the nature and intensity of the tectonics. These results permitted the discovery of PGE anomalies up to 1,9ppm, which were studied in detail later. During this first stage, about 931 rock samples were analysed for Pt and Pd using plasma, NAS, Canada. On its own budget resources, the BRGM (Direction des Affaires Minières) realized 5350 rubb-holes and 8 trenches (360m in total length) in three intrusions (Lavatrafo West and South; Andohankiranomena) which permitted to appreciate the distribution of PGE and the discovery of elongated anomalous zones (up to 300 m long and 10 m wide) despite the existence of an over burdening lateritic cover.

In the highly anomalous zones, 10 drill holes were realized (621m in total length) in the above mentioned intrusions. Samples were systematically taken every 50 cm and analyzed for Pt and Pd using the method indicated above. The analytical data were processed, leading to the discoveries of mineralized bodies with the highest tenors ((Pt+Pd) up to 8.4 g/t in sector Lavatrafo 7W). All this work became possible thanks to cooperation with the scientific team supported by the EEC and the operation teams founded by the BRGM. In all, during the three years of study, about 15.000 samples (rock, soil and stream sediment) were analyzed for Pt and Pd.

Petrographic studies allow for definition of the nature of the mineral distribution throughout the complex and the importance of secondary reequilibration (granulitic to greenschist facies). The age and origin of the complexes as well as the behaviour of PGE during magma fractionation were studied through geochemical studies (major and trace elements distribution and isotopic characteristics).

Mineralogical studies of PGE-bearing phases (PGM) allow for the specification of : 1) the nature of the main PGE carrier; 2) the temperature of ore deposition; 3) and the time of deposition with respect to other mineral phases. LASER ablation and ICP-MS analysis were also employed for determination of trace elements in mineral phases.
The internal organization of the mafic-ultramafic complexes, their petrology, geochemistry and mineralogy were investigated by the GIS (BRGM, CNRS) team (T. Augé, C. Beny, C. Guerrot, O. Legendre, M. Robert) while structural geology and isotope geochemistry by other BRGM collaborators (A. Cocherie, A.M. Fouillac, V. Johan, J. Le Métour).
In alaskan-type complexes (East Coast of Madagascar and French Alps), mineralogical studies were mainly developed to define the type of PGE mineralization and consequently the areas to prospect.

3. ANALYSIS OF RESULTS

3.1. <u>THE ANDRIAMENA AREA</u>

Two types of basic-ultrabasic complexes were defined : 1) the North Andriamena-type complex with chromite deposits and 2) the West Andriamena-type complex with PGE concentrations.

3.1.1. <u>The North Andriamena-type complexes</u>

In these complexes, there is a crude relation between the size of the chromite deposit and the volume of the intrusions. Chromitites here are enriched in Ru, Os and Ir in the same manner as those from ophiolites.

As for the latter, the nucleation of chromite around early PGM (mainly laurite, erlichmanite, Ir and Pt-rich osmium and irarsite) could be invoked for the genesis of PGE-anomalous rocks. Pt-bearing minerals are rare (one telluride in Bemavo Cr42) despite the existence of alluvial sperrylite.
It is thought that in North Andriamena, undifferentiated rocks could be the roots and/or the feeeder dykes of West Andriamena type complexes (see later) despite the different compositional evolution of chromite and associated PGM.

3.1.2. The West Andriamena-type complexes

Enrichment in PGE ((Pt+Pd) up to 8.4g/t) has been found in these complexes which are small mafic to ultramafic intrusives emplaced in a granulitic basement. A different type of PGE mineralization is defined considering : 1) the geological setting of the intrusion; 2) the internal structure of the ultramafic complexes; 3) the PGE distribution.

Geological environment - a possible Pan-African rifting

The granulitic basement, locally retrometamorphosed into the amphibolite facies is composed of a heterogeneous layered series with igneous and sedimentary derived rocks thought to be Archean in age and a charnockitic series. The latter is intrusive into the above, composed essentially of acidic and mafic charnockites, locally layered, and showing remnants of magmatic textures.

The basement was affected by two tectonometamorphic events. The first, which generated granulite to amphibolite facies regional metamorphism, is characterized by isoclinal folds associated with S_1 foliation transposed onto the primary S_0 layering. The second event, which resulted in greenschist facies metamorphism, is marked by the development of subvertical N-S shear-zones both in the basement rocks and the intrusions. This second event is thought to be responsible for the emplacement of the ultramafic complexes (Fig. 1). Evidence for a N-S strike-slip system during this process comes from the sigmoïdal map patterns of the intrusions with subvertical margins, the asymmetrical distribution of lithological facies and the presence of fractures of variable orientation ranging from distensive to shear and filled by magma.

Most of the intrusives were emplaced under a low grade granulitic facies (< 5 kb) compared to those from North Andriamena where a lithostatic pressure between 7.5 kb and 19 kb was estimated considering paragenetic reaction between one intrusion and the host granulitic shield.

The West Andriamena intrusions may be possibly related to a Pan-African rift whose products are recognized over 100 km in length. The U-Pb dating of single zircons by stepwise evaporation methods from three samples, one plagioclase-rich pyroxenite and two granitic differentiates gave respectively : 790 ± 13 Ma, 780 ± 11 Ma and 784 ± 5 Ma dates. These ages are generally younger than those occurring in westerly rifts of the Arabo-Nubian shield.

Nevertheless, ENd calculated at 790Ma for whole rocks coming from the ultramafic complexes are very negative, clustering around -22. Depleted mantle values for the West Andriamena rocks imply a very long crustal residence time. To allow to decipher the real meaning of the ages obtained, acquisition of new isotopic data is in progress.

Constitution of the West Andriamena ultramafic complexes

Three lithological zones may be distinguished in these complexes having either a funnel or dome-like shape (fig. 1) : (1) coarse grained dunite to peridotite, mainly harzburgite, (2) coarse grained to pegmatitic orthopyroxenite, locally cut by chromite veins, (3) fine-grained pyroxenites more or less differenciated (orthopyroxenite to clinopyroxenite, plagioclase-rich pyroxenite), with local disseminations of PGE-barren base metal sulphides (pyrrhotite, pyrite, chalcopyrite, traces of pentlandite), gabbro and granite generally close to the periphery of the complex. The conditions of crystallization were relatively static for the rocks of zones (1) and (2), adcumulates to heteradcumulates, and were more dynamic for those of zone (3) meso- to orthocumulates due to magma flow close to the margins or within sills and dykes.

Two types of complexes may be distinguished : (1) the orthopyroxenite-type complex and (2) the clinopyroxenite-type complex , the latter one having undifferenciated fine-grained clinopyroxenite, and rare orthopyroxenite with minor chromitite and higher Ti, P and alkali contents. In these complexes, the boundaries between zones are marked by the appearance of new liquidus phases. In the orthopyroxenite-type complex, orthopyroxene appears between zone (1) and (2) and clinopyroxene between zone (2) and the differenciated rocks of zone (3), giving the crystallization order : olivine - orthopyroxene - clinopyroxene - plagioclase. In the clinopyroxenite-type complex, clinopyroxene appears earlier together with orthopyroxene. Parental magmas from both types of complexes derive from SiO_2-saturated tholeiitic liquids with variable amount of incompatible elements and alkalis, and with variable Ca/Al ratio.

During fractional crystallization, FeO/(FeO + MgO) varies from 18 to 70 with a concomitant increase of Al_2O_3, TiO_2 and FeO and decrease of MgO and SiO_2. The cryptic variation of mafic phases is compatible with this magmatic evolution despite some overlaps between rocks-types and the extent of metamorphic reequilibration.

A new type of Pt-Pd mineralization

The PGE anomalous zones occur in intrusives characterized by a high PGE background, as indicated by the positive correlation between the grade of the PGE ore and the PGE tenors of the host-rocks. However there is no relationship between the size of the intrusion and the grade of PGE mineralization. The highest tenors were recognized in sector 7 within the southern intrusion, 750 m long and about 100 m wide, otherwise having a high PGE background (112 ± 32 ppb to be compared to that of barren intrusions, below 20 ppb).
High Pt and Pd contents ((Pt + Pd) up to 8.4 g/t) occur in different rock-types : dunite, harzburgite, orthopyroxenite, clinopyroxenite, chromitite and their metamorphic equivalents (amphibolite) and corresponding alterites. These rocks occur in zone (1) and mainly in zone (2) in the orthopyroxenite-type complex (sector 10) and in zones (1) and (3) in clinopyroxenite-type complex (sector 7). In the former, the highest PGE contents are found in late, narrow, often boudinated chromite dykes, locally cross-cutting crudely layered massive chromitites and altered pyroxenites.

In all the complexes, the PGE mineralization occurred during the formation of early cumulates before the late-stage crystallization of evolved pyroxenite, gabbro and granite.
PGE anomalies in rocks and soils appear as multiple subparallel, elongated but discontinuous zones which seem to be controlled by the shape of the intrusion and locally by the existence of former lithological and structural planes rather than by a specific rock type. Two PGE-enriched bodies with an average of (Pt+Pd) content of 1 to 2 g/t have been recognized in two intrusions (300 m x 50 m x 10 m) and (70 m x 50 m x 5m), respectively. The distribution of (Pt+Pd) and (Pt/Pd) along a cross section perpendicular to the axis of anomalous zone have a wavy character which may be related to the cooling of the intrusion.
Two kinds of PGE patterns may be defined in : 1) the orthopyroxenite-type complex and 2) the clinopyroxenite-type complex (fig. 2). In the first, the Ru, Os, Ir concentrations are relatively constant whereas those of Rh, Pt and Pd vary from a negative to a positive slope on the PGE pattern ($1.9 < Pt/Ir < 10.3$; $0.8 < Pt/Pd < 5.11$). The second one shows a strongly positive slope ($82 < Pt/Ir < 936.7$; $0.9 < Pt/Pd < 1.6$) due to lower Ru, Os and Ir concentrations and especially to high Pt and Pd contents. The highest Pt and Pd tenors (8.4 g/t) were found in this clinopyroxenite-type complex both in altered dunite and clinopyroxenite (fig. 2). The role of alteration in concentrating the PGE has yet to be defined.
There is a major decoupling between the PGE partitioning in

mineralized zones and the indicators of magmatic differentation such as FeO/(FeO + MgO), Ta/Th, REE or the elements Cr, S, Ni and Cu.

The PGM association is dominated by arsenides, while sulpho-arsenides and sulphides, native metals, alloys and tellurides are less frequent. Among the arsenides, sperrylite is the most abundant whatever the type of complexes. Ru-, Os- and Ir-bearing PGM (laurite, erlichmanite and hollingworthite) are often included in chromites and silicates, whereas Pd-rich phases are interstitial and hence later than the other PGM, chromites and silicates. The order of appearance of the PGM, their chemical nature and the extents of their solid solution between laurite and erlichmanite, irarsite and hollingworthite, and between irarsite, platarsite and sperrylite, demonstrate PGE fractionation. This is corroborated by the distribution of PGE in rocks and by the variation of Pt/Ir and Pt/Pd ratios.
The evolution of the ore-forming system is identical for sectors 7 and 10 and indicates a progressive decrease of fS_2 and an increase of other volatiles, such as arsenic (fig.3). In the sector 10, all the PGE fractionation stages are observed, whereas in the sector 7, only the late stages (arsenide-rich) are present. The effect of fractionation are apparent at any scale : between the different complexes such as for sectors 7 and 10, along hectometric anomalous zones, and between two juxtaposed samples (distance less than 1 m).

The following pecularities were observed : (1) the PGE were enriched only in slightly differentiated rocks ; (2) the decoupling between Pt/Ir and Pt/Pd ratio occurred with the magmatic differentation indexes ; (3) PGE-barren and enriched intrusions existed close together ; (4) arsenides are the main PGE carrier, which is related to a strong As activity; (5) there was an absence of correlation between massive chromite, sulphide and PGM concentration ; (6) the same positive correlation existed between PGE mean values of anomalous zones and host-rocks in sectors 7 and 10; and (7) the pegmatitic facies in orthopyroxenite was associated with small chromite-rich veins of variable orientation characteristics of hydraulic fracturing.

All of these support the idea of existence of PGE-enriched fluids related to magmas and it is suggested that fluid might have escaped from the magmas at a certain stage of differentiation (e.g. zone (2) with orthopyroxenite). The separation of a fluid phase from the magma might have been facilitated by fluctuations in the thermal gradient after the appearance of orthopyroxene at the liquidus. These fluids could have used preexisting lithologic and structural planes to penetrate the earlier formed parts of the intrusions. PGM could then have precipitated from the fluids

during subsequent cooling. If the evolution of the Pt/Pd ratio is related to a temperature gradient, as expected from the wavy character of the PGE repartition, their extensive precipitation occured within the cooler zones. These zones may correspond to local lithological and structural discontinuities formed during the magma injection.
In this way, the magmatic conduit represented by the dyke-like intrusion of sector 7 could have channelled and trapped high temperature fluids from an underlying magma chamber. The coarse-grained orthopyroxene zone in sector 10 would represent the site of fluid separation.

3.2. ALASKAN TYPE COMPLEXES

3.2.1. The East Coast of Madagascar

This area was selected because of the existence of huge basic-ultrabasic complexes with detrital PGM in local stream beds down-stream, especially isoferroplatinum thought to be derived from alaskan-type complexes as in the Antanambo-Manampotsy area.

In the East Coast of Madagascar, field geology is complicated by the presence of a tropical main forest below which is an overburdening lateritic cover normally thicker than that of the Andriamena area. In 1988, geochemical exploration and rock sampling were done in three areas : 1) Antanambo-Manampotsy, 2) Anosibe and 3) Antanambombato; the two former areas being located up-stream of platinum-rich placers, and the latter being representative of cretaceous annular intrusive complexes. In three other areas, samples (some of them carrying large sulphide concentrations) were obtained from drill cores obtained in the sixties for Ni-Cu prospection by the BRGM. A typology of mafic-ultramafic complexes from the east Coast was proposed from preliminary data.

The most relevant results were obtained in the Antanambo-Manampotsy area with the highest Pt and Pd stream sediment tenors recorded in Madagascar (100 and 58 ppb, respectively) and the discovery of intrusive basic complexes locally carrying some minor Pt and Pd anomalies (respectively 170 and 40 ppb). The intrusions correspond to sub-meridian feeder-dykes probably belonging to a rift system. The rock assemblage is composed of clinopyroxenite, wehrlite, magnetite-rich gabbros (olivine-gabbro, leucogabbro) and monzonite associated with basalts, ferrobasalts more or less iron-rich. The liquid composition indicates a derivation from an alkaline magma rich in titanium (TiO_2 up to 4.07 at %), phosphorus (P_2O_5 up to 0.44 at %), and slightly enriched in potassium (K_2O up to 0.44 at %).

Spherical Pt-Fe nuggets (0.1 to 1 mm in diameter) contain a large variety of inclusions of silicates (K-feldspar, plagioclase, clinopyroxene and amphibole), glass and platinum-group minerals (Os-rich alloys, laurite, erlichmanite, cooperite, braggite, kashinite, hollingworthite, keithconnite), either trapped or exsolved from a Pt-Fe-Cu-rich solid-solution. This mineral assemblage is similar to those from alaskan-type complexes. PGE (Pt+Pd) enrichment up to 0.5 g/t have been found in clinopyroxenite from the Antanambao-Manampotsy area but the extend and importance of the PGE-enriched zones are insufficiently defined.

3.2.2. The French Alps

The first alluvial Pt-Fe alloy was discovered during gold recovery (Fisher et al., 1988). A mineral study of heavy concentrates (Johan et al., 1990) showed that PGM (average size 130 µm) association was mainly composed of isoferroplatinum (92 %) associated with (Os, Ir, Ru) alloys (3-5 %), native gold and (Au, Cu, Ag) alloys (4-5 %). Isoferroplatinum contains numerous inclusions of alloys, sulphides, arsenides, and Pd-tellurides, which often exhibit a drop-like shape indicating their original entrapment in liquid state.
The presence of gold-copper alloys sometimes reaching the composition of tetraauricupride, of shandite, of (Ni,Pt) Sn alloys included in gold grains and the content of gold in some isoferroplatinum indicate a common origin for PGE and Au mineralization.

The composition of gold is now used as a prospection tool. Cu-rich gold and isoferroplatinum nuggets up to 1mm were found in the Bleone river, 80 km up-stream from the site of the (Pt, Fe) nugget discovery. The primary source of this PGE mineralization may occur in the upper part of the Durance river, either in the Pelvoux massif or in the Jurrassic ophiolites as indicated by the high PGE tenors on some concentrates.

A geothermometer (fig. 4) has been proposed from the pseudoternary phase diagram of the Pt+(Fe) - Os+(Ru)-Ir (Rh) system. The representative temperature of equilibration (fig.4) from the alloys of the Durance river is lower (750 °C) than that of Fifield (800 °C) or Alaska and the Ourals (850 °C).

In the isoferroplatinum from the Durance river, the composition of the silicate glass inclusions indicates an origin from a calc-alcaline magma, a fact which may exclude ophiolites as a possible source for PGE mineralization. However, in Corsica, preliminary data obtained from ophiolitic mantle peridotites, which belong to the Jurassic alpine belt, indicate the existence of (Pt+Pd) anomalies. In anomalous rocks, there is some evidence for the crystallization of PGM (mainly alloys and tellurides) following that of pentlandite, from a reducing fluid exsolved from a circulating magma. These mineral phases (<1 μm in size) were found in rocks even with Pt, Pd, Os and Ir contents as low as 20, 10, 5 and 2ppb respectively. The existence of (Pt, Fe) alloys, copper-rich phases and the enrichment of the ore-forming system in Ni, Sn and Pb show some similarities with the Durance mineralization. However the temperature of formation is lower in alpine peridotites (below 610 °C) than in Durance (750 °C). This may indicate several PGE sources in the Alps as well as for Alaskan type mineralization.

3.3. TYPOLOGY OF MAFIC-ULTRAMAFIC COMPLEXES

A new classification of worldwide mafic-ultramafic complexes, based on the order of appearence of minerals after olivine in cumulates allows for the identification of the high metallogenic potential for complexes with early-forming orthopyroxene. This is indicative of a derivation from SiO_2-saturated tholeiitic parental magmas which are known to occur in active margins but also in intracratonic areas as shown by the composition of Bushveld and Stillwater parental magmas. The presence of local PGE enrichment in some ophiolites (type II after Rocci et al., 1975) having affinities with immature island arc magmatism (SiO_2-saturated tholeiites) is in agreement with this hypothesis.

The influence of alkalis in magmas on PGE concentration is still debatable. They may favor the presence of high PGE concentrations in alaskan-type complexes which have clinopyroxene as an early phase.

The proposed typology for the distribution of worldwide ultramafic complexes shows that the PGE potential of alkaline-complexes related to rift zones; tholeiitic to calc-alcaline complexes from active margins; as well as those of ophiolitic cumulates derived from oceanic to immature island-arc tholeiites, are insufficiently known.

4. CONCLUSIONS

Four main objectives were proposed for the EEC project on "Factors governing the concentrations of PGE in layered complexes". The first, the discovery of complexes mineralized in PGE with the PGE concentration (Pt+Pd), up to 8.4 g/t, in the West Andriamena zone, shows that the aims of the project were accomplished. In three years, from 87 to 90, a cooperative effort between the prospection team of the

BRGM and the scientific team of the GIS (BRGM, CNRS) lead to a discovery of a new type of PGE mineralization. The reader may recall that at the beginning of the project, alluvial sperrylites were known only as well as the existence of ultramafic and mafic intrusions.
Furthermore, the importance of alaskan-type complexes characterized by PGE concentrations preferentially enriched in platinum was taken into consideration.

The second objective concerning the structural, petrological and geochemical characterization of zones with high metallogenic potential in the Andriamena complexes was less successful because of their complexity of the zones and their variation between each other. However, we succeeded in finding the PGE enrichments despite the absence of petrological and structural markers in the field. For example, PGE concentrations are absent in chromite or sulphide concentrations or in specific rock-type, and in pegmatitic or hydrothermally altered facies. The only known common denominator of PGE-enriched rocks is their low degree of magmatic differentation.
The discovery of high grade Pt- and Pd concentrations formed by arsenides leads to new prospection tools distinct from those currently used for the PGE in sulphide- or chromite-bearing mafic and ultramafic complexes.

As far as the prospection cost is concerned, the collaboration between the BRGM prospection team and the scientific team of the GIS (BRGM, CNRS) allows the establishment of an efficient prospecting approach in areas with lateritic cover. PGE concentration in stream sediment was used to define areas which had to be prospected more intensively. In soils and laterite, auger drilling has revealed underlying anomalous zones within the mineralized host-rocks. The location and extent of the anomalous zones were obtained through trenches. In the Andriamena area, this approach coupled with rock sampling was efficient in defining complexes with high PGE potential. However, this method has still to be tested to become an effective prospection tool.

The presence of PGM-arsenides indicates a strong Pt and Pd enrichment linked to that of arsenic, which is responsible for the decoupling of PGE concentrations and sulphide or chromite occurrences. This implies that a specific ore-dressing process is necessary to recover the PGE. If this kind of fractionation occurs in layered mafic-ultramafic complexes as it seems to be the case within a majority of alaskan-type complexes, the currently used benefication methods of PGE extraction should be revisited.

To better understand the genesis of this new type of PGE mineralization in the West Andriamena zone, it must be chemically modelled. The model should involve the separation of a fluid phase enriched in PGE from a magma at an early stage of differentation. This requires a better knowledge of the evolution of magma chamber and especially the permeability of freshly formed cumulates and must take into account the role of fluids in the concentration of PGE. It must also consider the role of chromite and sulphide deposits and other effects of fluid interaction with surrounding rocks. This may constitute a new prospection tool for this type of deposits which cannot be detected by existing geophysical methods.

5. REFERENCES

Papers (Published and Submitted)

Auge T. and Legendre O.
(1991)
Pt-Fe NUGGETS FROM ALLUVIAL DEPOSITS IN EAST MADAGASCAR.
Submitted to Can.Miner.

Cocherie A., Auge T. and Meyer G.
(1989)
GEOCHEMISTRY OF PLATINUM-GROUP ELEMENTS IN VARIOUS TYPES OF SPINELS FROM THE VOURINOS COMPLEX
Greece, Chem. Geol., 77, 27-39.

Cocherie A., Volfinger M. and Meyer G.
(1987)
DETERMINATION OF THE NOBLE METALS IN CHROMITE AND OTHER GEOLOGICAL MATERIALS BY RADIOCHEMICAL NEUTRON ACTIVATION ANALYSIS
J. Radioanal. Chem., 113, 133-143.

Johan Z., Ohnenstetter M., Fisher W., Amosse J.
(1990)
PLATINUM-GROUP MINERALS FROM THE DURANCE RIVER ALLUVIUM, FRANCE
Mineral. Petrol., 42, 287-306.

Johan Z., Ohnenstetter M., Slansky E., Barron L.M., Suppel D.
(1989)
PLATINUM MINERALIZATION IN THE ALASKAN-TYPE INTRUSIVE COMPLEXES NEAR FIFIELD, NEW SOUTH WALES, AUSTRALIA.
PART 1. PLATINUM-GROUP MINERALS IN CLINOPYROXENITES OF THE KELVIN GROVE PROSPECT, OWENDALE INTRUSION.
Miner. Petrol., 40, 289-309.

Johan Z., Slansky E. and Ohnenstetter M.
(1991)
ISOFERROPLATINUM NUGGETS FROM MILVERTON (FIFIELD, N.S.W., AUSTRALIA) : A CONTRIBUTION TO THE ORIGIN OF PGE MINERALIZATION IN ALASKAN-TYPE COMPLEXES.
C.R. Acad. Sci. Paris, 312, II, 55-60.

Ohnenstetter M.
(1991)
PGE ENRICHED UPPER MANTLE PERIDOTITES IN MONTE MAGGIORE OPHIOLITES (CORSICA, FRANCE) : MINERALOGICAL EVIDENCE FOR ORE-FLUID METASOMATISM.
Mineral. Petrol., accepted.

Ohnenstetter M., Bechon F., Ohnenstetter D.
(1990)
GEOCHEMISTRY AND MINERALOGY OF LAVAS FROM THE ARAKAPAS FAULT BELT, CYPRUS : CONSEQUENCES FOR MAGMA CHAMBER EVOLUTION
Mineral. Petrol., 41, 105-124.

Ohnenstetter M., Karaj N., Neziraj A., Johan Z., et Cina A.
(1991)
LES DIFFERENTS TYPES DE MINERALISATION EN PGE DES MASSIFS OPHIOLITIQUES DE TROPOJA ET DE BULQIZA, ALBANIE : VERS UNE RECONNAISSANCE DU POTENTIEL PLATINIFIERE DES OPHIOLITES
C.R. Acad. Sci., Paris, série II, in press.

Ohnenstetter M., Rossi Ph.,
(1987)
SIGNIFICATION DES COMPLEXES BASIQUES - ULTRABASIQUES ASSOCIES AUX GRANITOIDES DANS L'EVOLUTION DE LA CHAINE VARISQUE DU SUD DE L'EUROPE.
Bull. Soc. géol. Fr., (8), 3, 801-810.

Slansky E., Johan Z., Ohnenstetter M., Barron L. and Suppel D.
(1991)
PLATINUM MINERALIZATION IN THE ALASKAN TYPE INTRUSIVE COMPLEXES NEAR FIFIELD, N.S.W., AUSTRALIA PART II. PLATINUM GROUP MINERALS IN PLACER DEPOSITS AT FIFIELD
Mineral. Petrol. 43, 161-180.

Reports

Aubourg V.
(1990)
ETUDE D'ECHANTILLONS REPRESENTATIFS DES COMPLEXES BASIQUES A ULTRABASIQUES DE MADAGASCAR
rapport de DEA, 80 p.

Auge Th. and Martel-Jantin B.
(1989)
LE PLATINE A MADAGASCAR : RESULTATS ET PERSPECTIVES.
Note BRGM 28 02 1989.

Johan V.
(1990)
CONDITIONS DE CRISTALLISATION DES INTRUSIONS BASIQUES ET ULTRABASIQUES ET DE LEUR ENCAISSANT (Andriamena-Madagascar).
Note BRGM 17 12 1990.

Johan Z., Auge Th., Cocherle A., Johan V., Le Metour J. and Ohnenstetter M.
(1988)
GUIDES DE PROSPECTION POUR LES GISEMENTS DE PLATINOIDES. ETUDE DE LA ZONE D'ANDRIAMENA (MADAGASCAR)
Rapport BRGM 88 MDG 069 GIS. Contrat CEE N° MA1M-0008-F.

Johan Z., Auge Th., Cocherle A., Martel-Jantin B.
GUIDES DE PROSPECTION POUR LES GISEMENTS DE PLATINOIDES. ETUDE DE LA ZONE D'ANDRIAMENA (MADAGASCAR).
Rapport préliminaire (avril 1988-mars 1989).

Legendre O., Auge Th., Johan Z. and Ohnenstetter M.
(1990)
LES MINERAUX DU GROUPE DU PLATINE DE LA ZONE OUEST ANDRIAMENA (MADAGASCAR)
Rapport BRGM R31829.27p.

Martel-Jantin B. and Auge T.
(1988b)
LE DOUBLE INTERET DU DEVELOPPEMENT DES CHROMITES DANS LA ZONE D'ANDRIAMENA (CENTRE NORD DE MADAGASCAR)
Note BRGM, 30 11 1988.

Martel-Jantin B. and Auge T.
(1989)
CONVENTION PLATINOIDES ET SUBSTANCES CONNEXES. MISSION PLATINOIDES ANDRIAMENA.
Rapport technique de la mission 1988. Rap BRGM 89 DMDG 003.

Martel-Jantin B., Auge T., Rakotomanna D.
(1987)
CONVENTION OMNIS-BRGM. MISSION PLATINOIDES ET SUBSTANCES CONNEXES.
1987. Rapport préliminaire, 53 p., 5 tabl. 31 pl.

Martel-Jantin B., Auge T., Rakotomanana D.
(1988)
CONVENTION OMNIS-BRGM. MISSION PLATINOIDES ET SUBSTANCES CONNEXES.
Andriamena 1988. Rapport préliminaire. BRGM Tana Rap 88 TAN 02.

Martel-Jantin B., Johan Z., Auge T., Ohnenstetter M.
(1988a)
CONVENTION PLATINOIDES ET SUBSTANCES CONNEXES. MISSION PLATINOIDES ANDRIAMENA
Rapport technique de la mission 1987. Rap BRGM 88 MDG 018; 113p.

Martel-Jantin B. and Ohnenstetter M.
(1990)
BRGM MADAGASCAR.
Rapport mensuel. Projet Platinoïdes. Oct. 90.

Ohnenstetter M.
(1989a)
COMPTE RENDU SUR L'ETAT D'AVANCEMENT DES TRAVAUX RELATIFS A LA PROSPECTION DU PLATINE DE LA DURANCE.
Note BRGM avril 89.

Ohnenstetter M.
(1989)b
COMPTE RENDU SUR L'ETAT D'AVANCEMENT DES TRAVAUX RELATIFS A LA PROSPECTION DU PLATINE DE LA DURANCE
Note BRGM mai 89.

Ohnenstetter M.
(1989c)
COMPTE RENDU SUR L'ETAT D'AVANCEMENT DES TRAVAUX RELATIFS A LA PROSPECTION DU PLATINE DE LA DURANCE.
Compléments au rapport de mai 1989. Note BRGM juin 1989.

Ohnenstetter M.
(1989d)
REMARQUES PRELIMINAIRES SUR LA REPARTITION DES PGE DANS LES TRANCHEES 2 ET 3 DU SECTEUR LAVATRAFO (S7S)
Note BRGM oct. 89.

Ohnenstetter M., Rakotomanana E.D. et De Bretizel P.
(1989)
RAPPORT PRELIMINAIRE DE LA MISSION PLATINOIDE DANS LA ZONE OUEST ANDRIAMENA ET SUR LA COTE EST DE MADGASCAR
89 TAN 05.

Ohnenstetter M.
(1990)
NOTE SUR LA REPARTITION DES PGE DANS LES MASSIFS ULTRAMAFIQUES A POTENTIEL PLATINIFERE ELEVE DE LA ZONE OUEST ANDRIAMENA (SECTEUR D'ANDRIAMENA, S10 ET DE LAVATRAFO SUD, S7S)
Note BRGM 1.4.90.

Ohnenstetter M.
(1990)
COMPTE RENDU DE MISSION EN ALBANIE DU 23 AOUT AU 6 SEPTEMBRE : LE POTENTIEL CHROMIFERE ET PLATINIFERE DES OPHIOLITES
Rapport BRGM 38p.

Ohnenstetter M. and Calvez J.Y.
(1990)
NOTE SUR L'AGE DES COMPLEXES DE TYPE WEST ANDRIAMENA, MADAGASCAR; CONSEQUENCES
Note BRGM 13 02 90.

Ohnenstetter M., Johan Z., Legendre O. and Hohan V.
(1990)
FACTORS GOVERNING CONCENTRATIONS OF PGE IN LAYERED COMPLEXES.
Rapport préliminaire (Juillet 89-décembre 1989).

Ohnenstetter M. and Rakatomanana E.D.
(1990)
NOTE SUR LES RESULTATS GEOCHIMIQUES PRELIMINAIRES (Pt-Pd) CONCERNANT LES ECHANTILLONS "ROCHES" ET "STREAM SEDIMENTS" DE LA CAMPAGNE 1989 A MADAGASCAR.
Note BRGM 18 02 90.

Ohnenstetter M.
(1991)
LITHOLOGIE DES SONDAGES (C1, C2 et C3) DU MASSIF DE LAVATRAFO SUD (S7S) : VERS UN MODELE DE MISE EN PLACE DE LA MINERALISTION PLATINIFERE.
Rapport BRGM GDR 911. 55p.

Martel-Jantin B., Eberle J.C. and Ohnenstetter M.
(1991)
CONVENTION PLATINOIDES ET SUBSTANCES CONNEXES. PROJET PLATINOIDES ANDRIAMENA.
Rapport technique de la mission 1990.

Communications (chronological order)

Suppel D.W., Barron L.M., Spencer R., Slansky E., Johan Z., Ohnenstetter M.
(1987)
PLATINUM IN BASIC AND ULTRABASIC INTRUSIVE COMPLEXES AT FIFIELD, NEW SOUTH WALES
J.J. Frankel Memorial Lecture "platiniferous horizons in layered intrusions", University of New South Wales.

Johan Z., Ohnenstetter M.
(1989)
PGM FROM THE DURANCE RIVER ALLUVIUM, FRANCE / IMPLICATIONS OF MAFIC AND ULTRAMAFIC COMPLEXES IN THE ALPS
Terra abstracts, 1, 2, 16.

Johan Z., Ohnenstetter M., Slanski E., Barron L.
(1989)
PGE MINERALIZATION IN THE OWENDALE INTRUSIVE COMPLEX, FIFIELD, NSW, AUSTRALIA.
Terra abstracts 1, 2, 16.

Ohnenstetter M.
(1989)
METASOMATISM IN THE MONTE MAGIORE MANTLE PERIDOTITES (CORSICA, FRANCE) : EVIDENCE FROM PT, PD, RH and AU ENRICHMENT.
Terra abstracts 1, 2, 20.

Johan Z., Auge T., Cocherie A., Ohnenstetter M., Johan V., Le Metour J.
(1989)
PLATINUM MINERALIZATION IN ANDRIAMENA ZONE, MADAGASCAR
28 th Intern. Geol. Congr. Washington D.C. Abs 2,3 July 9-19 1989.

Cocherie A., Auge Th., Johan Z., Ohnenstetter M., Volfinger M.
(1989)
GEOCHEMICAL STUDY OF PGE AND AU IN CHROMITITES AND PYROXENITES OF PRECAMBRIAN ULTRAMAFIC INTRUSIVE BODIES, CENTRAL NORTH MADAGASCAR
5th International Platinum Symposium., Bull. Geol. Soc. Finland, 61, 1, 32.

Johan Z., Ohnenstetter M., Slansky E., Barron L;
(1989)
LATE STAGE PGE MINERALIZATION IN CLINOPYROXENITES OF THE OWENDALE INTRUSIVE COMPLEX, FIFIELD, N.S.W. AUSTRALIA
5th International Platinum Symposium., Bull, Geol. Soc. Finland, 61, 1, 51.

Ohnenstetter M., Johan Z., Fisher W., Amosse J.
(1989)
PLATINUM GROUP MINERALS FROM THE DURANCE RIVER ALLUVIA, FRANCE
5th International Platinum Symposium., Bull. Geol. Soc. Finland 61, 6.3, 46.

Slansky E., Johan Z., Barron L.M., Ohnenstetter M., Suppel D.
(1990)
SURFACE ANALYSIS OF PGE MINERALS FROM FIFIELD,N.S.W. AXAA-90, EIGHT AUSTRALIAN SCHOOLS AND CONFERENCE ON X-RAY ANALYSIS AND SURFACE ANALYSIS
Univ. of Melbourne 11-16 february, 1990.

Barron L.M., Slansky E., Suppel D., Johan Z., Ohnenstetter M.
(1990)
LATE TO POST MAGMATIC PGE MINERALISATION IN THE FIFIELD PLATINUM PROVINCE AND THE OWENDALE INTRUSIVE COMPLEX, NSW
Geol. Soc. of Australia, Tenth Australian Geological Convention, Hobart, Univ. of Tasmania, February 4-9, 1990.

Legendre O.
(1990)
A POSSIBLE EPITAXY OF LAURITE ON RUTHENIRIDOSMINE FROM OPHIOLITIC CHROMITITE : GENETIC IMPLICATIONS
15th general meeting of the International Mineralogical Association (Beijing, 27 June- 3 July 1990), 1, 259-260.

Auge T. and Legendre O.
(1990)
MINERALOGIE DES PLATINOIDES ALLUVIONNAIRES, REGION D'ANTANAMBAO-MANAMPOTSY (COTE EST DE MADAGASCAR) : ESSAI D'INTERPRETATION.
Journées de Minéralogie et Cristallographie (Rennes, France, 4-8 sept. 1990).
Bull. liason Soc. Fra. Min. Crist., 2 p 210.

Ohnenstetter M., Johan Z., Auge T., Cocherie A., Legendre O., Martel-Jantin B., Rakotomanana D.
(1990)
THE WEST ANDRIAMENA COMPLEXES IN MADAGASCAR : A NEW TYPE OF PT-PD MINERALIZATION
15th Colloquium of African Geology, Nancy 10-13 septembre 1990, p.218.

Ohnenstetter M., Ohnenstetter D., Johan Z.
(1990)
CLASSIFICATION DES COMPLEXES MAFIQUES-ULTRAMAFIQUES SUR LA NATURE ET LA REPARTITION DES MINERALISATIONS EN PGE (ELEMENTS DU GROUPE DU PLATINE) ASSOCIEES
Principaux résultats scientifiques et techniques BRGM 1989.

Ohnenstetter M., Johan Z., Auge T., Cocherie A., Legendre O., Martel-Jantin B., Rakotomanana D.
(1990)
LES COMPLEXES ULTRAMAFIQUES PAN-AFRICAINS D'OUEST ANDRIAMENA A MADAGASCAR / UN NOUVEAU TYPE DE MINERALISATION EN PT ET PD.
Principaux résultats scientific et techniques BRGM 1989.

Slansky E., Johan Z., Ohnenstetter M., Barron L.M., Suppel D.
(1990)
LES MINERALISATIONS PLATINIFERES DANS LES COMPLEXES ALASKEENS PRES DE FIFIELD, N.S.W., AUSTRALIE.
PART. 2. LES MINERAUX DU GROUPE DU PLATINE DANS LES PLACERS DE FIFIELD.
Principaux résultats scientifiques et techniques BRGM 1989.

Legendre O., Auge T., Ohnenstetter M., Johan Z.
(1990)
LES MINERAUX DU GROUPE DU PLATINE DU SECTEUR OUEST ANDRIAMENA (MADAGASCAR).
Principaux résultats scientifiques et techniques BRGM 1989.

Cocherie A., Ohnenstetter M., Auge T., Legendre O.
(1990)
PROCESSUS MAGMATIQUES ET MINERALISATIONS EN PLATINOIDES : EXEMPLE DES PYROXENITES D'ANDRIAMENA (MADAGASCAR)
Principaux résultats scientifiques et techniques BRGM 1989.

Ohnenstetter D., Ohnenstetter M., Glauser M. and Schaufelberger F.
(1991)
FIRST OCCURRENCE OF ALLUVIAL SPERRYLITE IN THE SWISS ALPS: COMPARISON WITH OTHERS MINERALIZATION OF THE ALPS.
IAGOD, 6th Intern. Platinum Symposium, July 8-11, Perth.

Ohnenstetter M., Cina A., Johan Z., Jaraj N. and Neziraj A.
(1991)
PGE MINERALIZATION IN OPHIOLITIC MANTLE AND CUMULATES OF ALBANIA : PRELIMINARY RESULTS
IAGOD, 6th Intern. Platinum Symposium, July 8-11, Perth.

WU X., Ohnenstetter M. and Johan Z.
(1991)
HYDROTHERMAL SYNTHESIS OF RHODIUM-BEARING PYRRHOTITE AND ASSOCIATED RHODIUM - BEARING PHASES.
EUG VI, Strasbourg 24-28 March p.107.

Auge T. and Legendre O.
(1991)
ALLUVIAL PLATINUM GROUP MINERALS FROM THE MANAMPOTSY AREA, EAST MADAGASCAR
6th International Platinum Symposium
IAGOD 1991, 7-12 July, Perth, Australia.

Legendre O.
(1991)
ROLE OF NI METAL IN THE FORMATION OF PLATINUM GROUP MINERALS FROM THE "MASSIF DU SUD" OPHIOLITIC CHROMITITE (NEW CALEDONIA)
6th International Platinum Symposium
IAGOD 1991, 7-12 July, Perth, Australia.

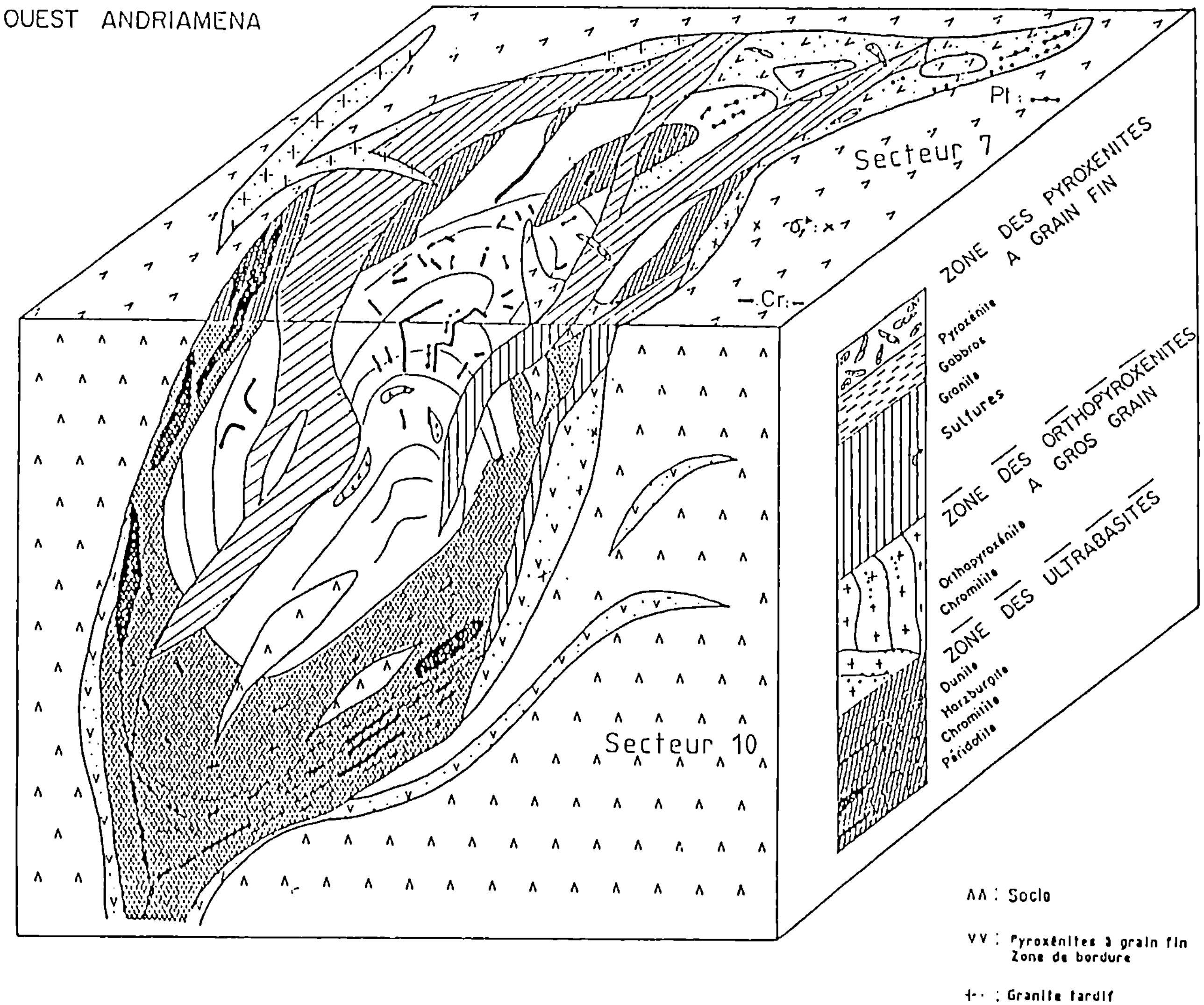
Ohnenstetter M., Johan Z., Cocherie A., Eberle JM., Martel-Jantin B., Rakotomanana D.
(1991)
AN INFILTRATION METASOMATISM MODEL FOR A NEW TYPE OF PT-PD MINERALIZATION IN PAN-AFRICAN COMPLEXES OF MADAGASCAR.
IAGOD 1991, 7-12 July, Perth, Australia.

Orberger B. and Ohnenstetter M.
(1991)
PLATINUM GROUP ELEMENTS IN THE NAN -UTTARADIT MAFIC-ULTRAMAFIC BELT, NORTHERN THAILAND
IAGOD 1991, 7-12 July, Perth, Australia.

Slansky E., Johan Z., Barron LM., Ohnenstetter M. and Suppel D.
(1991)
SURFACE ANALYSIS OF PGE MINERALS FROM FIFIELD, N.S.W. IAGOD 1991, 7-12 July, Perth, Australia.

MODELE GÎTOLOGIQUE DES MINERALISATIONS
CHROMIFERES ET PLATINIFERES
DE LA ZONE OUEST ANDRIAMENA

Fig. 1



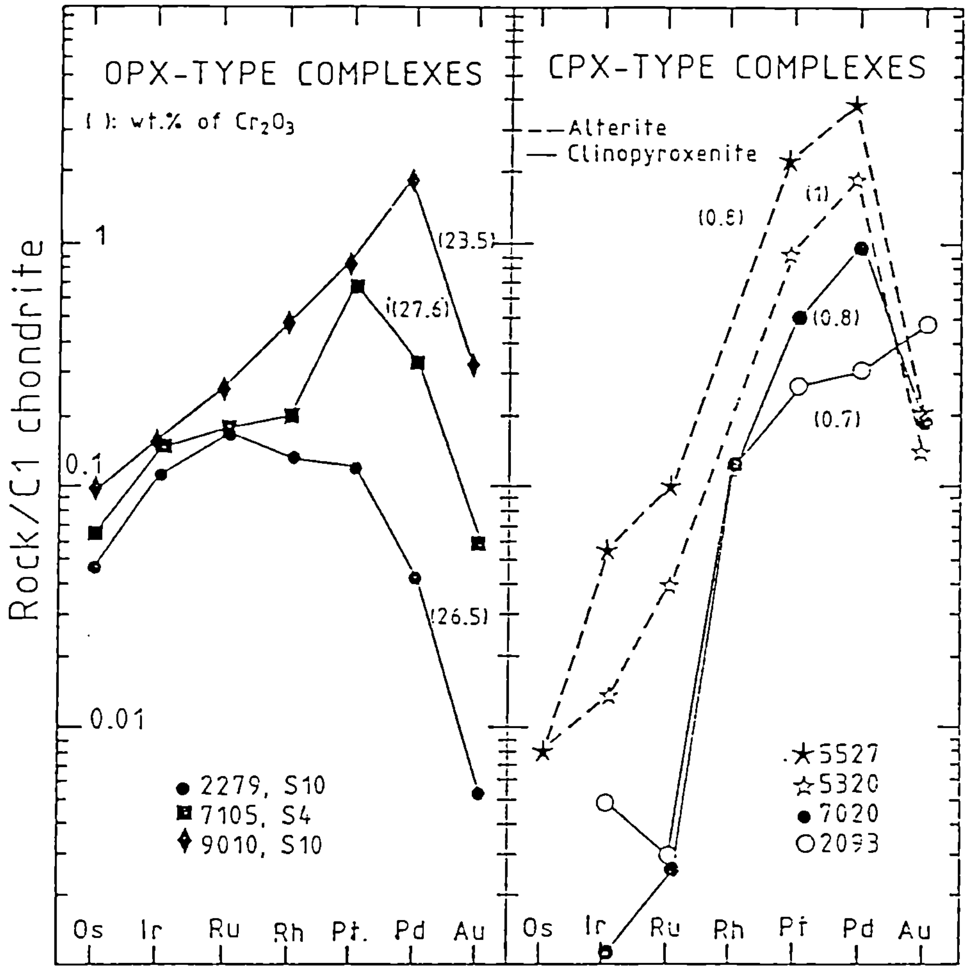


Fig. 2 - PGE distribution in the two types of mafic-ultramafic complexes.

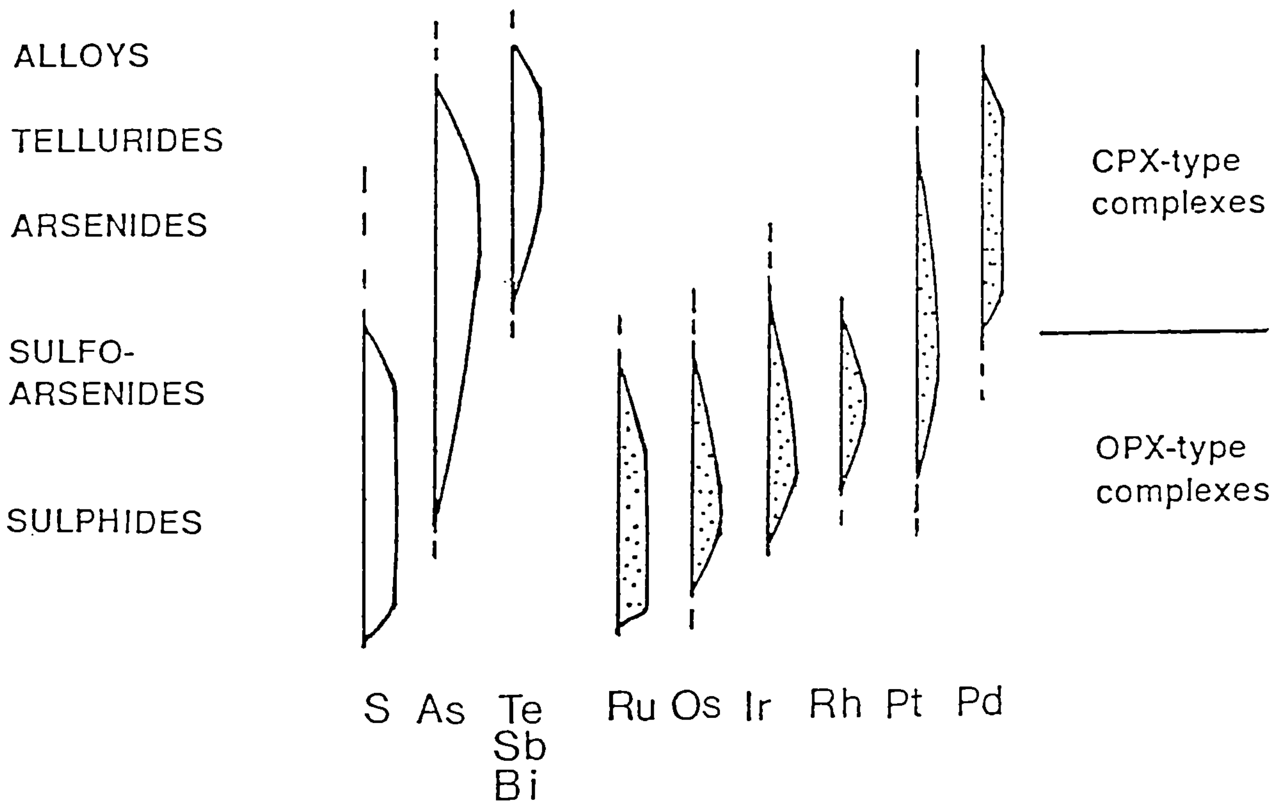


Fig. 3 -Nature of PGE-bearing phases during PGE fractionation

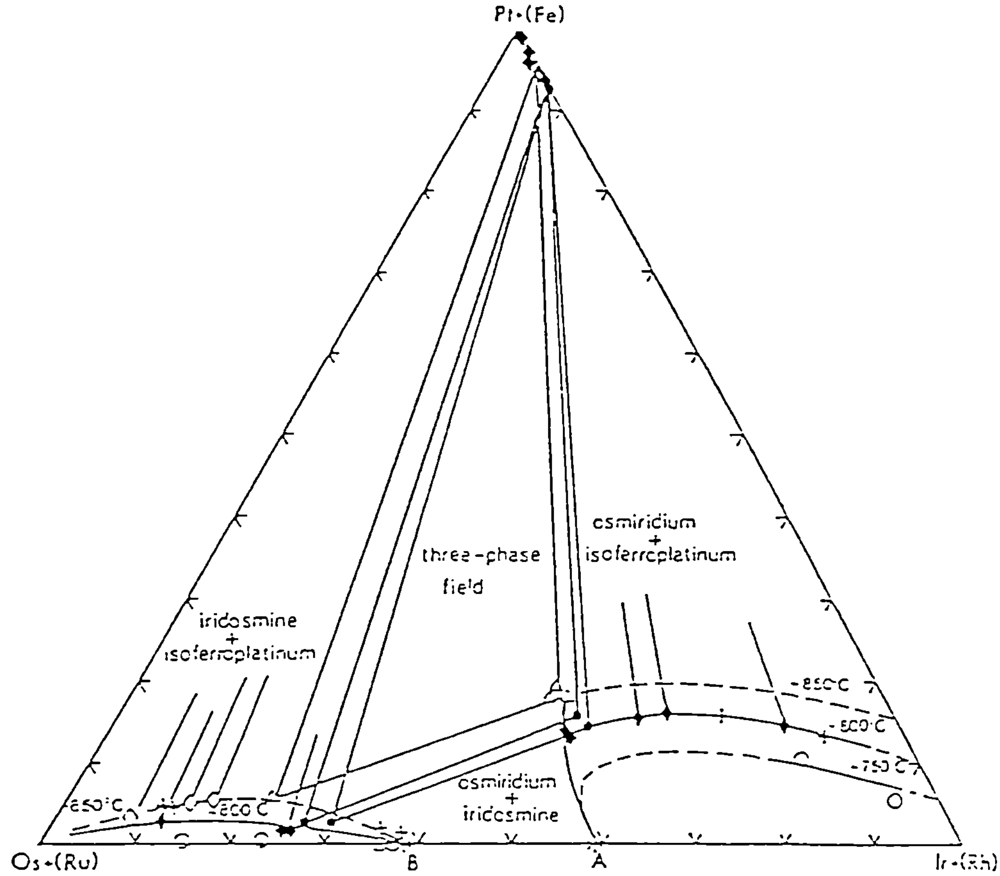


Fig. 4. Pseudoternary phase diagram of the Pt + (Fe) - Os + (Ru) - Ir + (Rh) system. Fifield nuggets are filled diamonds for two-phase fields and full circles for a three-phase field. Open diamonds and triangles are data from Alaska for two-phase fields and a three-phase field, respectively, while crosses denote data from the Urals (both sets of data from Toma and Murphy, 1977). Open circles are data from the Durance river (Johan et al., 1990). Asterisks at A and B indicate miscibility limits from experimental data (Vacher et al., 1954; Raub, 1964). Isotherms are estimated from the binary solvus in Pt-Ir system (Raub and Plate, 1956)

DEVELOPMENT OF EXPLORATION METHODS FOR ALKALINE ROCKS RICH IN BASTNAESITE-TYPE RARE EARTH MINERALS

Project Leader: G. MORTEANI
Technical University of Munich, Institute for Applied Mineralogy and Geochemistry, Garching, Germany

Contract MA1M-0014-D

1. OBJECTIVES AND INTRODUCTION

The EC project "Development of exploration methods for alkaline rocks rich in bastnaesite-type rare earth minerals" (MA1M-0014-D(B)) started in February 1988. The Technical University of Munich (Germany) - Institute for Applied Mineralogy and Geochemistry (Prof G. Morteani) and the Universita di Trento (Italy)- Dipartimento di Ingegneria (Prof. A. Fuganti) were parties to the contract with the European Community.

Among the REE mineralizations in general, carbonatite-bound or carbonatite-related deposits are of overwhelming economic importance. Carbonatites are usually associated with SiO_2-undersaturated rocks in igneous complexes along major rift or fault zones. The REE mineral of most economic interest is bastnaesite.

The EC has no REE sources of its own. Very limited literature data indicated that near the village of Kizilçaören, about 120 km west of Ankara, Turkey (Fig. 1), bastnaesite, barite and fluorite-bearing veins with carbonatitic affinity are found. This bastnaesite occurrence seemed to be not only the nearest potential REE source for the EC economy but also a research target suitable to develop advanced exploration methods applicable to a prospection within, but also outside the EC for bastnaesite deposits. In this context it should also be mentioned that the prospection for REE mineralizations is difficult, because many REE ores are not familiar to prospectors without specific experience in this very special field.

In the first phase of the project the types of ores, including mineralogy and geochemistry had to be defined in order to form a basis for mineral preparation tests to be performed at the BRGM in Orleans (project no. MA1M-0054/67).

In the second phase the geological setting of the mineralization and the genesis of the deposit of Kizilçaören had to be studied and methods for the identification of targets for regional and detailed REE exploration had to be developed.

There are more than 100 different minerals known to contain lanthanides in more than trace amounts. Monazite, a REE phosphate (REE[PO4]), and bastnaesite, a mixed REE fluorocarbonate (REE[F/CO3]) are the most important and up to now the only ones of economic interest. The distribution of the REEs in the two minerals is quite similar, the most abundant being Ce, La, Nd and Pr (in decreasing order) but with the important difference that monazite usually contains around 5 to 10 % ThO2 and 3 % yttrium oxides which are virtually absent in bastnaesite. Although Th is only very weakly radioactive, monazite is contaminated by daughter elements of Th such as 228Ra which are much more active and therefore require careful handling during processing. This complication is obviously not encountered in the treatment of most of the bastnaesites.

The total abundance of the REEs in the earth's crust is 145 ppm i.e. 0.014%. From the available data the cutoff grade in the worlds most important bastnaesite mine at Mountain Pass (USA) seems to be 8 % REO, equivalent to about 6.8 % REEs. An enrichment factor of about 1:5000 is therefore required to produce a deposit of economic interest.

It should be noted that in spite of their name, the REEs are not extremely rare. For example Ce is 5 times more abundant than Pb and even Tm, the rarest REE, is more abundant than iodine.

Up to 1980 the Mountain Pass mine in U.S.A. was the main supplier of light REEs in the world, followed by monazite as a placer byproduct in Australia, Brazil, China, India, and Malaysia. Since 1980 bastnaesite has also been produced in increasing amounts by China and the USSR.

2. MATERIALS AND METHODS

In order to achieve the project tasks the following investigations were performed:

- Computer aided evaluation of the literature existing on the geological setting, the mineralogical and chemical composition and exploration methods of bastnaesite occurrences worldwide.

- Surface mapping and sampling of REE-ores and their host rocks in the study area and of available drill cores.

- Evaluation of the regional geotectonic setting by computer aided statistical evaluation of lineaments from satellite imagery and aerial photographs.

- Examination of thin and polished sections, particularly of the REE-ores, carbonatites and associated volcanic rocks, in order to define the mineral parageneses and textures of the ores and country rocks.

- X-ray diffraction and chemical analyses by XRF, NAA, DCP to determine the ore grade and the mineralogical and chemical composition of the carbonatites and volcanic rocks.

- Chemical analysis of single mineral grains in selected thin sections of ores and country rocks with SEM - EDAX and/or electron microprobe.

- Determination of stable oxygen and carbon isotope composition of calcites and dolomites from carbonatitic veins and ores.

- Determination of the initial 87Sr/86Sr ratios in carbonatites and volcanic rocks in order to define their origin and the degree of crustal contamination.

- Fluid inclusion studies directed to determine the composition of the fluid phase in the carbonatites and REE-ores.

- Visit to the bastnaesite deposit of Mountain Pass in California in order to compare this bastnaesite deposit of outstanding economic importance with that of Kizilçaören.

3. RESULTS

3.1 INTRODUCTION

In 1959 the Turkish Geological Survey, M.T.A., carried out a regional airborne radiometric survey, which resulted in the discovery of an important radiometric anomaly in the Kizilçaören area approximataly 120 km west of Ankara. The subsequent field work by geologists of M.T.A. led to the discovery of a bastnaesite-fluorite-barite mineralization producing the anomaly. The extent and type of this mineralization was defined by field mapping and some drill holes. No reports on the results have been published by M.T.A.

3.2. GEOLOGY

In the tectonic sketch map in Fig. 1 it can be seen that the REE deposit of Kizilçaören is located within the Sarkaya zone (OKAY, 1986), formerly called the Izmir-Ankara-zone, which is located north of the Anatolian-Taurian-zones. The geology of the mineralized area, according to our own detailed mapping, is shown in the geological sketch map of Fig. 2.

The oldest rocks found in the area belong to a basement consisting of lower Paleozoic rocks of very low to low grade metamorphism, e.g. greywackes, sandstones, phyllites, glaucophane schists, calcareous schists, and marbles. A fault separates the basement from the overlying Upper Paleozoic to Triassic Kizilçaören Formation, which consists of pelites, sandstones, mudstones and spilites. Along this steeply dipping fault the northern Kizilçaören Formation has been elevated with respect to the southern Mesozoic ophiolite complex, which occurs between the basement and the Kizilçaören Formation.

Phonolites and trachytes, in the form of subvolcanic stocks, agglomerates and volcanic breccias, are the product of an intense Tertiary volcanic activity. These volcanic rocks are found predominantly along the tectonic contact of the ophiolitic suite with the Kizilçaören Formation. This steeply dipping tectonic discontinuity was apparently used by the volcanic rocks as the ascent path.

3.3 HOST ROCKS

The host rocks of the mineralization are mainly greywackes of the Kizilçaören Formation and the volcanic rocks overlying the Kizilçaören Formation (Fig. 2). These volcanic rocks consist of partly hyaline ignimbrites, vent breccias, ashflow tuffs and other very fine grained volcanoclastic rocks. The hyaline and very fine grained volcanic rocks are classified as phonolites, trachytes, trachy-phonolites, alkali-rhyolites, and alkalifeldspar-trachytes based on chemical analyses and norm calculations.

Holocrystalline phonolites and trachytes form a chain of hills extending from the Kocasivri Tepe in the western part to the Yalincak Tepe in the eastern part of the study area (Fig. 2). Microscopic investigation shows that the phonolites are composed of sanidine, aegirine augite, hastingsitic to edenitic hornblende, sodalite, analcime and leucite.

Well-developed flow texture and mineral reactions are often observed. The trachytes are composed mainly of sanidine, plagioclase, augite and hornblende.

The phonolites and trachytes have the following average trace element contents (in ppm): Sr and Ba (1000), Rb (150), Hf (10), Th (200), La (150), Ce (250), Nd (60), Sm (10), Eu (3), Tb (2), Yb (3), Lu (1), and Y (40). The REE contents give a REE-pattern enriched in light REEs as it is typical for alkaline rocks.

3.4 CARBONATITES AND ORES

All carbonatites contain some REE - minerals, fluorite and/or barite, but the ores contain also variable amounts of carbonates, and both occur in veins and dikelets. A clear cut distinction between fluorite-barite-REE ores and carbonatites on the basis of mineralogical properties and structure is therefore difficult. According to STRECKEISEN (1980) rocks with more than 50 vol.% carbonate were defined as carbonatites.

3.5 CARBONATITES

Carbonatites with no or very weak mineralization occur in the form of dikes - up to some m in width - and in the form of veinlets, both in volcanic rocks and in greywackes (Fig. 2). The following REE concentration ranges were found in the carbonatites (in ppm): La (650 - 7500), Ce (1200 - 8500), Nd (450 - 2300), Sm (30 - 220), Eu (7 - 53), Tb (1 - 8), Yb (2 - 15), and Lu (0 - 2).

The REE - pattern of the carbonatites show a strong enrichment in the light REEs, as is typical of carbonatites worldwide. The Ba content ranges from 3000 to 250000 ppm, of Sr from 1000 to 16000 ppm, of Y from 50 to 200 ppm and of thorium from 50 to 250 ppm.

The main minerals in the carbonatites are calcite (dolomite), fluorite, barite, phlogopite and different REE-minerals, mostly bastnaesite and REE-phosphates. Alkali feldspar, pyrochlore, richterite and apatite are rarely found. Pyrite and manganese oxide minerals are also present. The grain size of the REE-minerals in the carbonatites rarely exceeds 50 μm. The REE-minerals are often associated with a clear young calcite generation, which is coarser than the older one.

Microprobe analyses of the REE-minerals of the carbonatites suggest that not only bastnaesite ($(Ce,La,Nd,Pr,Sr,Ca,Th)(CO_3)F$) but also fine grained monazite ($(Ce,La,Sr,Pr,Ca,Nd)PO_4$) exist, both of complex composition.

Some other REE-minerals like hollandite, a Ba-Mn-oxide with some wt.% of La and Ce, seem to be present, but their precise identification is impossible due to very fine grain size and complex composition.

X-ray diffractometer analyses of REE-mineral separates show only bastnaesite and thoro-bastnaesite, so that the amount of other possible REE-minerals can be presumed to be very low.

3.6 ORES

Poor carbonatitic ores with up to 7 wt.% REEs occur mainly interstitially in breccias and in the form of veins, and consist predominantly of fluorite, barite and bastnaesite in a calcite matrix. As in the carbonatites, two generations of calcite can be distinguished by microscopic investigation, the older one is coarse grained whereas the younger one is fine grained and occurs in patches and veinlets intimately associated with REE-minerals.

The richest fluorite-barite-bastnaesite ores occur both in greywackes and in the volcanic rocks. These ores form layers, lenses, impregnation zones, breccia zones up to 40 m in thickness, and veins in the Kizilçaören Formation.

A banded and schlieren texture is evident not only in some of the thick ore lenses but also in thin apophyses cementing intensely brecciated host rock areas.

These ores have the following ore mineral contents:

Fluorite:	15 to 60 %
Barite:	25 to 50 %
Bastnaesite:	up to 20 %
Fe-Mn ore minerals:	up to 10 %

At least three different phases of mineralization can be distinguished by microscopic investigation:

i) In a first phase of mineralization coarse grains of fluorite and barite (up to 2 cm in diameter) and felty aggregates (up to 50 μm in diameter) of bastnaesite were formed,

ii) during a second phase of mineralization, following a deformation event, the cataclastically deformed minerals of the older generation are cemented by a very fine grained (10-50 μm) generation of fluorite and barite. The bastnaesite of this mineralization is up to 20 μm in grain size.

iii) the youngest bastnaesite mineralization, which is rarely observed, occurs in association with fluorite and barite as a filling in tiny pore spaces. The grain size of this latest mineral generation is up to 20 μm.

Typical average REE-contents of the richest ores are (in ppm): La (35000), Ce (33000), Pr (2400), Nd (6000), Sm (300), Eu (80), Gd (110), Tb (21), Dy (60), Ho (10), Er (28), Tm (4), Yb (27), and Lu (3.7). The REE-pattern of the REE-ores shows high contents of the light REEs and no Eu-anomaly. The REE-ores contain also up to 120000 ppm Ba, 6000 ppm Sr, 2 ppm Hf and 900 ppm Th.

3.6 CONCLUSIONS AND ADDITIONAL COMMENTS

The close spatial association and similar Sr-initials ratio makes a close genetic relationship of trachytes, phonolites, carbonatites and REE ores very probable. The coexistence of different types of primary fluid inclusions in the apatite and the presence of carbonatite blebs in the phonolites confirm the genetic relation between these rocks and the known immiscibility of carbonatitic and silicate magmas.

The brecciated structures show that the fluorite-barite-bastnaesite mineralization formed during the explosive Tertiary volcanism. An Oligocene intrusion age of approx. 26 Ma was shown for the trachytes, phonolites and carbonatites by our own K/Ar & Rb/Sr radiometric age determinations, and by DELALOYE and ZGENC (1983). Brecciation of the country rocks cemented by carbonatitic and ore material indicates that during magmatic activity and ore formation the country rocks underwent hydraulic fracturing.

C-O isotopic values of the calcite (d13C = -7 to -2 o/oo PDB; d18O = +7 to +11 o/oo SMOW) and microthermometric data (Th > 600°C) of inclusions in apatite of the fresh carbonatites are interpreted as primary igneous values.

Monophase CO_2 and two phase low saline H_2O fluid inclusions in barite as well as two phase high saline H_2O fluid inclusions with daughter minerals in fluorite and calcite indicate that polyphase fluid systems were acting during the ore formation.

A hydrothermal interaction with an external fluid at low temperatures (150 - 250°C) is suggested by C-O isotopic data on calcite and dolomite (d13C = -2 o/oo to +2 o/oo PdB; d18O = +14 o/oo to +27 o/oo).

The fenitisation usually associated with carbonatitic magmatism is almost absent. This seems to confirm that the ore formation took place in a shallow and rather cool environment, inhibiting reaction of the country rocks with the fluid phase escaping from the solidifying alkaline rocks.

The geochemical and textural data indicate that at the beginning of the crystallization of the carbonate rich rocks most of the REEs were incorporated into calcite and apatite, typical carrier of REEs in this type of magmatic rocks. During the late phase of cooling, after solidification and after a deformation, the calcite was remobilised by a hydrothermal activity demonstrated by fluid inclusion and isotope compositions.

During this process the REEs were released from the calcite lattice forming their own mineral phases such as bastnaesite and monazite. The important role played by the influx of low temperature fluid phases into the cooling carbonatitic rocks for the formation of REE mineralizations explains the fact that such mineralizations are typically observed in subvolcanic to volcanic settings where the access of vadose waters to the cooling rocks is easy. The oxidizing environment produced by the vadose waters is documented by the presence of primary barite and manganese and iron oxides. In deep-seated carbonatitic intrusions hydrothermal overprinting as well as REE mineralizations are mostly lacking, instead sulfide and apatite mineralizations like in Palabora (South Africa) or pyrochlore, apatite mineralzations like at Araxa (Brazil) or Lueshe (Zaire) are found. The most promising targets for bastnaesite mineralizations are therefore alkaline complexes connected with carbonatitic rocks in subvolcanic setting, followed by a hydrothermal remobilization and upgrading of the REEs. Unfortunately such settings are until now unknown within the EC.

The ore reserves at the Kizilçaören deposit, as calculated by M.T.A. from surface mapping and core drillings to a depth of 190 m, are about 1 million tons REO with an average ore grade of 3-5 % REOs. The main ore bodies are all very similar in composition. The bastnaesite is always very fine-grained (20 to 50 μm).

The mineralization is set in a landscape of ondulating hills in average only 30 meters high, with an adequate water supply and good dirt roads giving access to the area. The main road from Ankara to Izmir and an electric power supply are only a few km away. This situation makes the start of a low cost open cut selective mining operation very easy.

The main problem is not the ore grade, the ore reserves or the high mining costs, but the very fine grain size of the bastnaesite. This makes the production of a commercial concentrate of better than 90% until now impossible (project no. MA1M1-0054/67). An additional problem is at the moment the impact of very low price REE products by China on the world market.

4. REFERENCES

DELALOYE M. and ZGENC I. (1983): Petrography and age determinations of the alcaline volcanic rocks and carbonatite of Kiziliçaören district: Beylikahir - Eskisehir, Turkey.- Schweiz. Mineral. Petrogr. Mitt., 63, 289-294.

DEMIRTASLI E. (1975): Iran, Pakistan ve Trkiyedeki Alt Paleozoyik yasli Kayalarin Stratigrafik korelasoyonu; Cumhuriyetin 50. Yili Yerbilimleri Kongresi, M.T.A., 204-222.

OKAY A.I. (1986): High-pressure/low-temperature metamorphic rocks of Turkey; in: Geological Society of America Memoir 164, Blueschists and Eclogites (eds. Evans B.W. and Brown E.H.), 432 pp.

STRECKEISEN A. (1980): Classification and nomenclature of volcanic rocks, lamprophyres, carbonatites and melilitic rocks.- IUGS subcommission on the systematics of igneous rocks. Geol. Rdsch., 69, 197-204.

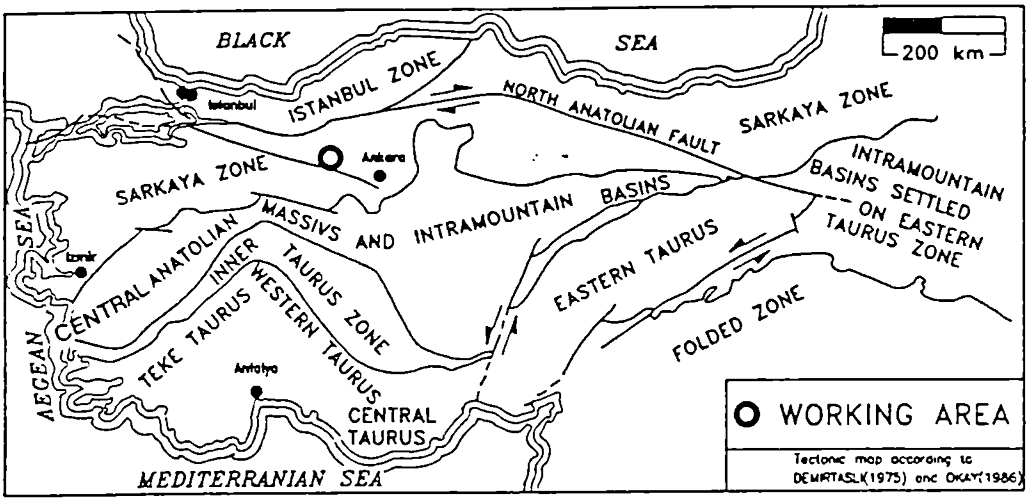
5. LIST OF PUBLICATIONS AND ORAL COMMUNICATIONS ON CONTRACT RESEARCH

HATZL, T., MORTEANI, G., FUGANTI, A., KIENAST, P. and BLAMART, D. (1990): Petrographie und Geochemie der Bastnaesit-Fluorit-Baryt Vererzung bei Kiziliçaören, Provinz Eskisehir, Türkei.- Berichte der Deutschen Mineralogischen Gesellschaft, European Journal of Mineralogy (Beiheft), Abstract, 2, 92.

HATZL T., MORTEANI G., FUGANTI A., KIENAST P. and BLAMART D. (1990): Petrology and geochemistry of the bastnaesite-fluorite-barite mineralization near Kiziliçaören, Province Eskisehir.- International Earth Sciences Congress on Aegean Regions (IESCA 1. - 6.10.90, Izmir-Turkey), Abstracts, 83-84.

HATZL T., GRNER F. and MORTEANI G. (1990): Fluid inclusions in carbonatites and fluorite-barite-bastnaesite ores of Kiziliçaören, Province Eskisehir.- International Earth Sciences Congress on Aegean Regions (IESCA 1. - 6.10.90, Izmir-Turkey), Abstracts, 228-229.

HATZL T., BLAMART D., MORTEANI G., KIENAST P. and FUGANTI A.: A Tertiary bastnaesite ((REE)CO_3F)-fluorite-barite mineralization associated with carbonatites and alcalic volcanic activity at Kiziliçaören (Eskisehir Province), Turkey.- EUG VI Strasbourg March 1991, Terra abstracts, 3, 1, 408.



PONTIDES: ISTANBUL ZONE, SARKAYA ZONE
ANATOLIDES: CENTRAL ANATOLIAN MASSIVS AND INTRAMOUNTAIN BASINS
TAURIDES: TEKE TAURUS, INNER TAURUS ZONE, WESTERN TAURUS, CENTRAL TAURUS, EASTERN TAURUS

Fig. 1: Tectonic sketch map of Turkey after DEMIRTASLI (1975) and OKAY (1986) showing the position of the REE deposit of Kizilçaören.

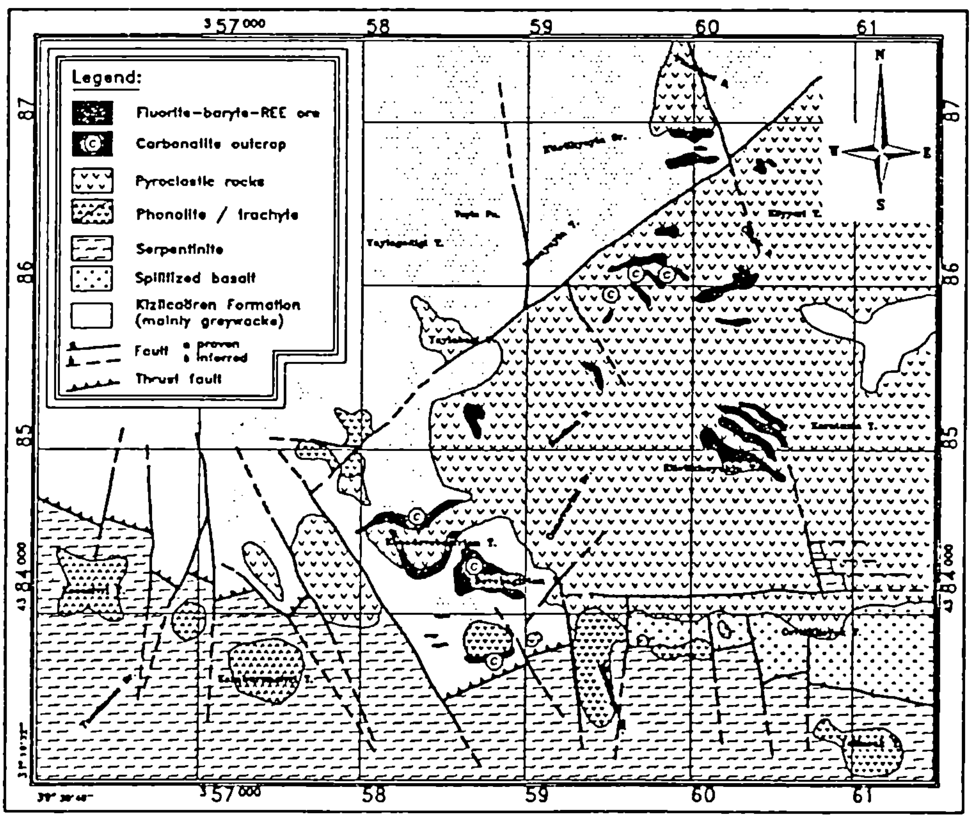


Fig. 2: Geological sketch map of the area of Kizilçaören showing the position of the REE deposits.

FACTORS CONTROLLING THE CONCENTRATION AND DISTRIBUTION OF MINERALIZATIONS RICH IN TUNGSTEN AND ASSOCIATED METALS IN THE PELORITANI MOUNTAINS (NE-SICILY)

Project Leader: N. LA ROSA*)
Ente Minerario Siciliano, Palermo, Sicily, Italy

Contract MA1M-0031-I

1. OBJECTIVES

Since 1982, the most significant discoveries of (previously unknown) tungsten (scheelite) ores in the crystalline basement of Peloritani Mountains (NE-Sicily) had been essentially realized in the framework of EEC/EMS cooperation (La Rosa, 1988). The objective of the present research was to define the geostructural and physico-chemical factors controlling the formation, in low-grade metamorphic environment (Mandanici Unit), of scheelite-rich although spatially restricted orebodies, including their provisional economic potential. In addition the preliminarily checked (in the form of limited stratabound occurrences) but poorly known tungsten metallogenesis in the medium-high metamorphic grade Aspromonte Nappe overlying the Mandanici Unit were investigated. Location and synoptic geologic and metallogenic sketch map of the investigated area are shown in Fig. 1 (from: Omenetto et al., 1988).

2. MATERIALS AND METHODS

The research programme has been carried out through multidisciplinary investigations, namely: detailed petrographic microtextural analyses with evaluation of chemical-mineralogical equilibria and interpretation of the geothermo-barometric evolution of W-mineralized sequences; geochemical analyses of mafic (amphibolites) lithologies associated with scheelite ores; experimental geophysical (geoelectric) survey in two selected areas. Data were compared with previous informations to obtain the following results:

<u>Aspromonte Nappe</u> - definition of exploration tools of general applicability, <u>i.e.</u> on the basis of particular (La Favière <u>l.s.</u>) type of the known ore-bearing outcrops, recognition of adequate sets of features (particular lithologic associations, metamorphic facies changes,

*) Project coordinator. Scientific-technical results are also due to M. Chiarodia, V Meggiolaro, P. Omenetto, S. Primon & R. Sossi.

metasomatic geochemical balance, type of basic volcanism, granitization evidence, etc.) mostly favourable to tungsten concentration in high-grade metamorphic environment.

Mandanici Unit - multidisciplinary investigation and metallogenic interpretation of the mineralized sequences and ore structures, well-exposed in the new open-cut mining workings independently realized by EMS, and preliminary assessment of the industrial applicability of tungsten ore. On the Tyrrhenian side of Peloritani Mts., where the Mandanici Unit crops out mostly as limited "windows" below the Aspromonte Nappe, geognostic (geological/geophysical) investigation has been performed on a major structural and exploration problem: the definition of the surface-closest position of the Mandanici/Aspromonte boundary sequence, proved to be a very promising "tungsten carrier".

3. ANALYSIS OF RESULTS

3.1 RESEARCH TARGET 1: ASPROMONTE NAPPE

Low-grade (<1% WO_3) tungsten ores in Ca-silicate fels, gneisses and amphibolites, not connected with base metal mineralization, are strictly limited to the structural lower portion of the Aspromonte Nappe (AN) and crop out only along the Jonian slope of the Peloritani Mountains, showing no spatial relationship with the underlying Mandanici Unit (MU) main tungsten ores in the "black" phyllite sequence (Fig. 2). In the upper, conventional transition MU (green phyllites)/AN some tungsten-bearing amphibolites also exist but associated to a new-defined, gold- and silver rich polymetallic horizon[(1)] in addition to massive pyrrhotite-magnetite (Zn, Cu, Ni) lenses (Bafia-Val Pomia area). The last metalliferous sequence mostly develops in the Western Peloritani domain affected by an intense tectonic overprint, as it was demonstrated by both geological and geophysical investigation. The two tungsten-bearing series are also different in as their geodynamic settings, the first one pertaining to the tholeiitic series while the second shows a calcalkaline affinity.

3.2 RESEARCH TARGET 2: MANDANICI UNIT

The detailed investigation of the "fresh" exposures in the numerous trenches performed by EMS permitted a tiered-up attempt of progressive tungsten concentration analysis in (a) the Mangiaracina-type scheelite-rich and (b) the tourmaline-scheelite (with arsenopyrite) ores (Fig. 2). Although largely epigenetic on local scale, the lateral persistence (also supported by geophysical survey) of (a) and (b) mineralizations has been regionally confirmed from Jonian to Tyrrhenian slopes of Peloritani Mountains, partim at depth suitable for mining under the AN cover. This fact

(1) Analyses of the polymetallic ores of "Kieslager" type in the Val Pomia/Bafia area revealed, in the dominant chalcopoyrite with minor amounts of sphalerite and galena mineralization, Cu-Pb sulphosalts, Bi-tellurides, gold and silver with grades up to 1 ppm and 50 ppm respectively.

suggests a sequence-bound character ((a): transition black phyllites-paragonite marble-green phyllites; (b): black phyllites + Pb + Zn + F + Ag stratiform horizon) for tungsten (+/- B, P, Cl, F, As, Na, Si like in same present-day epithermal systems which produce tungsten-bearing silica sinters) protoconcentrations, although examples of poorly evolved, disseminated stratiform ores are very scarce. Main concentration agent appears to be (also on isotopic, geochemical and mineral equilibria grounds) a pronounced activity of metamorphic hydrothermal fluids, chronologically corresponding to the main Hercynian phase of regional thermal metamorphism. Later overthrusting of the AN at the paragonite marble level induced tectonic fabric and enhanced tungsten grades in the most prominent (a)-type orebodies. Tourmaline-scheelite (b) ores are better developed near the thermal peak (andalusite isograde) of the thermal regional metamorphism on the Peloritani Tyrrhenian slope.

4. CONCLUSIONS

Tungsten ores in the Peloritani Mountains (NE-Sicily) had been discovered essentially in the framework of European Economic Community/Ente Minerario Siciliano R&D cooperation programmes. The present research resulted in: 1) the final assessment of the Peloritani tungsten target; 2) the discovery of a new target (the Peloritani gold).

4.1 TUNGSTEN TARGET

a) Aspromonte Nappe high grade metamorphic sequences: low grade tungsten (scheelite) ores linked to amphibolites, Ca-silicate fels, pegmatitic-aplitic gneisses, marbles, quartzites. Concentration derives from the composite influence of closely spaced volcanic (mafic), perianatectic, contact/granitic, and retrograde metamorphic environments (modified "La Favière-type" ores). These ores occur world-wide, but concentration seemingly results from the matching effects of different physicochemical processes, not ubiquitous and not equally intense, normally precluding a great economic interest (mostly reported are localized and small-scale mining operations). As Peloritani Mountains are concerned, this type of tungsten ore lacks (both in grade and in size) practical significance.

b) Mandanici Unit low grade metamorphic sequences: based on the preceeding exploration data and on the preliminary assessment of the few mining workings (trenches) already done, provisional appraisal of the orebody consistency results as follows:

Mangiaracina-type ores: very high (up to 50% WO_3) tungsten grades; individual, discontinuous lenses; size parameters of the lenses unpredictable, except for the Mangiaracina orebody where stripping by trenches indicates an extension of 20 m along strike and a maximum thickness of 1 m (perpendicularly to strike, observed 2-3 m; further, norhtward extension under the Aspromonte Nappe cover unknown).

Tourmaline-scheelite (with arsenopyrite) ores:

1) Vacco mine sector: about 0.20-0.25 Mt of ore with average grade of 1% WO_3.
2) Mela sector: 3 Mt of low grade ore (scheelite contents normally < 0.5%, with local sections reaching up to 3% $CaWO_4$).

An additional, significant remark is the following: in contrast with the Mangiaracina-type tungsten ore, the tourmaline-scheelite mineralization invariably shows a strict spatial connection with small-sized (30-40,000 t) bodies with very high Pb, Zn, F grades (10% Pb, 8% Zn) and significant silver values (100 to 1000 ppm in tout-venant).

4.2 GOLD TARGET

Tungsten discoveries and the performed, complete geological-metallogenic assessment of the Peloritani Mountains domain allowed realistic correlation with specific segments of the Circummediterranean Hercynian Chain, and in particular with the Montagne Noire (similar Cambrian sequences and overall metal spectrum (W, F, B, Pb, Zn), presence of tourmaline-scheelite and scheelite black-schist ores, common F-bearing scheelite skarns linked to Hercynian granites). Very interesting, in this context, is the preliminary, at present only restricted to Bafia-Val Pomia area, definition of gold-bearing polymetallic ores within the "oldest" volcano-sedimentary horizons of the "Cambrian" Mandanici Unit sequence. By taking into consideration the quite complete spectrum of correlation parameters with the Montagne Noire as tungsten, Pb, Zn and fluorine are concerned, the equivalent position (compared with Bafia-Val Pomia area) of the Salsigne gold-bearing sequences (Salsigne traditional mine and new orebodies in the "Schistes X") could represent a new, interesting target for future exploration in NE-Sicily.

5. REFERENCES AND ORAL COMMUNICATIONS

First Meeting of the Contact Group "GEOCHEMICAL METHODS IN EXPLORATION", Padova, September 15-16, 1988. E.C. Seminar on Exploration; Paris; November 21-23, 1989.

La Rosa, N. (1988) - SCHEELITE AND ASSOCIATED ORES IN THE METAMORPHIC ROCKS OF THE PELORITANI MOUNTAINS, N.E. SICILY. EUR 11521 - Summary reports of the subprogramme: metals and mineral substances (1982-85) - Volume 1., M. Donato & L. Van Wambeke (eds.,) Resources series, pp. 141-148.

Omenetto P., Meggiolaro V., Spagna P., Brigo L., Ferla P., Guion J.L. (1988) - Scheelite-bearing metalliferous sequences of the Peloritani Mountains, Northeastern Sicily (with some remarks on tungsten metallogenesis in the Calabrian-Peloritan Arc). In: Boissonnas and Omenetto (eds), Mineral Deposits within the European Community. SGA Special Publication n. 6, 179-198).

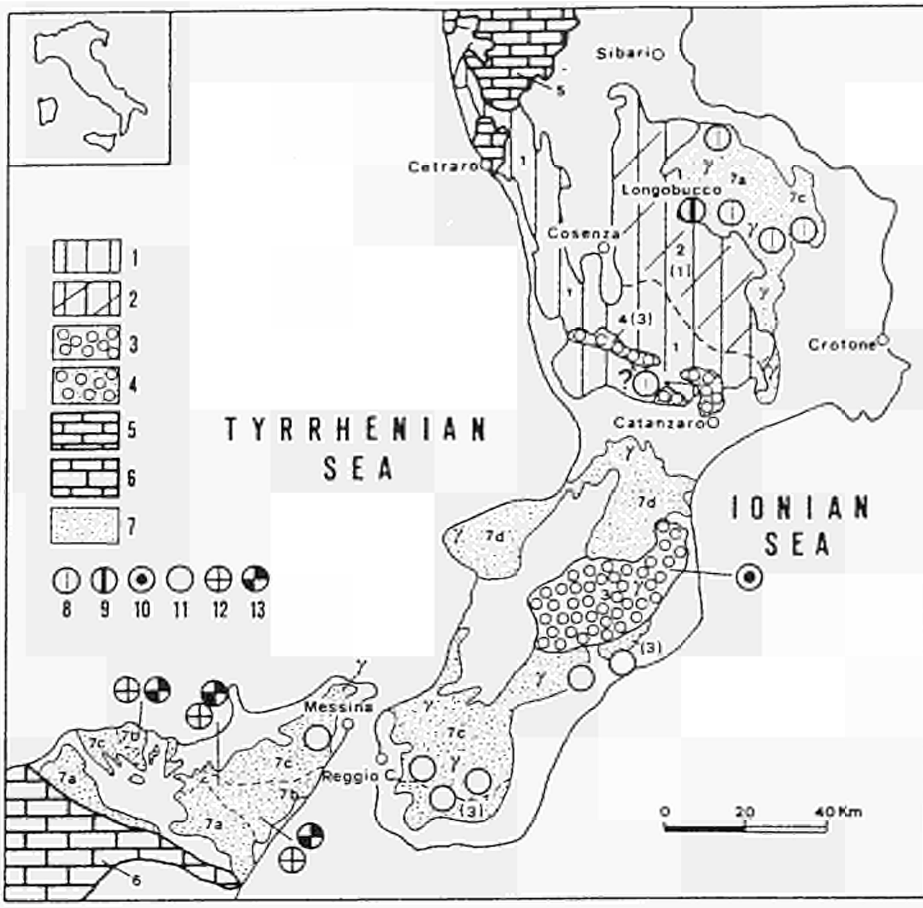


Fig. 1. Distribution of the most significant scheelite occurrences in the Calabrian-Peloritan Arc: tectonic sketch map according to Ferla et al. 1982–83 (model A by Lorenzoni, Zanettin Lorenzoni, Ferla and collaborators, bibliography 1978–1983, synoptic sketch map in Ferla et al. 1982–83). Different tectono-stratigraphic attributions (model B by Bonardi, Giunta and collaborators, bibliography 1976–1984, synoptic sketch map in Bonardi et al. 1982, with later modifications) are indicated in brackets in the map. Basically, according to A the CPA is formed by juxtaposed Alpine *l.s.* and Hercynian ranges; according to B, it is a composite belt of Alpine l.s.age. A brief comment to legend: the CPA is a metamorphic/magmatic rock belt comprised between the Appennine Range *(5)* and the Sicilian Maghrebids *(6)*. The northern sector is dominated by the Alpine Chain *(1)* Europe-vergent and (foll. A) overlain by M. Gariglione Unit *(2)*. According to A, the southern sector (and the Longobucco-Sila p.p. region) is the domain of the Africa-vergent Hercynian range *(7)*: a pre-Hercynian metamorphic basement *(7b, c, d)* overthrust and overturned on its Paleozoic volcano-sedimentary cover *(7a)*. According to B, the existence of the Hercynian Range is to be rejected. In the sector of CPA south of Catanzaro, an eo-oligocenic age is assigned to the piling-up of the Africa-verging tectonic units (austroalpine and insubric elements of the Thetys southern margin) then lying independent of the northverging Alpine tectogenesis. The hercynian vs. alpine interpretation involves also the larger extension of Stilo Unit *(3)* according to B, and the association of Stilo Unit with Hercynian Range in the Tiriolo Unit *(4)* according to A. Factually, in the whole complex *(7)* the age of the main metamorphic and magmatic events is unanimously considered as pre-alpine l.s.: late Hercynian granitoids (γ) are particularly widespread in the Calabrian sector of the range. *Scheelite ores*: *8* skarns of Longobucco region, in the contact aureole between late Hercynian granodiorites and Bocchigliero (Mandatoriccio p.p.) units. W–Cu–Zn (garnet, fluorite, hedenbergite, idocrase; minor amphibole, epidote, scapolite); *9* vein skarn/greisen and hydrothermal vein stockworks with Zn, Pb, fluorite and minor scheelite in the granodiorites of Longobucco region; *10* disseminated Mo–W "porphyry-type" ores in the granodiorites and microgranites of Bivongi area (Stilo Unit); *11* "La Favière type" l.s. ores (skarn and skarnoid facies) with probable composite influence of volcanic (mafic), perianatectic, contact/granitic, and retrograde metamorphic environments, in the medium-high grade (p.p. metagranitic) sequences of Aspromonte Nappe *(7c)* in Southern Aspromonte and Northeastern Peloritani Mountains; *12* stratabound tourmaline + scheelite ores in the Mandanici Unit (*7b*, SE- and NW-Peloritani Mts.-cf. text); *13* stratabound Mangiaracina-type high grade scheelite ores in the Mandanici Unit (*7b*, SE- and NW-Peloritani Mts.-cf. text).

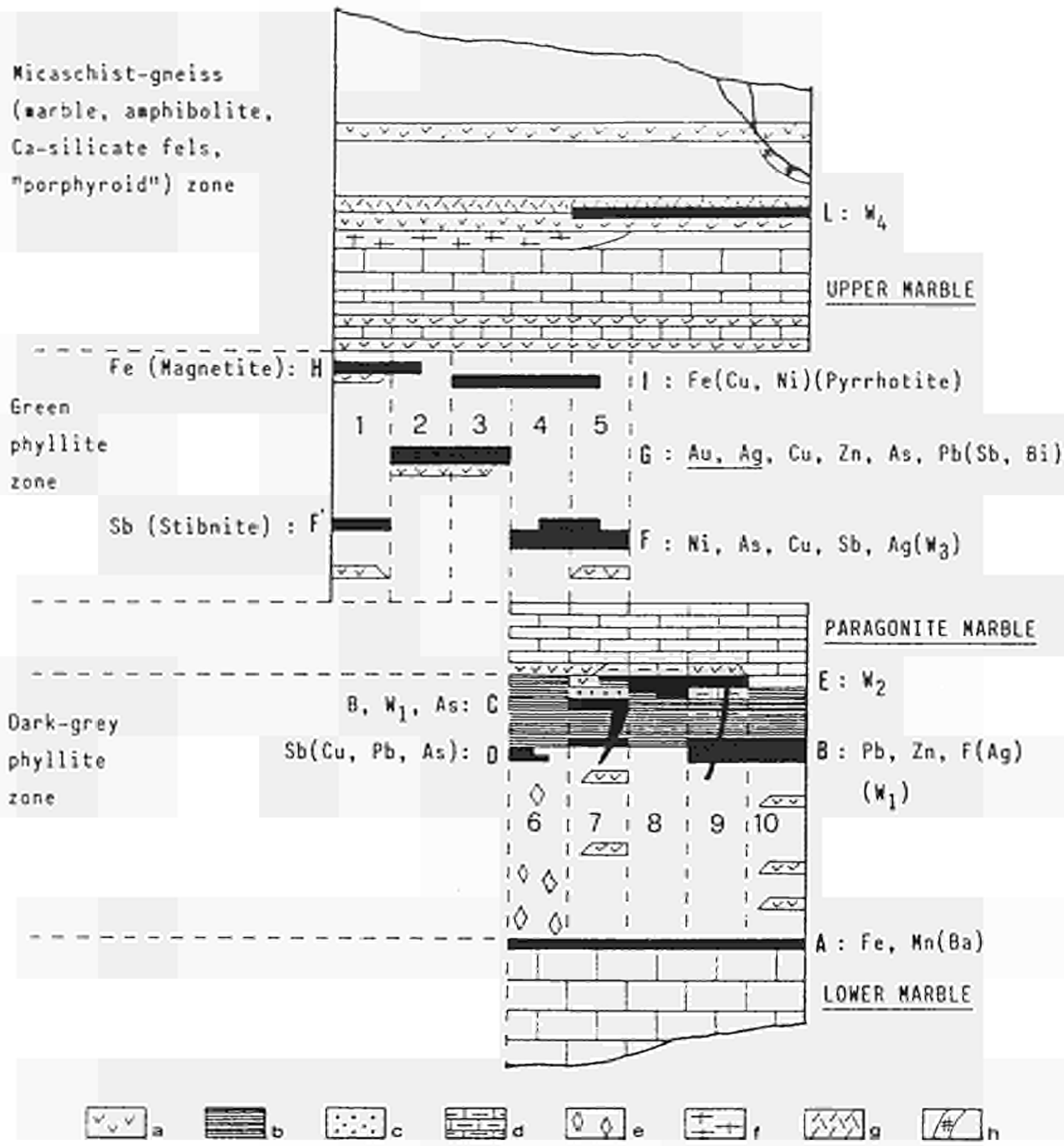


Fig. 2 - Composite metallogenic sequences in the Peloritani Mountains, comprising the Mandanici Unit (Lower Marble, Dark-grey Phyllite zone, Paragonite Marble and Green Phyllite zone) and the basal section of the Aspromonte Nappe bound to the Upper Marble. Additional significant lithologies: a) metabasites; b) graphitic phyllites, locally strongly sheared "black schists"; c) quartzites; d) calcschists; e) carbonate (siderite) phyllites; f) "porphyroids"; g) Ca-silicate fels; h) granitoid (pegmaplitic) veins. Section reference: (Western Peloritani, Tyrrhenian slope): 1) Montagnareale-Patti; 2) Bafia-Val Pomia; 3) Upper Mela basin; (Eastern Peloritani, Jonian slope): 4) Upper Vacco basin; 5) Southwest Fiumedinisi (San Carlo); 6) Ali'-South Fiumedinisi; 7) West Fiumedinisi (Vacco and Migliuso mines), T. Cerasiera (Mela); 8) East Fiumedinisi; 9) Tripi; 10) Giampilieri.

COMPARATIVE STUDY OF METALLOGENY RELATED TO GRANITE-SEDIMENT-FLUID INTERACTIONS AND LINEAMENTS IN THE CALEDONIDES AND HERCYNIDES - PART 1

Project Leaders : JANE A. PLANT
British Geological Survey (NERC), Keyworth, United Kingdom

M. CUNEY, B. POTY
Centre de Recherches sur la Géologie des Matières Premières, Minérales et Energétique
(CREGU), Nancy, France

G. MORTEANI
Technical University of Munich, Germany

Contract MA1M-0038-UK

PREFACE

This report summarizes the research results of a joint project of the BGS and the following participants: Technical University of Munich, Department for Applied Mineralogy and Geochemistry, Germany (MA1M-0039-D), Centre de Recherches sur la Géologie de l'Uranium (CREGU), Nancy, France (MA1M-0040-F), Hahn-Meitner Institute Geochemistry Working Group, Berlin, Germany, University of Leicester, Department of Geology, United Kingdom, and University of Nantes, France.

1. OBJECTIVES AND INTRODUCTION

The overall aim of the project has been the development of a robust metallogenic model and derived exploration criteria for granite-associated ore deposits based on integrated geochemical, geophysical and geological studies of selected granites in the French and German Hercynides and the British Caledonides.

At the outset of the investigation many fundamental aspects of granites and their related mineralization in the Caledonides and Hercynides were poorly understood, partly because scientists working in the Hercynides or Caledonides had no knowledge of the geological setting or geochemical characteristics of granites in the other orogenic belt. The relative importance of mantle and crustal sources and their metal contents was particularly controversial while only qualitative information was available on the role of processes such as magmatic fractionation and hydrothermal alteration which control the distribution of ore forming elements in granite plutons. There was also little understanding of the roles of simple or batch melting relative to fractional crystallization processes, of the relationship between mineralogy and the distribution of ore forming elements in granites and their mineralizing systems or of the significance of active crustal lineament systems in magma emplacement and hydrothermal alteration.

2. MATERIALS AND METHODS

A common database for each of the three study areas has been prepared and a common terminology developed for use in Caledonian and Hercynian terranes. A sophisticated three stage model has been developed based on advanced petrogenetic modelling combined with detailed mineralogy, and field and geophysical studies. This involves (i) Partial melting of a protolith (in some cases previously enriched in ore forming elements), (ii) High degrees of fractional crystallization (up to 50 %), (iii) Intense water-rock interaction. The fist two stages represent the magmatic stage, the latter metalliferous mineralization processes and the formation of economic ore deposits. Detailed geochemical, geophysical and geological exploration criteria have been developed based on the model to identify Sn-U granites and subsequently potential areas of metalliferous mineralization associated with them. The criteria developed are suitable for screening digital datasets using image analysis and geographical information systems.

3. ANALYSIS OF THE RESULTS

3.1 THE MAGMATIC STAGES (PARTIAL MELTING AND FRACTIONAL CRYSTALLIZATION)

Advanced petrogenetic modelling of the Marche granites in he French Massif Central, the Fichtelgebirge granites of the Bohemian massif and the Cairngorm granite in the Scottish Grampian Highlands combined with studies of available isotopic data suggest that the distinctive features of Sn-U leucogranites, such as their high contents of radioelements (U, Th, K, Rb) and other incompatible elements (Be, Li, Sn), their high Mg/Li and Rb/Sr, and low K/Rb ratios and distinctive REE patterns are attributable to high degrees (up to 50 %) of fractional crystallization of parental magmas and cannot be attributed to simple or batch partial melting of an upper crustal (S-type) or juvenile protolith.

Suitable parental (calc-alkaline) magmas are most readily generated in the Caledonides and the Fichtelgebirge by lower crustal assimilation-fractional crystallization (AFC) processes, although the relative proportions of crust and mantle components vary. The parental magma of the Cairngorm granite comprised predominantly juvenile material, whereas higher proportions of crust were incorporated in the parental magmas of the Fichtelgebirge Sn-U granites. In the Marche granites the parental magma may have been generated predominantly by crustal melting. In the Fichtelgebirge, the crustal component probably comprised Moldanubian material containing levels of Sn and U approaching those of average crust whereas there is evidence that the crustal component involved in the Marche granites was previously enriched in Sn and U.

The Cairngorm granite represents one intrusion and perhaps a single magma pulse associated with the emplacement of the East Grampian batholith, whereas the Fichtelgebirge and the Marche granites studied include several intrusions with different geochemical characteristics. The different intrusions are associated with structural and geochemical heterogeneities, which have been exploited and enhanced by subsequent hydrothermal events at the late-orogenic and post-orogenic stages of deformation.

The Sn-U granites of the Hercynides and Caledonides are late to post collisional and show a close temporal association with major crustal transcurrent shear systems generated in the Fichtelgebirge and Grampian Highlands by brittle failure of the upper crust. The shear systems were the result of orogenic transpression which continued after the main collision events and the cooling and subsequent isostatic uplift of the crust. In the Grampians the Cairngorm Sn-U granite and other evolved intrusions of the East Grampian batholith generally lie along the Deeside lineament, possibly in tensional structures conjugate to the main direction of shearing. There is only limited evidence of contemporaneous tectonic activity along the structures which controlled the emplacement of the granites, suggesting that the rise of granite magmas effectively sealed the lineament systems. In contrast to the Fichtelgebirge and Grampian Highlands, the shear systems into which the Marche granites were emplaced were complex ductile-brittle structures which remained active during and following granite intrusion.

The form and mechanism of emplacement of the Sn-U granites differ between the three regions studied. Detailed integrated gravimetric and magnetic studies of the Caringorm intrusion indicate that it is a large volume dome-shaped pluton with steep sides extending to approximately 12 km depth in the crust (an alternative model indicates depths of 7-8 km). Geophysical models combined with regional structural data suggest that it was emplaced in a series of approximately ring-shaped fracture systems probably in a regional pull-apart structure conjugate to the main direction of late transcurrent shearing. In contrast the Western Marche granites form thin slabs from 2 to 4 km in thickness with deeper roots (locally down to 6-7 km). The Western Marche granites are emplaced in a transform shear zone between two domains characterised by predominantly horizontal structures; large mylonitic bands are developed at the margins and within the granites. The early Fichtelgebirge granites (older group) also form a large slab which dips southeastwards, although the younger granites of the Fichtelgebirge have steep contacts and occur as stocks.

3.2 EXPLORATION CRITERIA FOR Sn-U GRANITES

Some of the most important criteria are as follows :

1) Geochemical features of Sn-U granites.

These include low K/Rb, Sr, Sr/Y and high [illegible], Cs/K and K/Ba ratios, and REE patterns that are enriched in light REE, with marked negative Eu anomalies. The most incompatible large ion lithophile (LIL) elements (U and Rb) are enriched independently of other LIL elements, such as Ba, and negatively correlated with high field strength (HFS) elements such as Zr; levels of the HFS elements Sn and Ta are relatively high and levels of Zr, Hf and Ti are low. The geochemical characteristics are most conveniently summarised using trace-element diagrams normalized to primordial mantle, and chondrite-normalised REE plots.

2) The age relationships and structural setting of the granites

The granites which were emplaced during post-collisional transpressive shearing are the most favourable targets in the Caledonides and Hercynides.

3) Geophysical features (e.g. negative gravity anomalies)

The granites are associated with Bouguer gravity anomaly lows due to the density contrast between the large volume intrusions and the variable but higher density host rocks. Magnetic anomalies are often associated with granites, due either to a metamorphic aureole or to magnetic components of the intrusion. There is a marked contrast between the magnetic characters of the granites, Marche and Fichtelgebirge being non-magnetic while the Cairngorm granite includes magnetic components. Following the identification of Sn-U granites based on these criteria other criteria indicative of the presence of mineralization are required.

3.3 ASSOCIATION OF Sn-U GRANITES WITH MINERALIZATION AND FORMATION OF ECONOMIC ORE DEPOSITS

The Sn-U granites identified using these criteria may be barren or mineralized and there is no simple relationship between the degree of fractionation and the presence of mineralization. The Western Marche granite for example, is the least fractionated but the most mineralized intrusion, whereas the reverse is true in the case of the Cairngorm granite. Additional criteria are thus required to identify the subset of intrusions with the potential for the discovery of ore deposits. Comparison of the characteristics of the largely unmineralized Cairngorm granite with the results of new and detailed investigations of the alteration phenomena and mineral deposits associated with the Western Marche and Fichtelgebirge intrusions suggests additional exploration criteria to indicate the presence of metalliferous mineralization associated with Sn-U granites.

The mineralized Western Marche and Fichtelgebirge granites differ markedly from the Cairngorm intrusion : (1) in their degree of peraluminosity, (2) in their muscovite content, (3) in their biotite chemistry (high Al/Mg ratios), and (4) in their accessory mineral parageneses.

a) Accessory minerals and the behaviour of uranium

The behaviour of U is important as an indicator of water-rock interaction phenomena and the presence of mineralization generally. Hence the mineralized Hercynian granites contain uranium predominantly in low-thorium uraninite from which it is readily leachable by oxidized hydrothermal solutions (such intrusions generally have high contents of uranium in water samples as well as in stream sediments). Uraninite is a common accessory phase in the Fichtelgebirge granite, where minor mineralization has been identified but it has not been found in the Western Marche granite, probably because of weathering or hydrothermal alteration. A high uranium content (up to 7 weight %) in monazite crystals is shown to be indicative of the presence of uranium deposits in mineralized granites.

In the Cairngorm granite uranium is held in refractory phases, except in roof-zone pegmatites, and is therefore largely unavailable for hydrothermal mineralization. In addition, the geophysical evidence indicates that, at depth, the Cairngorm intrusion contains a large proportion of magnetic, uranium-poor granite. The aeromagnetic signature of the Cairngorm granite appears to be in marked contrast to that of the Fichtelgebirge granites, which have little or no magnetic response. Magnetic susceptibility results suggest that the Marche granites are very weakly magnetised. This contrast may be due to the Marche and Fichtelgebirge granites being more reduced since they contain ilmenite whereas Cairngorm is more oxidized and contains magnetite.

b) The size and dimension of the granites

The Cairngorm granite consists of a large and relatively homogeneous body, which was emplaced into an anhydrous crustal setting. Movement on major shear systems which would have favoured water-rock interaction, appears to have been brought to an end by the emplacement of the granite. In contrast the tabular form of the Fichtelgebige and Western Marche granites would have increased chemical and physical gradients between the granites and their enclosing metamorphic rocks thereby providing more favourable sites for hydrothermal alteration and ore deposition.

c) Lineaments

Granites emplaced into active ductile shear zones such as those of the Western Marche appear more favourable for mineralization than stock-like intrusions (such as Cairngorm or the G2-G4 Fichtelgebirge granite) which were emplaced into brittle structures. Within such granites the identification of broad lineaments, which are several kilometers in width, by Landsat MSS and TM satellite imagery provides important information of the potential for mineralization. The lineaments require checking in the field using structural and petrological methods to identify structural anisotropy developed in the granites during the magmatic stage. This type of lineament may control magma genesis and the emplacement of later more evolved granites as in the Western Marche area; large lineaments have also been identified in the Fichtelgebirge and possibly (based on geophysical evidence) along the northern margins of the East Grampian granites. The Hebanz mineralized episyenites are located on the Fichtelgebirge lineament and the Großschloppen uranium deposit is located at its western margin. Late granites enriched in U, Sn, W, Li, F, Be and/or Rb located within such lineament systems are particularly favourable sites of mineralization and can be detected by rock, soil or stream sediment geochemistry. All of the intragranite mineralization in the Marche area is located near such intrusions. In the Fichtelgebirge granite, Sn anomalies occur in granite surrounding the Hebanz mineralization and may reflect the presence of buried, more evolved, granites.

d) Hydrothermal circulation :

Most of the features associated with mineralization processes affecting Sn-U granites reflect water-rock interaction phenomena, some of which are late and are clearly attributable to meteoric fluids. For example the U mineralization in the Western Marche granites occurs in episyenites in brittle structures formed several tens of millions of years after granite magmatism. Overall, de la Roche diagrams best discriminate between mineralized and unmineralized Sn-U intrusions because they integrate the effects of magmatic fractionation with those of water-rock interaction.

It is not clear, however, to what extent high temperature water-rock interaction processes which are initiated during the late stages of magmatism result from interaction with magmatic fluids or with fluids derived by metamorphic dewatering of the host rocks. For example, the Cairngorm granite, which has almost no thermal metamorphic aureole, is not associated with mineralization whereas the mineralized intrusions studied in the Fichtelgebirge and Marche have well defined metamorphic aureoles. Evidence of the presence of a metamorphic aureole for the Marche granite is presently unclear however.

4. CONCLUSIONS

Further studies are required to elucidate the significance of metamorphic grade and hence the water content of granite host rocks in determining the potential of observations on the nature and extent of metamorphic aureoles as exploration criteria for granite associated ore deposits. Additional studies are also required to refine information on the effects and significance of different types of alteration phenomena as indicators of the presence of economic mineralization, and mass-balance calculations should be carried out to determine the source of water, metals and ligands in ore-forming systems associated with Sn-U granites. The magnetic properties of granites appear to provide a valuable exploration guide, but additional aeromagnetic data are required for the Marche and Fichtelgebirge granites. More detailed magnetic surveys of the Cairngorm granite would provide information on the internal from of the intrusion.

5. PUBLICATIONS AND ORAL COMMUNICATIONS ON CONTRACT RESEARCH

Simpson, P.R., Tarney, J., Henney, P.J. and Plant, J.A.: Report on progress in UK contribution to "Comparative study of metallogeny related to granite-sediment-fluid interaction and lineaments in the Caledonides and Hercynides". 1st CEC contact meeting. Padua, Italy. September, 1988.

Cornwell, J., MacDonald, A.J.M., Walker, A. and Vigneresse, J-L.: A comparison of the geophysical characteristics of the Cairngorm granite (Scotland) and the Western Marche granites (France). Poster presentation. EUG V, 20-23 March 1989, Strasboug.

Hecht, L., Henney, P.J., Morteani, G. and Spiegel, W.A.: Study of the mafic enclaves of the Fichtelgebirge granites, West Germany. Oral presentation. EUG V, 20-23 March 1989, Strasbourg.

Henney, PJ., Hecht, L., Morteani, G. and Spiegel, W.A.· Comparison of the late Caledonian appinites of Scotland and Hercynian redwitzites of Germany : high-K mafic magmas associated with granite magmatism. Oral presentation. EUG V 20-23 March 1989, Strasbourg.

Plant, J.A., Henney, P.J., Simpson, P.R., and Tarney, J · Report on progress in UK contribution to "Comparative study of metallogeny related to granite-sediment-fluid interaction and lineaments in the Caledonides and Hercynides". 2nd CEC contact meeting. Paris, France. November, 1989.

COMPARATIVE STUDY OF METALLOGENY RELATED TO GRANITE-SEDIMENT-FLUID INTERACTIONS AND LINEAMENTS IN THE CALEDONIDES AND HERCYNIDES - PART 2

Project Leader: G. MORTEANI
Technical University of Munich, Institute for Applied Mineralogy and Geochemistry, Germany

Contract MA1M-0039-D

PREFACE

This project was part of a joint investigation by CREGU (Nancy, France), BGS (Nottingham, United Kingdom), and the Technical University of Munich (Germany) which ended in February 1990. The results of the joint investigation are presented in the Summary Final Report for contract MA1M-0038-UK.

The contract of the Technical University of Munich with the EC covered additionally the period from February 1990 to July 1990. The present report summarizes the additional investigations carried out in that period by the Technical University of Munich.

1. OBJECTIVE OF THE RESEARCH

The time left after the end of the official cooperation was used to conclude the investigations in the following three subjects that proved to be very important for understanding of the metallogeny in the Fichtelgebirge area:

1.) The age of the U mineralization and related episyenitization at the Hebanz locality with Sr-isotope investigations.

2.) The uranium and tin mineralizations in the Rudolfstein mine.

3.) The sequence in time and space of the different granite-associated mineralizations in the Fichtelgebirge area.

2. MATERIALS AND METHODS

2.1 THE AGE OF THE URANIUM MINERALIZATION AND EPISYENITIZATION

An open problem was the age of the episyenitization and U mineralization at Hebanz. The Hebanz locality is the best example for such a type of mineralization in the whole Fichtelgebirge area. For Rb-Sr radiometric age dating 10 whole rock samples from a drillcore showing increasing degrees of sericitization were selected (Fig. 1). The radiometric dating was preceded by detailed petrographic investigation of the alteration zones by thin section microscopy and chemical analyses by XRF and NAA. Special emphasis was given to the determination of volatile and valuable elements.

2.2 STRUCTURES, PETROGRAPHY AND GEOCHEMISTRY OF THE GREISEN AND U MINERALIZATION OF THE RUDOLFSTEIN LOCALITY

A structural analysis of the zones of the Rudolfstein mine mineralized with uranium and tin was done to see if there is a significant difference in the orientation of the zones mineralized with uranium and those with tin mineralization. Petrographical investigations using thin- and polished sections and chemical analyses of barren and mineralized rocks and ores determined the mineralogical and chemical changes associated with the different mineralization events.

3. ANALYSES OF RESULTS

3.1 THE AGE OF THE URANIUM MINERALIZATION AND EPISYENITITIZATION

Detailed petrographical and geochemical studies (described in the Summary Final Report for contract MA1M-0038-UK) show that among the different types of alterations connected with uranium mineralization, sericitization produces the strongest fractionation in the Rb/Sr ratios. Microscopic and chemical investigations show that U mineralization within the episyenite of Hebanz is closely associated with a phase of intense hematitization and sericitization.

Fig. 1 shows the 87Sr/86Sr ratios of 11 whole rock samples plotted against their position in the alteration profile. The solid line represents the measured 87Sr/86Sr ratios in the samples. The dashed lines represent the calculated 87Sr/86Sr ratios of the samples for different times in the past. The best estimate for the time of alteration is that age at which all samples show the same 87Sr/86Sr ratio, which is at about 210 Ma.

3.2 STRUCTURES, PETROGRAPHY AND GEOCHEMISTRY OF THE GREISEN AND U MINERALIZATION OF THE RUDOLFSTEIN LOCALITY

The Rudolfstein U- and Sn deposit was investigated first for tin and later, after the second world war, it was mined for uranium (Teuscher & Weinelt, 1972). Statistical evaluation of the orientation of mineralized zones showed that the greisenization occurs along SE-NW trending fractures with a mean strike of 141° and dip of 83° SW which represents one of the main structural trends in the Fichtelgebirge. The zones of late-stage uranium mineralization, connected with a deep reddening of the granite, are perpendicular to the direction of greisenization and strike 61° and dip 79° NW. Most of the late- and post-Hercynian hydrothermal activity including greisenization and uranium mineralization (veins and episyenites) is associated with SE-NW trending structures. These structures are also present at a regional scale in the western part of the Bohemian Massif. Only some late-stage uranium mineralized structures (e.g. at Rudolfstein locality) are clearly related to another tectonic orientation of late Cretaceous to early Tertiary age.

The greisen shows a typical sulfide paragenesis including arsenopyrite, pyrite and chalcopyrite. Inclusions of small sphalerite stars in chalcopyrite indicate the high temperature formation. Cassiterite was not found. The silicate paragenesis in the greisen is dominated by secondary white micas, quartz and topas, the latter replacing feldspars. Some fluorite is also common.

The geochemical data show that in the greisen Sn is enriched only very slightly as compared to As, Cd, Cu, Zn, Ag and W relative to the unaltered rocks. An explanation for the predominance of sulfide minerals and the lack of Sn enrichment at Rudolfstein may be the depth of erosion. At the famous Sn deposit of Ehrenfriedersdorf in the nearby Erzgebirge the Sn ore is found at a higher level than the sulfide parageneses (Felix et al., 1985 in Tischendorf, 1989). Thus it is probable that most of the Sn was deposited at higher levels, now eroded. In fact, almost all of the Sn in the Fichtelgebirge has been extracted since medieval times from placers produced by the erosion of the granite bodies.

The reddened zones (perpendicular to the greisen) in the Rudolfstein mine contain rich torbernite concentrations. These are particularly common at the intersection of the reddened zones with the greisens. At Rudolfstein these torbernite-bearing reddened zones were the exclusive U ores. 50-60 tons U at an average grade of 600 ppm were proven (Schmid & Weinelt, 1978). The torbernite mineralization of Rudolfstein probably represents remobilized U precipitated along fault zones which were formed or at least reactivated by brittle deformation during uppermost Cretaceous to early

Tertiary times. This view is supported by the fact that the direction of the reddened zones is parallel to young fracture systems and also by a U/Pb age of 67 ± 7 Ma determined from uranophane from the nearby Großschloppen U mine (Carl & Dill, 1985).

3.3 METALLOGENETIC MODEL

Figure 2 summarizes the sequence of granite-associated mineralizations in the Fichtelgebirge area. For each of the main events in the mineralization sequence the figure lists the dominant tectonic direction, the ore paragenesis, and the type of wall rock alteration including the associated chemical changes.

4. CONCLUSIONS

In the Fichtelgebirge two distinct types of granite-related mineralization exist, a hydrothermal U mineralization and a greisen-bound As, Cu, Zn, Ag, Cd, and W mineralization. Primary cassiterite mineralizations could not be found in the studied greisen zones near Weissenstadt. Most of the cassiterite was probably deposited, like in similar settings of the Erzgebirge, at higher, now eroded, levels. The erosion of these cassiterite deposits produced the well known alluvial tin deposits of Weissenstadt, among others.

Several phases of U mineralization spanning a long period of time can be distinguished in the Fichtelgebirge. The first phase of U mineralization is represented by pitchblende-bearing quartz veins at the northern margin of the G1 granite at Großschloppen (320-300 Ma, see Final Report MA1M-0038). The second phase involved precipitation of U as pitchblende and other oxides in episyenitized G1 granite between 280 and 210 Ma, with a maximum concentration at about 210 Ma. During late Cretaceous or early Tertiary (Alpine) times the U was again remobilized and concentrated along young faults and fractures of the granites forming, for example, the torbernite mineralizations at the Rudolfstein uranium mine.

5. REFERENCES

CARL, C. and DILL, H. (1985): Age of the secondary uranium mineralizations in the basement rocks of the northeastern Bavaria, F.R.G.- Chem. Geol. (Isotop. Geosc. Sec.), 52, 295-316. Amsterdam.

DILL, H. (1985): Die Vererzung am Westrand der Böhmischen Masse -Metallogenese in einer ensialischen Orogenzone-. - Geolog.Jb., D73, 3-461

ESSO ERZ GmbH (1982): Uran - Explorationsprojekt, Raum Grosschloppen.- Report of the ESSO ERZ GmbH, Nürnberg.

FELIX, M., BESSER, M. and KLUJEV, O.S. (1985): Zur Characteristik der vertikalen Zonalität primärer geochemischer Aureolen endogener Zinnvererzungen des "Quarz-Kassiterit-Gangtyps".- FFH C 309, 275-288.

SCHMID, H and WEINELT, W (1978): Lagerstätten in Bayern.- Geologica Bavarica, 77, 160pp, München.

TISCHENDORF, G (1989): Silicic magmatism and metallogenesis of the Erzgebirge.- Central Institute for Research of the Earth Potsdam, 107 (ICL Publication No. 0171), 316 pp, Potsdam

TEUSCHER, E.O. and WEINELT, W. (1972): Die Metallogenese im Raume Spessart - Fichtelgebirge - Oberpfälzer Wald - Bayerischer Wald.- Geologica Bavarica, 65, 5-73, München.

5. PUBLICATIONS AND ORAL COMMUNICATIONS ON CONTRACT RESEARCH

MORTEANI, G. (1988): Report on progress in the German contribution to "Comparative study of metallogeny related to granite-sediment-fluid interaction in the Caledonides and Hercynides". 1st CEC contact meeting, Padua, Italy, September, 1988.

HECHT, L., HENNEY, P., MORTEANI, G. and SPIEGEL, W. (1989): Comparison of Appinites (Scotland) and Redwitzites (Northeast Bavaria, FRG): Potassic basic magmatism associated with late orogenic granites.- Poster presentation, EUG V, Terra abstr., 1, OS01-43, p. 280, Strasbourg.

HECHT, L., HENNEY, P., MORTEANI, G. and SPIEGEL, W. (1989): Enclaves in the Hercynian granites of the Fichtelgebirge, FRG: Evidence for crustal and mantle input to granite magmatism.- Poster presentation, EUG V, Terra abstr., 1, OS01-50, p. 282, Strasbourg.

MORTEANI, G., SPIEGEL, W. and HECHT, L. (1989): Episyenitization of the Hercynian Granites of the Fichtelgebirge, NE-Bavaria (Germany, F.R.).- Poster presentation, 79th Annual Meeting of the Geologische Vereinigung, Leoben (February 1989), Terra abstr., S6/11., p. 25.

MORTEANI, G. (1989): Report on progress in the German contribution to "Comparative study of metallogeny related to granite-sediment-fluid interaction in the Caledonides and Hercynides". 2nd CEC contact meeting in Paris, France, November, 1989.

HECHT, L., SPIEGEL, W. and MORTEANI, G. (1990): Geochemische und petrographische Untersuchungen an den Alterationszonen der Fichtelgebirgsgranite (NO-Bayern).- Poster Presentation, DMG Meeting, Würzburg (September 1990), Beih. z. Eur. J. Mineral. Vol. 2, No.1, p. 93.

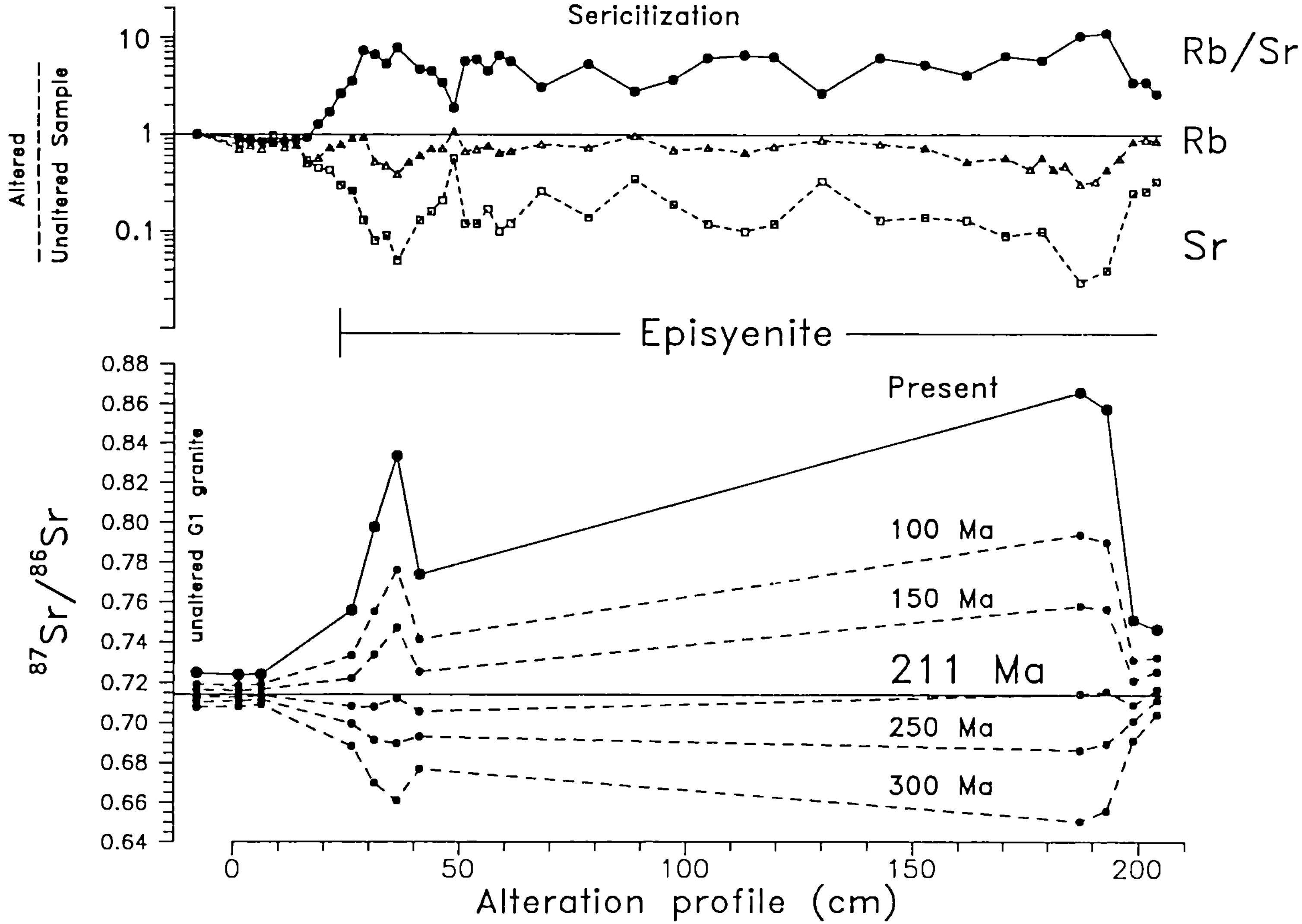


Fig. 1 : Lower part : Measured (solid line) and calculated (dashed line) $^{87}Sr/^{86}Sr$ ratios plotted against position in the alteration profile, Upper part : Rb/Sr-ratio, Rb and Sr values of whole rock samples in the alteration profile normalized to the unaltered G1 granite.

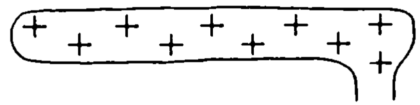
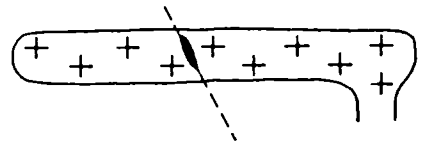
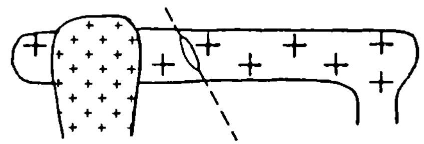
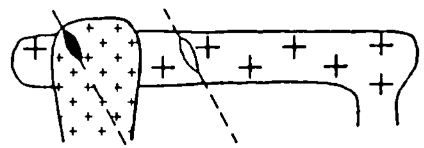
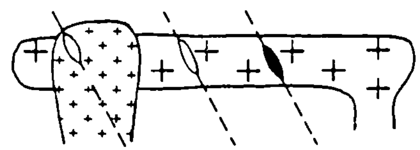
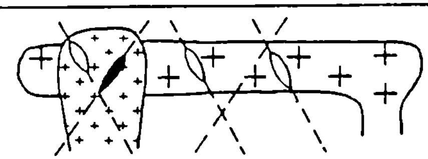
Sketch	Age (Ma)	Event	Structure	Mineralization Ore paragenesis	Fluid - granite - interaction Alteration	 enriched	 depleted
	**318**	Intrusion of older granite group					
	**320 - 300**	Vein-type U-mineralization (Großschloppen)	**SE - NW**	**U** Pitchblende Several sec. U-minerals Gold, Sulfides, etc.	Silicification* Sericitization* Hematitization* Chloritization Albitization	Si Fe^{3+} Mg, Fe Na	 Sr, Ca, Na Fe^{2+} K, Rb, Ca, Sr
	**290 - 280**	Intrusion of younger granite group					
	**ca. 280**	Late-magmatic Sn-mineralization in greisen (G4 granite, younger group)	**SE - NW**	**Sn** Cassiterite Arsenopyrite Pyrite Chalcopyrite, etc.	White mica Topas and Quartz in Greisen*	Rb, K F Si	Sr, Ca, Na
	**ca. 210**	U-mineralization disseminated in episyenites of G1 granite (older group)	**SE - NW** **SSE - NNW**	**U** Pitchblende Uranophane etc.	Quartz-leaching Sericitization* Hematitization* Chloritization Carbonatization	 Fe^{3+} Mg, Fe, Li, F Ca, CO_2, REE	Si Sr, Ca, Na Fe^{2+}
	**ca. 60 - 70**	U-mineralization in reddened fault zones	**SW - NE**	**U** Torbernite	Hematitization*	Fe^{3+}	Fe^{2+}

Fig. 2 : Simplified model of the sequences of the granite-associated mineralization in the Fichtelgebirge. (*) = Alteration associated with mineralization.

TECTONIC CONTROLS ON CHROME ORE LOCALIZATION IN OPHIOLITES, GREECE

Project Leader: I. VACONDIOS
Institute of Geology and Mineral Exploration (IGME), Athens, Greece

Contract MA1M-0068-GR

1. OBJECTIVE

The primary goal of the project was to further the understanding of the structural setting of ophiolitic chrome ores in order to aid subsurface exploration.
The three largest ophiolites of Greece (Vourinos, Othris and Pindos) contain over 1600 km^2 of peridotites potentially hosting chromite orebodies. Within this vast expanse of peridotite, the distribution of chrome ores is as follows :

a. At Vourinos, over 750 chrome occurrences have been mapped and, at present, there are four working mines. Ore potential is estimated at over 6 million tons.

b. In the Othris ophiolite, only about a dozen occurrences are known but these include two working and one abandoned mine : total ore estimates for these mines is in excess of 1.5 million tons of massive ore.

c. Hundreds of chromite showings and minor occurrences are known in the Greek Pindos, but as yet none has demonstrated economic potential.

By geochemical criteria, the supra-subduction zone ophiolites of Vourinos and the Pindos ought to contain the same inherent high potential as chrome hosts; conversely, the fertile peridotite of Othris ought to be barren. Thus, we hypothesize that structural setting, in addition to tectonogenetic affinity, is the controlling factor in preservation and position of economic chromite deposits.

The most promising target for future exploration is the uppermost 100 to 200 m of peridotite underlying known ore districts or promising chromite showings. Ophiolitic chrome orebodies are highly deformed, irregular in shape, and comprise small exploration targets. The potential of large volumes of ore-hosting peridotite cannot be evaluated by outcrop mapping. Exploration drilling over a grid is not cost efficient. However, recent research at Vourinos demonstrates a close correspondence between local structure and the position of orebodies. The present project develops and applies this correspondence to a viable chrome ore exploration strategy in the following ways :

1. Vast areas of "ore destructive" tectonic domains can be screened out as exploration targets.

2. Specific types of tectonic ore "traps" are identified : recognition of these "traps" during exploration mapping locates areas deserving explorative drilling;

3. The tectonic interpretation of ductile and brittle fabric measurements improves the accuracy of siting exploratory boreholes, and allows successful targeting of "blind" chrome orebodies.

2. MATERIALS AND METHODS

The present phase of tectonic research relies on field mapping of key tectonic features. Systematic mapping of the following structures is required : primary (ridgecrest) structures such as dunite/harzburgite contacts, chrome ore layers, the approximate position of the petrologic Moho where preserved; high temperature deformation fabrics such as orthopyroxene and spinel foliation and fabrics, fold systems, structural "layering"; intermediate temperature (lithospheric imprint) mylonitization, mineral cataclasis fabrics, mylonite zones and ductile shears; brittle field structures such as shears and faults.

Structural mapping on 1:20,000 and 1:50,000 scale has been conducted as reconnaissance "tectonic" exploration in the Pindos and Othris ophiolites, respectively. Detailed 1:500 to 1:1000 scale structural maps have been used to discriminate drilling targets in several ore districts of Vourinos.
The interpretation of aero-magnetic anomalies and lineaments has proven to be helpful in determining the general structural framework in the Othris area, and locating potential host peridotites under obscuring sedimentary cover.

3. ANALYSIS OF RESULTS

Structural analysis in the Pindos, Othris, and Vourinos ophiolites shows that deformation during emplacement controls the distribution of chrome ores.

3.1. At Vourinos, we have discriminated three types of structural traps (figure 1), each dominant in specific structural-tectonic domains, as follows :

3.1.1. In areas where high temperature fabrics parallel the emplacement thrust (thrust parallel domains), ores are entrapped along mylonitic surfaces with their extensions parallel to the emplacement lineation of Vourinos.

3.1.2. In areas where high temperature fabric parallel tear systems in the emplacement front (tear parallel domains), ores are located in axial zones of folds generated as a response to transcurrent ductile shear accompanying slab detachment and emplacement; orebodies align with spinel lineations that parallel fold axes;

3.1.3. In domains over which thrust parallel geometries grade to tear parallel geometries, ores are trapped in Z-folds within dunite bodies that preferentially accomodate ductile emplacement shear.

3.2. As for Vourinos, reconnaissance structural exploration in the Pindos ophiolite has located thrust and tear parallel structural fabrics. Unlike Vourinos, the tear parallel fabric is chiefly present as pervasive mylonitic cataclasis imprinted directly into higher temperature fabrics. This cataclasis highly strains the mantle section, and has accomodated far greater displacement than within Vourinos. Pyroxenite dikes and mantle layering are commonly reduced to boudins by this imprint, and the "largest" chrome occurrence has been elongated to a single 10 cm by 300 m structural layer.
This sort of ductile emplacement strain appears to have been an ore destructive phenomenon. Further structural reconnaissance of the Pindos (Dramala area) is based on locating domains where this mylonitic-cataclasis imprint is weak or lacking entirely; on a model integrating the Vourinos and Pindos ophiolites as the leading and trailing edges (respectively) of an emplacing slab (figure 2), ores in the Pindos may have greater potential for preservation along the slab margins where cooler emplacement conditions dominate.

3.3. The mantle section of the Othris ophiolite has been dismembered and severely imprinted by mylonitic cataclasis during obduction : the petrologic Moho itself was destroyed during obduction, and ophiolitic imbricate sheets stacked in reverse stratigraphic order such that the highest of these sheets, a plagioclase lherzolite nappe, obscures most other sections of the ophiolite. In general chrome occurrences are rare, in keeping with the inherently ore negative petrologic potential of fertile lherzolite host rocks. Where present, ores are restricted in position to thrust surfaces intersecting the tectonically destroyed petrologic Moho (figure 3). The original host to ores is a harzburgite unit, itself tectonically diminished along with most of the near-Moho section.

Site unique ore traps apparently coincide to positions where thrust parallel structures rotate into tear systems.

4. CONCLUSIONS

Chromite deposits in ophiolitic hosts are confined to structural "traps" generated during ductile obduction processes and accentuated by brittle emplacement strain.

For all areas studied, oceanic structures are deformed into obduction-oriented geometries, and overprinted by ductile and brittle ophiolites, a single obduction geometry reconciling ductile fabric elements (imprinted mantle layering and mineral orientations, lithospheric mylonitic fabrics and folding) trend either northwest, parallel to the emplacement front, or north-east, parallel to tear systems accompanying obduction.
Emplacement structures appear to generate around the position of dunite bodies and chrome ores themselves : Thus, rigid ore bodies become entrapped within detachment-related ductile structures and provide the critical points for generation of brittle structures. If emplacement is accomplished primarily by ductile cataclasis (as at the trailing end of an obducting slab), chromite ore zones can become dissipated to sub-economic size (as for large areas in the Pindos ophiolite). Ores are best preserved where emplacement is dominated by brittle structures (as for Vourinos), so that ores are entrapped but not destroyed within zones of mylonitic-ductile deformation.

Exploration criteria for chrome ore bodies in ophiolites resulting from and confirmed by our present research are as follows :

1. Location of ophiolitic sections originally in close proximity to the petrologic Moho or spreading ridge.

2. Analysis of obduction strain : the position of zones accomodating earliest detachment-obduction via ductile deformation are those most likely to contain ore bodies; subsequent brittle deformations emphasize the positions of these zones, and are useful for targeting of dunite and/or ore rich sections.

3. Determination of position within the obducting mantle slab : trailing end strain (generally via ductile cataclasis) tends to be ore destructive.

4. Evaluation of potential ore "traps" : the most efficient of these are mylonite zones parallel to the emplacement front, and/or ductile emplacement structures deforming into a tear parallel geometry.

5. Spinel fabrics are highly affected by ductile overprint in such a way that spinel lineations and chrome ore fold axes indicate the elongation directions of potential orebodies.

5. CONTRIBUTING SCIENTISTS AND INSTITUTIONS

This project involved the active participation of a large group of scientists from several organizations.

5.1 INSTITUTE OF GEOLOGY AND MINERAL EXPLORATION (I.G.M.E.)

- Mr. Elias GRIVAS
- Dr. Anne RASSIOS

: Kozani Branch, Kamvounion 13, Kozani 50100, GREECE

- Mr. Iosef VACONDIOS
- Dr. G. KONSTANTOPOULOU
- Mr. George VRACHATIS

: Department of Economic Geology, Mesoghion 70, Athens 11527, GREECE

- Dr. Georgeta MEMOU
- Dr. George SKIANIS

: Deparment of Geophysics, Mesoghion 70, Athens 11527, GREECE

- Dr. Eleutheria DIMOU : Department of Mineralogy and Petrology, Mesoghion 70, Athens 11527, GREECE

5.2 UNIVERSITIES

- Prof. Adolphe NICOLAS : Department of Earth Sciences, University of Monpellier, FRANCE

- Dr. Lesley WRIGHT : c/o Deparment of Geology, University of Southampton, UNITED KINGDOM

- Prof. George MIGIROS : Department of Mineralogy and Geology, Agricultural University, Iera Odos 75, Athens 11855, GREECE

- Prof. Maria ECONOMOU : Department of Geology, University of Athens, Panepistimiopolis, Athens 15784, GREECE

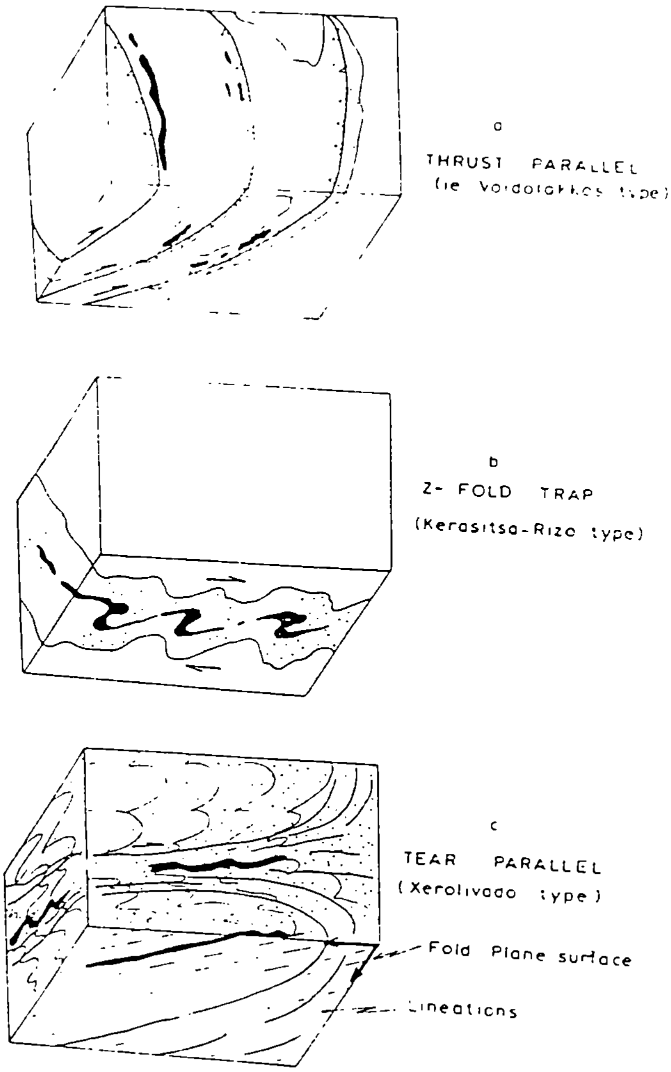


Figure 1. Schematic diagram of thrust-parallel (5a), Z-fold (5b), and tear-parallel (5c) ore traps of Vourinos. Stippled areas are dunite, white is harzburgite, and black are ore bodies.

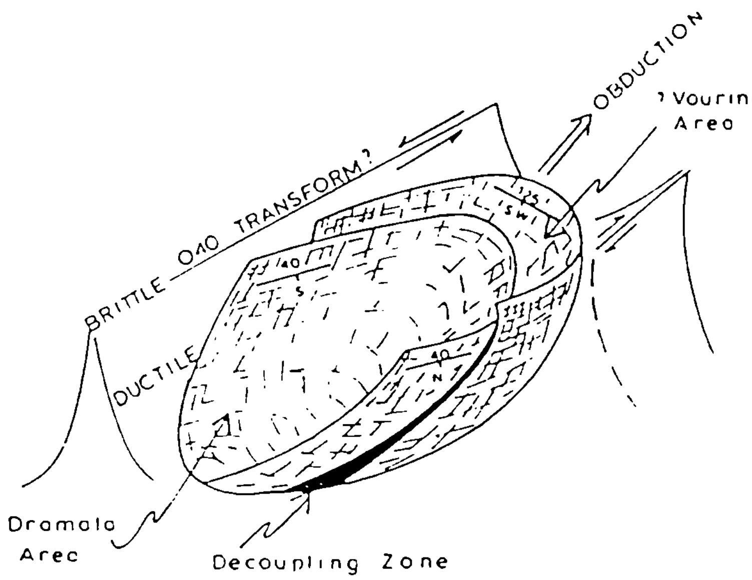


Figure 2. Speculative model showing geometry and position of Pindos (Dramala area). Dramala and Vourinos in a single NE-directed obducting thrust sheet.

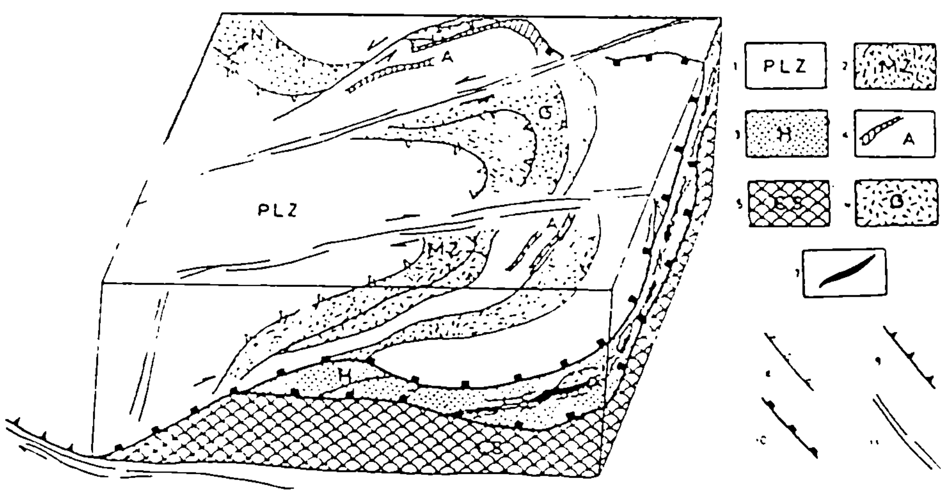


Figure 3. Block diagram illustrating structural history and major chrome ore traps in the southwest Othris ophiolite.
Legend : 1. plagioclase lherzolite; 2. Mixed zone; 3. Harzburgite; 4. Amphibolite zones; 5. Undifferentiated ophiolitic crustal section rocks; 6. Gabbro cumulates; 7. Chrome ore bodies; 8. Internal thrusts; 9. Basal thrust to ophiolitic nappes (on flysch); 10. Thrusts surrounding ore-bearing surface; 11. Tear fault systems.

PLATINUM GROUP ELEMENT MINERALISATION IN TWO BASIC/ ULTRABASIC COMPLEXES IN NORTHERN PORTUGAL : (A) THE PLATINUM GROUP ELEMENTS : MINERALOGY AND ANALYSIS, (B) STRUCTURAL AND LITHOLOGICAL CONTROLS ON MINERALISATION

Project Leaders: H.M. PRICHARD
Department of Earth Sciences, The Open University, Milton Keynes, United Kingdom

and

A. RIBEIRO
Departamento de Geologia, Universidade de Lisboa, Portugal

Contract MA1M-0075-C

1. OBJECTIVE

Traditionally Pt and Pd were thought to be restricted to continental basic and ultrabasic igneous layered complexes especially the Bushveld complex of South Africa. Recently there have been studies for PGE in a number of different geological environments, other than those normally considered sources of Pt and Pd. Ophiolite complexes were thought to contain only Os, Ir and Ru at or below 1ppm levels. Recent EEC funded research led to the discovery of unusually enriched Pt and Pd values associated with podiform chromitite in the Shetland ophiolite complex (Prichard et al., 1987). The Bragança and Morais massifs of northern Portugal contain similar podiform chromite concentrations. They occur in ultramafic lithologies within the Upper Allochthonous Thrust Complex (UATC) of Bragança (Ribeiro et al., 1990) which are thought to be of sub-continental mantle origin (Marques, 1989) representing a potential and unstudied geological environment where PGE may be concentrated.

The purpose of this 2 year project was to determine the grade and distribution of platinum-group elements (PGE) within the Bragança and Morais complexes of north-eastern Portugal. The aim was to utilise the relationship between the PGE and their host lithologies in terms of primary igneous rock type, metamorphic grade, deformation state and alteration to understand the processes which are most important in concentrating and redistributing the PGE. This was a collaborative project between the UK and Portugal, combining the regional geological expertise of the geologists from the Portuguese Geological Survey, the structural and metamorphic expertise of the team at Lisbon University and the platinum exploration expertise at the Open University.

Participants to the project were: HM Prichard (project leader), J C Bridges and C R Neary for the UK team, and A Ribeiro (project coordinator), F. Marques, F. Barriga and J. Munha for the Portuguese team.

This report is a summary of the cooperative work performed by both the UK and Portuguese teams. A detailed description of the work performed by the Portuguese team is reported separately, as a companion paper, in the next article of this volume.

2. MATERIALS AND METHODS

The Portuguese Geological Survey personnel have produced detailed maps of the Bragança and Morais massifs at a scale of 1:25,000. The team at Lisbon University have reexamined the structural features of the massifs. The Open University group have sampled lithologies from both massifs with special emphasis on the chromitites. The primary PGE and chromite data is almost exclusively the work of J.C. Bridges. Noranda drill cores have been sampled and a stream sediment collection programme designed to discover PGE-bearing placers has been carried out in the vicinity of the massifs. Whole rock analysis for all 6 PGE were obtained from Analytical Services and Genalysis, in Australia. Potential pathfinders for the PGE were analysed using an ED XRF. Microscope searches for the PGM were followed by analysis using a Jeol 820 scanning electron microscope with a Kevex ED analytical system. Analyses of chromites were obtained using a MK9 Cambridge electron microprobe. The sulphur content of the sample with the most sulphide (BRAG 64) was measured by SO_2 pressure measurement in a baratron after oxidation with CuO and cold trapping of water and CO_2.

3. RESULTS

Ultramafic lithologies within the UATC, studied during this project, include pyroxenites, hornblendite and harzburgite (identified here for the first time) with lenses of dunite sometimes containing chromite mineralisation. Many concentrations of chromite occurring in the Bragança area have been exploited with extraction in excess of 100,000 tons. Chromite within dunite occurs as discontinuous layers with up to 90 % modal chromite. Layers exposed in-situ are less than 15 cm thick and occasionally a discontinuous chromite layer is folded and rarely nodular chromite is present. The maximum diameter of grains varies from 0.1 to 10 mm and they are often split by late pull apart cracks.

Chromite grains are geochemically unzoned except for alteration effects. Towards grain edges or cracks there is often a marked depletion in Al and Mg and an enrichment of Fe^{+++} and Fe^{++}. The range of chromite compositions is : Cr_2O_3:46.4% - 61.0 %, MgO:7.4 - 14.0%, Al_2O_3:6.9 - 19.1 %, TiO_2: 0.09 - 0.24 % and FeO (Total): 12.3-23.3 %. Variation occurs in the Cr_2O_3. There is, however, some evidence for a systematic decrease in the average grades of Cr_2O_3 from west to east across the UATC ultramafic rocks of the Bragança massif (Figure 1). Cr_2O_3 values of 58 - 61 % [Cr/(Cr+Al) values of over 80] commonly occur in the west whereas samples to the east have Cr_2O_3 values of between 49 and 55 % [Cr/(Cr+Al) values of 65-78].

PGE analysis during this project has confirmed the presence of anomalies associated with chromite mineralisation in the UATC unit of the Bragança massif (Neiva, 1947) but has not reaffirmed other anomalies described by him. Analysis from sediments gave low values including two samples from the Bragança area which have total PGE values of 51 and 120 ppb. Outside this area only one sample produced a PGE value (80 ppb Pt) of any significance. This was taken from the Rio Tuela downstream of Bragança. By contrast gold was observed commonly in panned samples including from the Rio Tuela, from a stream draining the Bragança massive north of the Abecido chromite mines and from the Rio Sabor south of Morais.

All whole rock PGE analyses of the pyroxenites, peridotites, hornblendites and dunites have low values (total PGE below 60 ppb and usually between 2 - 15 ppb)(Table 1). Dunites and pyroxenites from the UATC (BRAG 43 and BRAG 141) and from the ophiolitic Morais dunites of the Noranda cores (DD1-77) with higher accessory sulphide have slightly enriched Pt and Pd values.

The chromite-rich samples sometimes have significantly enriched PGE concentrations (Table 1). There is a range of total PGE values, in samples analysed, from 24 ppb in sample BRAG 70 to 11,200 ppb in BRAG 57 from Derruida. The highest overall PGE tenors are in some of the more massive chromitites. The PGE-enriched samples are distributed throughout the UATC (Figure 1). The two most anomalous PGE values come from Derruida (11.2 ppm total PGE) in the south east and from Cabeço da Pedrosa (6.0 ppm total PGE) in the north west. Other samples of chromitite from Derruida are not enriched in PGE. Localities in Bragança also found to have greater than 0.5 ppm total PGE are, from north to south, Tuela, Minas de Abicedo, Lentiscais, Sardoal and Campos. The significant grades of PGE are widely distributed between the chromite quarries but there is an interesting geographical distribution of samples with different Pt/Pd ratios. In the NW (newly mapped Manto de Catrões tectonic unit) 5 out of 7 of the chromites analysed have high Pt/Pd ratios between 5 and 12 whereas elsewhere all (20) chromitites have a Pt/Pd ratio of less than 3. In general the individual PGE tend to be concentrated together and samples with the most abundant Pt are all massive chromitites. Although Ni and Cu show a significant correlation with each other, there is no significant correlation between these elements and any of the six PGE. BRAG 64 has the highest Ni and Cu value, thin section examination revealed it to have the most base-metal sulphide and analysis gave 168 ppm sulphur. All the chromite-rich samples have As levels below detection limit of an ED XRF apart from BRAG 64 (26 ppm), BRAG 70 (7 ppm) and 47 BRG (6 ppm).

The most common chondrite normalised PGE pattern for the chromite-rich lithologies is a predominantly negative slope with Os, Ir and Ru greater than Rh, Pt and Pd, typical of podiform chromitites, for example BRAG 71 (Figure 2). Chromite-rich samples with less than 70 % chromite or more display a number of patterns. Positive slopes belong to the most anomalous PGE-rich sample, BRAG 57. BRAG 28 also has a positive slope but with a less steep gradient and there are some almost flat patterns. Throughout the samples there is often an upturn or a downturn from Pt to Pd, disrupting the smooth profiles. With the exception of BRAG 78 and BRG 172 all the samples from the south and east have flat or positive slopes between Pt and Pd. In contrast some samples from the north west of the area have anomalously high Pt/Pd ratios with distinctive negative slopes between Pt and Pd, for example BRG 155 and 142.

In most PGE-bearing samples none or only one or two platinum-group minerals (PGM) were observed but in one section from BRAG 57 twenty PGM were located. The PGM (2 μm to 45 μm in size) are either located at the edges of chromite grains where they have irregular and embayed outlines or they are totally enclosed as inclusions which are generally hexagonal or octahedral. Laurite (Ru [OsIr]S_2) is the most common PGM found in this study (Plate 1a) and is situated both throughout the chromite grains and at their edges. S loss has occurred from some laurites and a low reflectance material associated with laurite gives an analysis of Ru with traces of Mn and may be a ruthenium oxide. Minerals in the irarsite/hollingworthite/platarsite (IrAsS-RhAsS-PtAsS) series are found both at the edges and at the centre of chromite grains but Pt-bearing sulph-arsenides are observed only at the edge of chromite grains. Sperrylites ($PtAs_2$) were found as part of composite PGM grains with minerals of this series, again at the margin of chromite grains. Samples BRAG 64 and BRAG 57 contain Pd-S associated with Fe-Ni-S either on the edge or included within chromite (Plate 1b). A Pt-Pd-Cu alloy was discovered located along one edge of a pentlandite-magnetite assemblage within chromite.

4. DISCUSSION

Fractionation of the PGE is shown in the PGM assemblage. Laurites and irarsites, euhedral where they are enclosed by chromite, may have a primary origin, that is they crystallised at approximately the same time as the chromite. Pentlandite, located adjacent to or around some of these primary PGM also suggests an association with the PGE as they crystallised from the magma. Arsenic values are low enough to be of magmatic origin. A primary origin for the As-bearing PGM is suggested because they often occur as euhedral inclusions within chromite grains, sometimes adjacent to laurites, and chromite around them is fresh indicating that the As was not introduced during alteration. The Pt-bearing PGM, also inferred to have a primary origin, usually lie at the margins of chromite grains suggesting that the Pt-bearing grains started to crystallise later than the Ru-, Ir-, Os-, Rh-bearing grains which formed during the growth of the chromites. The PGM at the edges of the chromite grains have ragged and embayed outlines and show oxidation and sulphur loss possibly caused during serpentinisation.

Base metal sulphides are associated with Pd sulphides which are thought to represent exsolution from pentlandite at low temperatures. Although the Pd-bearing grains are not quantitatively characterised, owing to their small size, they are probably vysotskite (PdS). The stability field for this mineral was described by Cabri et al. (1978) as being at or below 800°C in the Pd-Pt-NiS system and therefore only likely to be formed at sub-magmatic temperatures; Experiments on the solubility of the PGE within sulphide-bearing systems at various temperatures suggest that at 500°C pentlandite is able to dissolve up to 12.5 wt% Pd and this was retained down to 300°C (Makovicky et al., 1986). If the Pd-bearing grains in this study are derived from the adjacent relict pentlandites then the release of Pd may occur with the start of the decomposition of pentlandite to millerite and magnetite.

The low Pt/Ir and Pt/(Os+Ir+Ru) ratios and flat to negative slope chondrite normalised patterns from Ru to Pt indicate that most of the chromitites have unfractionated PGE assemblages. Some samples, however, have high Pt/Ir ratios and positive slope patterns showing the presence of a fractionated assemblage. The marked change in slope at Pt in most samples indicates that Pd concentration is distinct from the main fractionation trend for the other PGE, suggesting different processes of concentration.

Pd enrichment is linked to the amount of base-metal sulphide present. BRAG 64 has the highest quantity of base-metal sulphide and this is the only sample where Pd is the most abundant PGE. It seems likely that the Pd was incorporated from the melt as the pentlandite crystallised during the chromite growth. Although there may have been some S loss from the whole rock due to oxidation during serpentinisation, the content has probably not changed much; there is no evidence to suggest that these rocks previously had a much greater amount of base-metal sulphide. The association of Pd with the base-metal sulphide allows a tenor of that element within sulphide to be calculated. This can be used to calculate a possible minimum concentration for this element within a silicate melt from which the chromite-rich rocks crystallised. The high tenor of Pd within some samples suggests that a process of preconcentration for Pd was necessary.

In order to explain this and the fractionation of the other PGE it is suggested that a model based on the work of Amossé et al. (1990) relating the effects of fO_2 to the solubility of the PGE within silicate melts is applicable. At the fO_2 likely during the formation of the chromitite ($\log_{10}^{-7}$ to $\log_{10}^{-5}$) the solubility of the PGE decreases. It is relatively less soluble than Pt and this may explain the observed fractionation in some of the samples as Pt is likely to be incorporated in minerals after Ir. The drop in solubility of the PGE may also explain the high Pd tenors of the pentlandite.

The trivalent chemistry of the chromitites from the UATC is similar to that of the Cyprus and Shetland complexes including low Ti values typical of ophiolite complexes. The chromite compositions also have a high (greater than 60) Cr/(Cr+Al) ratio suggesting that they formed by melting above a subduction zone (Dick and Bullen, 1984). This is consistent with a large degree of partial melting, associated with fluids from the subducting slab, producing residual harzburgite and with the presence of podiform chromite itself. Marques (1989) suggests that the UATC has a sub-continental mantle origin and it is suggested that the subduction zone was present beneath a continent or the subduction zone produced a volcanic arc that was accreted to a continent.

5. CONCLUSION

The mapping and structural work of the Portuguese team has confirmed the distinction between the polydeformed and polymetamorphic tectonic unit UATC and the monocyclic lower tectonic unit (Ophiolite Thrust Complex, OTC). The OTC shows all the characteristics of a typical ophiolite sequence - including a diagnostic sheeted dyke complex - and geochemistry with a distinct oceanic affinity. Progress has been made in the elucidation of the internal structure of these tectonic units. In the UATC the internal structure of the infracrustal segment is very complex and we can now choose between the two alternatives we put forward at the beginning of the project : repetition is caused mainly by thrusting and major recumbent folding can be ruled out. Some progress was made concerning the internal structure and differentiation of the OTC. There is a definite geochemical difference between Morais and Bragança, with more typical oceanic affinities in the geochemistry of Morais and a more transitional character in the Bragança tectonic slices of Zoio, Nogueira and Soeira.

The field relations, textures and geochemistry of the chromites from the Bragança polycyclic unit suggest a podiform rather than a stratiform nature. Significant PGE concentrations are restricted to chromite-rich samples within the Bragança massif. The distribution of the PGM within these samples indicates early crystallisation of Os-, Ir-, and Ru- bearing PGM within chromite grains followed by later formation of Pt-bearing PGM on the edges of grains. Pd-bearing minerals are associated with sulphides. This PGE mineralogy is similar to that described in the Shetland chromite-rich samples. The geochemistry of the PGE represented by chondrite normalised plots is complex. Present are both positive slopes (typical of stratiform complexes and more recently described as more fractionated assemblages) and negative slopes (typical of ophiolite complexes and more recently described as less fractionated assemblages). In addition there are unusual chondrite normalised patterns with irregular slopes. In particular Pd often does not lie on a straight line with other PGE perhaps reflecting a different process of concentration of this element.

This collaborative project has shown geographical variations in the Pt/Pd and chromite Cr/(Cr+Al) ratios both with high values in the north west which can be placed structually in context in the light of the newly mapped units in the Bragança complex.

6. ACKNOWLEDGEMENTS

We would like to thank drivers from the Portuguese Geological Survey for their competent help with transport. We gratefully acknowledge constructive advice from Professor I G Gass and Richard Lord. We appreciate the assistance of John Taylor with diagrams, Naomi Williams with SEM work, Andy Tindle with electron microprobe analysis, John Watson with XRF and Jon Maynard with S analysis.

7. FURTHER WORK

This 2 year project represents an initial study of the Bragança massif which needs to be followed by a systematic survey of the PGE with reference to the new structural work; one half of the area is still to be revised. The initial studies suggest that there may be a link between chromite composition and PGE concentration in Bragança and this needs to be explored to understand the processes which concentrate the PGE. The PGM types are relatively well known within the rock lithologies and stream sediment sampling has also revealed the presence of PGE in the river alluvium. In this area, therefore, there is the possibility of comparing the PGM in the secondary environment and in the rocks in order to understand the processes of weathering and transport of the PGE. Our work is already being followed up commercially by Ashchurch Exploration Co., Ely, Cambridgeshire, UK.

8. ORAL COMMUNICATIONS AND PUBLICATIONS OF THE OPEN UNIVERSITY GROUP

Contact group meetings in Bragança (1988), Shetland & Paris (1989), Bragança (1990) and Lisboa (1991). Presentations and abstracts for the 5th International Platinum Symposium in Finland (1989), Mineral Deposits Study Group meeting in Dublin (1990) and 6th International Platinum Symposium in Perth Australia (accepted). PhD thesis by J.C. Bridges : -"The genesis of platinum in the ultrabasic complexes of northern Portugal" (in preparation).

9. REFERENCES

1. Amossé J., Allibert M., Fischer W. & Piboule M.
EXPERIMENTAL STUDY OF THE SOLUBILITY OF PLATINUM AND IRIDIUM IN BASIC SILICATE MELTS-IMPLICATIONS FOR THE DIFFERENTIATION OF PLATINUM-GROUP ELEMENTS DURING MAGMATIC PROCESSES.
Chemical Geology, 81 ,1990, 45-53.

2. Bridges J.C., Prichard H.M., Meireles C. & Lord, R.A.
PLATINUM-GROUP MINERALS IN CHROMITE-BEARING ULTRABASIC ROCKS OF THE BRAGANCA MASSIF, N.PORTUGAL.
MDSG abstract volume, Johnston D. (ed.), 1990, p. 5

3. Cabri L.J., Gilles-Laflamme J.H., Stewart J.M., Turner K. and Skinner B.J.
ON COOPERITE, BRAGGITE AND VYSOTSKITE
American Mineralogist, 63, 1978, 832-839

4. Cotelo-Neiva J.M.
PLATINA NO DISTRITO DE BRAGANCA
Estudos, Notas e Trabalhos do Serviço de Fomento Mineiro, 3, 1947, 1-2, 19-24

5. Dick H.J.B. and Bullen T.
CHROMIAN SPINEL AS A PETROGENETIC INDICATOR IN ABYSSAL AND ALPINE-TYPE PERIDOTITES AND SPATIALLY ASSOCIATED LAVAS
Contrib. Mineral. Petrol., 86, 1984, 54-76

6. Makovicky M., Makovicky E. and Rose-Hansen J.
EXPERIMENTAL STUDIES ON THE SOLUBILITY AND DISTRIBUTION OF PLATINUM-GROUP ELEMENTS IN BASE METAL SULPHIDES IN PLATINUM DEPOSITS
In Metallogeny of basic and ultrabasic rocks, Gallagher M.J., Ixer R.A., Neary C.R. & Pritchard H.M., 1986, London : The Institution of Mining and Metallurgy, 515-425

7. Marques F.
ESTUDO ESTRUTURAL DAS ROCHAS CATAZONAIS DO SINFORMA DE V. BOA DE OUSILHAO (BRAGANCA, TRAS-OS-MONTES)
Unpub. MSc. Thesis Universidade de Lisboa. 1989, 195 pp.

8. Naldrett A.J. and Duke J.M.,
PLATINUM METALS IN MAGMATIC SULFIDE ORES
Science, 208, 1980, 1417-1424

9. Prichard H.M., Neary C.R., Potts P.J., Lord R.A. and Ward G.R.
DEVELOPMENT OF TECHNIQUES FOR THE DETERMINATION OF THE PGE IN ULTRAMAFIC ROCK COMPLEXES OF POTENTIAL ECONOMC SIGNIFICANCE : MINERALOGICAL STUDIES
Commission of the European Communities. Report EUR 11631, 1988, 163 pp.

10. Ribeiro A., Pereira E. and Dias R.
STRUCTURE OF THE CENTRO-IBERIAN ALLOCHTHON IN THE NORTHWEST OF THE IBERIAN PENINSULA.
In: Martinez-Garcia E., Dallmeyer R.D. eds., Premesozoic Geology of Iberia, Springer-Verlag, Heidelberg, 1990.

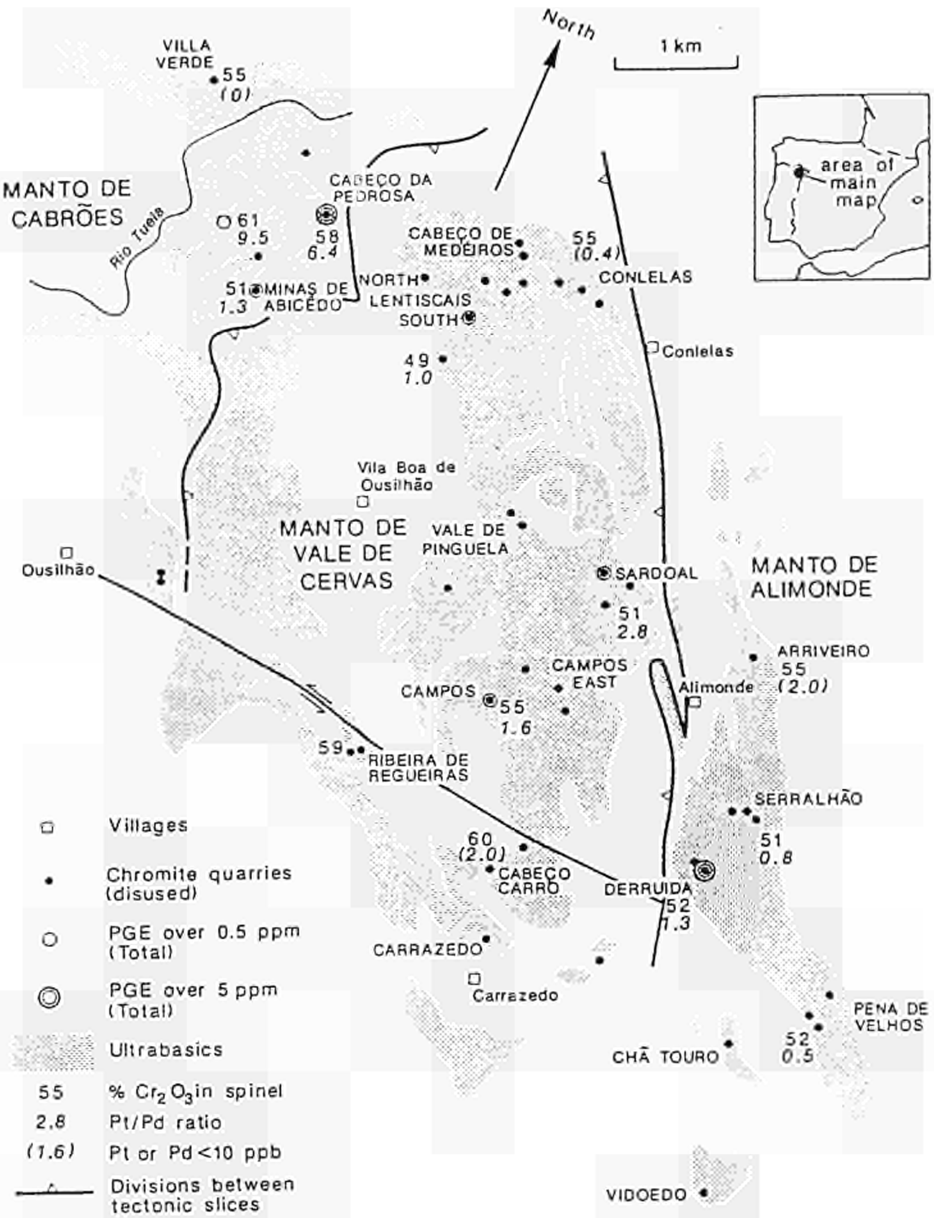


Fig. 1: Map of the UATC part of the Bragança massif.

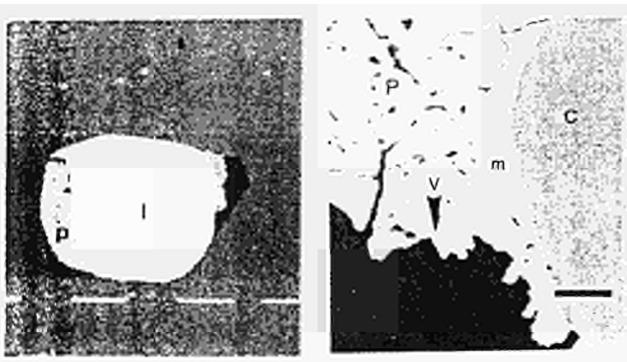


Plate 1a: Composite grain of laurite (l) with irarsite (i) partly surrounded by pentlandite (p) and enclosed by chromite.

Plate 1b: Tabular grain of Pd-S (V) on the edge of pentlandite (p) adjacent to silicate (s) and near the margin of chromite (c) with an altered magnetite rim (m). Scale bars 10 μm.

Sample No	Locality	% chromite	Os	Ir	Ru	Rh	Pt	Pd
BRG39	Vila Verde	80	18	18	58	7	0	2
BRG154	Tuela	70	56	135	145	118	250	43
BRG155	Tuela	65	50	130	125	135	235	22
BRG142	Cabeço Pedrosa	85	960	1350	1500	240	1650	260
BRG145	Cabeço Pedrosa	75	370	400	740	125	740	116
BRG152	Cabeço Carro	50	40	70	100	18	16	8
BRAG2	Abicedo	80	42	57	110	20	83	66
BRAG64	Lentiscais	35	70	56	140	36	86	180
BRAG71	Lentiscais	35	24	25	45	9	16	11
BRAG73	Lentiscais	50	28	26	54	5	8	8
BRAG76	Conlelas	30	46	42	185	8	6	14
BRAG78	Sardoal	75	160	180	310	46	51	18
BRAG28	Campos	90	88	250	390	120	510	340
BRAG45	Campos	75	78	118	225	45	155	90
BRG130	Alimonde	65	20	20	66	6	4	2
BRG134	Serralhão	65	34	32	60	5	2	2
BRAG52	Serralhão	65	34	50	69	13	52	83
BRAG53	Serralhão	55	22	28	44	7.5	40	45
BRAG51	Serralhão	55	18	14	62	5	2	4
BRAG39	Pena de Velhos	60	34	32	72	10	20	44
BRG55	Samil	50	38	32	86	6	2	4
BRAG57	Derruida	80	670	1600	1200	590	4200	3200
BRAG56	Derruida	50	28	26	38	3	2	4
		Rock type						
BRAG58	Derruida	dunite	4	14	14	4	10	11
BRG14	Derruida	pyroxenite	2	4	4	2	8	6
BRG133	Derruida	harzburgite	4	6	8	2	8	4
DD1-77	Morais	dunite	8	4	8	2	30	30

Table 1: Whole rock PGE analyses for the Bragança and Morais area.

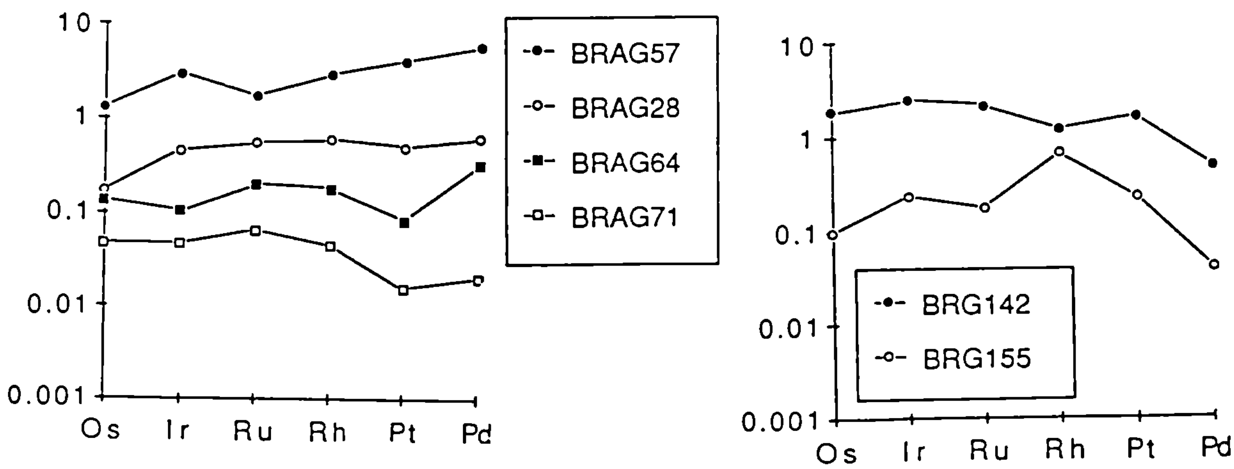


Fig. 2: Chondrite normalised graphs from the Bragança area. Chondrite values from Naldrett and Duke (1980)

RESEARCH AREA 1.2

METHODS OF GEOCHEMICAL PROSPECTING

HYDROTHERMAL FLUID ANOMALIES : A NEW STRATEGY FOR GEOCHEMICAL EXPLORATION IN PORTUGAL

Project Leaders: T.J. SHEPHERD
British Geological Survey, U.K.

and

J.M. SANTOS OLIVEIRA
Direcçao Geral De Geologia e Minas, Portugal

Contracts MA1M-0027 - UK & MA1M-0028 - P

1. OBJECTIVES AND INTRODUCTION

The primary objective of the project was to establish new criteria and methodologies for the exploration of concealed tin, tungsten, gold and silver deposits in the Hercynian granite-schist terrains of central and northern Portugal. The approach adopted was based on the concept of 'hydrothermal fluid anomalies' which proposes that orebodies occupy the focii of hydrothermal systems and are therefore enclosed by haloes of geochemically and mineralogically disturbed wall rocks due to fluid-rock interactions. Zonal patterns around ore deposits, whether primary or secondary in origin, form the basis of most modern geochemical exploration programmes. However, because the effectiveness of primary and secondary metal dispersion patterns diminishes rapidly as the depth of burial increases, hydrothermal fluid anomalies were considered to afford larger exploration targets for concealed ore deposits. By characterising the nature and form of the haloes (including their spatial relationship to trace element enrichments) it was intended to identify specific features that could be used as proximity guides to mineralization. Indices considered highly sensitive to fluid-rock interaction were the mineral isotope ratios $^{18}O/^{16}O$, D/H, $^{13}C/^{12}C$, $^{34}S/^{32}S$ and $^{87}Sr/^{86}Sr$, and the isotopic composition of fluid inclusions. A special aim of the project was to assess the extent to which fluid inclusion volatiles (H_2O, CO_2, CH_4, N_2) could be used to discriminate between barren and potentially auriferous systems. Since the size and geometry of hydrothermal fluid anomalies depend on many factors, ore deposits from contrasting geological environments were selected for study. This also served to facilitate the development of a comprehensive metallogenic model linking sediment- and granite-hosted precious metal deposits that could be used as a robust exploration strategy for other parts of the Central Iberian province.

2. MATERIALS AND METHODS

Investigations focussed on the schist-hosted Au-Ag and Sn-W deposits of the Gois region, central Portugal, and the intragranitic and granite-contact related Au-Ag and Sn-W deposits of the Vila Pouca de Aguiar-Vila Real region, northern Portugal (see figure 1). Both regions belong to the Central Iberian Hercynian Geotectonic Zone (CIZ) of the Iberian Meseta. The Gois region is located in the southern sector of the CIZ close to its boundary with the Ossa-Morena Zone; the junction comprising a major crustal lineament, the Coimbra-Badajoz Shear Zone. Compared to other regions of Portugal little is known of the geology which consists of a monotonous sequence of upper Precambrian to Cambrian phyllites, siltstones, mudstones and greywackes of the Complexo Xisto-Grauvaquico (CXG) overlain unconformably by Ordovician quartzites.

As shown in figure 1, the quartzites define NNW-SSE elongated outcrops thought to be controlled by similarly trending shear zones sympathetic to the Coimbra-Badajoz Shear Zone. Other major faults trend NE-SW and downthrow major basins of Tertiary sediments. Schist-hosted Au-Ag mineralization (Escadia Grande) is intimately associated with shear zones. Regional metamorphism is low greenschist facies, though locally there are areas of spotted schists thought to be related to near surface Hercynian granite cupolas. At Gois the spotted schists host numerous Sn-W-bearing quartz veins (Vale de Piao).
The Vila Pouca de Aguiar-Vila Real region lies in the northern sector of the CIZ, within the main Hercynian granite core of the Iberian Meseta. Here the granites intrude units of the CXG, Ordovician and Silurian metasediments, and comprise an older group of two mica granites succeeded by a suite of younger, porphyritic biotite granites that locally produce tourmaline greisens and muscovite granites by metasomatic alteration of the older granites. Faulting is dominated by NNE-SSW trending Hercynian faults that show repeated reactivation. Au-Ag mineralization is especially strong along the northern margin of the granite massif (Jales, Três Minas) whereas Sn-W mineralization is best developed in the southern part of the granite massif.

Using material from the selected ore deposits (Escadia Grande, Vale de Piao, Jales, Três Minas), the main analytical programme involved the following :

- Detailed chemical and isotopic analysis of rock, ore and vein quartz samples :
- Fluid inclusion analysis (microthermometry and mass spectrometric analysis of inclusion volatiles H_2O, CO_2, CH_4, N_2 in vein quartz).

- Stable isotope analysis ($^{18}O/^{16}O$, D/H, $^{13}C/^{12}C$, $^{34}S/^{32}S$ for minerals ; D/H and $^{13}C/^{12}C$ for inclusion fluids).
- Radiogenic isotope analysis (Rb-Sr and Sm-Nd for whole rocks, Rb-Sr for inclusion fluids).
- Evolved gas analysis (semi-quantitative measurement of trace sulphide, carbonate, graphite and kerogen content of black shales/schists).

To achieve the primary objectives, it was necessary however to establish reliable geological and geochemical baselines for estimating the superimposed effects of hydrothermal mineralization and alteration. This required strategic geological and structural mapping of selected ore deposits at 1:100 and 1:2000 scales, mineralogical and petrological studies of the ore assemblages and wallrocks, radiometric dating of the granites and mineralization, and illite-graphite crystallinity measurements of the metasediments. In conjunction with the above studies, complementary lithogeochemical surveys (local and regional) were carried out to identify geochemical signatures for different styles of mineralization. Multi-element data were obtained for more than 400 granite and schist samples.

This report presents a summary of the cooperative work carried out by BGS and DGGM teams. A detailed presentation of the studies carried out by DGGM on the above mentioned topics (geological and structural mapping; petrographic studies; ore mineralogy studies; chemical analyses; specific mineralogical studies; lithogeochemical studies) is given in the next article of this volume.

3. ANALYSIS OF RESULTS

Integrated mineralogical, chemical, isotope and fluid inclusion data for the schist-hosted Au-Ag deposits (Escadia Grande and Três Minas) show many features in common with granite-hosted deposits (Jales), implying a strong genetic affinity. This is expressed most simply by the development of a common mineral assemblage 'arsenopyrite-pyrite-galena-sphalerite-chalcopyrite' in association with gold and various Pb-Sb-Ag sulphosalts. The silver content of the gold varies slightly but is generally >15 %. However, the most compelling evidence is provided by combined fluid inclusion-stable isotope data. Contrary to previous ideas that the auriferous quartz veins are a distal expression of Hercynian granite-related magmatic/hydrothermal Sn-W mineralization, the present study demonstrates that the ore fluids have a strong, sedimentary geochemical signature and were either derived from the metasediments or have undergone substantial isotopic and chemical exchange with them. For both granite- and schist-hosted deposits the ore fluids are characterised by low salinity H_2O-NaCl-CO_2-CH_4-N_2 fluids containing relatively high levels of dissolved gases (up to 25 mol% non-aqueous volatiles) which in the case of Escadia

Grande, are compositionally indistinguishable from local metamorphic fluids in the CXG. D and ^{18}O values for Jales and Escadia Grande (-30 to 17‰; -12.5 to -5‰ respectively) plot well within the field ascribed to sedimentary metamorphic waters. $d^{13}C/_{CO2}$ values for the inclusion fluids are similar (-7.4 to - 11.3‰). Comparison of the CO_2 and CH_4 isotope systematics in the regional metamorphic and mineralized veins suggests that isotopically heavy CO_2 and isotopically light CH_4 have been added to the mineralizing fluids. The methane component is consistent with local derivation from organic matter in the CXG (typically ^{13}C of cu.-25‰). Unfortunately the compositional range for CO_2 cannot be interpreted unequivocally in terms of source; both decarbonation products and deep seated carbon fall within this range. It is significant that at Escadia Grande, arsenopyrites have ^{34}S values heavier than the wallrock pyrites implying a deeper sulphur source. Depending on the lithology of the wallrocks, two distinct volatile patterns can be recognised. Schist-hosted deposits have relatively low CO_2 and high CH_4 and N_2 contents whereas granite-hosted deposits show the reverse relationship. Stochastic modelling of the data suggests that the observed variation can be explained by the reaction of an auriferous H_2O-CO_2 fluid with ammonium in the wallrocks at low fluid/rock ratios to produce a H_2O-CO_2-CH_4-N_2 fluid:

$$3CO_2 + 8NH_3 = 3CH_4 + 6H_2O + 4N_2$$

For the schists the reservoir is effectively infinite (>500ppm NH_4^+) whereas for granite, values are typical <50ppm, thereby leading to an excess of CO_2. Microthermometric data for the Central Iberian gold deposits demonstrate that mineral deposition was accompanied by substantial phase separation of the ore fluids during vein opening. Flashing of CO_2 or CH_4-N_2 into the vapour phase in response to fluid decompression carries with it H_2S, causing destabilization of metal bisulphide complexes and the precipitation of gold. At a given pressure and temperature the role of CH_4-N_2 is to widen the immiscibility field in the system H_2O-CO_2 and thereby increase the tendency for fluid unmixing (Naden and Shepherd, 1989). Thus phase separation provides another important link between granite- and schist-hosted deposits.

Perturbations to the regional illite crystallinity pattern caused by localised hydrothermal fluid-rock interactions were found to be too small to be confidently identified, and therefore of little practical exploration significance. This confirms a more general conclusion from the study that wallrock alteration haloes associated with the schist-hosted deposits are very narrow. Trace element lithogeochemical anomalies for example are restricted to within 0.5 m of the vein. However considerable success was achieved in applying evolved gas analysis techniques to the Escadia Grande deposit. Here, patterns related to the oxidation of organic carbon, precipitation of carbonate and variation in trace sulphide linked to the total fluid flux through the shear zone indicate detectable wallrock disturbance up to 10 m from the vein. Such an anomaly may be regarded as a good example of a 'hydrothermal fluid anomaly'.

From the geochronological studies, it can be shown that the schist-hosted Escadia Grande mineralization is 30-40Ma older than the main period of granite emplacement and associated Sn-W mineralization. This refutes the 'Sn-W-Au-granite' hypothesis and suggests that exploration for precious metal deposits in the Central Iberian Belt can be extended to include pre-granite structures far removed from outcropping younger granites.

Lithogeochemical studies in the Gois and Vila Pouca de Aguiar-Vila Real regions based on proven methodologies indicate that whole rock and selective mineral sampling provide unambiguous lithogeochemical signatures for schist- and granite-hosted Au-Ag and Sn-W deposits. For the larger datasets ($n>10$), various multivariate statistical analysis tests were carried out on the data to aid interpretation; for smaller datasets ($n < 10$), appropriate non-parametric tests were used. Results for the schist terrains show a clear geochemical and spatial distinction between samples associated with Au-Ag mineralization (characterised by high levels of Ag, As, Cd, Sb and Zn) and those with Sn-W mineralization (characterised by Be, P, Rb, and W). Such signatures are thus considered reliable guides to the delineation of mineralized areas. However, because of differences in styles of mineralization and extent of wall rock alteration (shear zone vs, granite cupola), sampling strategies need to be carefully optimised (density, pattern of samples etc.). Of the two, the larger hydrothermal anomaly associated with a mineralized, sub-surface, granite cupola constitutes the easier target. In granitic terrains, as illustrated by the Vila Pouca-Vila Real region, lithogeochemical studies appear capable of differentiating between types of granite-related mineralization. For example, for hydrothermal tungsten deposits the trace element signature imprinted on the granite is expressed as positive F, Zn, Zr and negative Li anomalies; for pegmatitic-pneumatolytic cassiterite-wolframite deposits as positive B, Li, Sn and negative Zn anomalies. Surprisingly, hydrothermal anomalies associated with auriferous quartz veins are not characterised by elements diagnostic of the ore assemblages (e.g. As, Ag, Bi) but by a redistribution of elements characteristic to the host granite. In the case of the Jales Au-Ag mineralization, the granite proximal to the veins displays positive Ba, Pb, Sr and negative F, P, Rb anomalies. The strength, extent and coherence of these anomalies, even allowing for the small number of samples collected, validate the use of lithogeochemical prospecting in the region. This is probably due in part to the higher fracture permeability and mechanical competancy of these rocks. Thus it would appear that lithogeochemical surveys, when supported by good geological control and proper statistical treatment of the data can be used in conjunction with conventional geochemical techniques in prospecting for Au-Ag and Sn-W deposits.

4. CONCLUSIONS

The project demonstrates that Au-Ag and Sn-W deposits in central and northern Portugal are accompanied by haloes of chemical and isotopic disturbance which generally extend beyond the limits of detectable metal enrichment, in accordance with the concept of hydrothermal fluid anomalies. The size and geometry of these haloes, as determined by combined geochemical, isotopic and fluid inclusion studies, vary according to the style of mineralization and lithology of the host rocks. Whole rock lithogeochemistry appears to provide the most promising regional exploration methodology for delineating mineralized areas, especially in granite terrains. This is probably due to the higher fracture permeability of these rocks which allows greater fluid circulation and hence the development of more intense geochemical disturbance. Where the terrain is dominated by metasediments of the Complexo Xisto-Grauvaquico, anomalies tend to be narrow and tightly confined to the ore deposit. An exception to this rule are the broader anomalies associated with Sn-W deposits spatially related to sub-surface granite cupolas. Integrated fluid inclusion-stable isotope studies are best suited to the evaluation of potential mineralized structures and quartz veins. For example, the presence of (CO_2-CH_4-N_2) rich fluid inclusions is considered a good indicator of auriferous quartz veins. The value of such studies however is in their contribution to the understanding of ore processes and in particular the mechanisms of ore deposition. This type of information is pertinent to the distribution of ore shoots and is therefore important for mine development and the assessment of on-strike and vertical extensions of ore zones.

On a wider perspective, the project has been successful in identifying many features common to both sediment- and granite-hosted Au-Ag metal deposits, and through stable isotope and fluid inclusion studies the importance of metasediments in ore genesis. Thus the development of a comprehensive model for Au-Ag mineralization in the granite-schist terrains of central and northern Portugal provides a simplified and better model for exploration. Since these terrains are typical of the Central Iberian Geotectonic Belt, the concepts rationale and methodologies may be transposed and applied to other areas in Portugal and Spain.

By necessity, the investigations were exploratory in nature and have revealed new directions which now deserve further study. The most important of these is the need for an integrated geochemical-structural approach to mineralization.

This recommendation is strongly supported by the results of a structural analysis of gold mineralization in the La Codosera area, Spain (Contract n° MA1M-0032-C, this volume). By combining both methodologies, this would allow better definition of mineralized structures and facilitate interpretation of lithogeochemical anomalies.

PUBLICATIONS AND ORAL PRESENTATIONS

Castro Reis M.L., 1990: ILLITE CRYSTALLINITY; PROBLEMS IN THE SELECTION OF MATERIAL TO BE MEASURED. Conference abstract 'Phyllosilicates as indicators of very low grade metamorphism and diagenesis', University of Manchester, July, 1990.

Castro Reis M.L., and Machado M.J., 1991: DETERMINATION OF THE GRAPHITIZATION DEGREE OF THE CARBONACEOUS MATERIAL IN SCHISTS BY XRD. SOME ASPECTS OF THE INORGANIC MATRIX ELIMINATION. Submitted to Chemical Geology.

Naden J., and Shepherd T.J., 1989: THE ROLE OF METHANE AND CARBON DIOXIDE IN GOLD DEPOSITION. Nature, 342, 793-795.

Naden J., and Shepherd T.J., 1991: FLUID INCLUSION VOLATILES AND GOLD MINERALIZATION IN CENTRAL IBERIAN GRANITE AND SCHIST TERRAINS. Conference Abstract 'ECROFI XI-European current research on fluid inclusions' Firenze, April, 1991. Plinius, n° 5, 157.

Santos Oliveira J.M., 1990: THE ROLE OF THE LITHOGEOCHEMISTRY IN THE DELINEATION OF AU AND SN-W MINERALIZATION IN SCHIST TERRAINS OF THE GOIS REGION, CENTRAL PORTUGAL, Oral presentation, Symposium of Geochemistry, Lisbon, December 1990.

Shepherd T.J. and Spiro B., 1989: FLUID INCLUSION, MINERALOGICAL AND ISOTOPE STUDIES OF GOLD MINERALIZATION IN CENTRAL AND NORTHERN PORTUGAL. Oral presentation, CEC Contact Group Meeting, Paris, France, November 1989.

Shepherd T.J. and Santos Oliveira J.M., 1989: FLUID RELATED CHARACTERISTICS OF A BLACK SHALE-HOSTED VEIN-TYPE GOLD DEPOSIT, ESCADIA GRANDE, PORTUGAL. Poster Presentation at 'Gold 89 in Europe', Symposium International en Europe sur la métallogénie, l'exploration et la valorisation de l'or, Université Paul Sabatier, Toulouse, May 1989.

Simoes M., 1991: CONTRIBUTION TO THE PETROLOGICAL AND GEOCHEMICAL STUDY OF THE TRES MINAS GOLD REGION. Oral Presentation, 3rd Brasilian Congress, Sao Paulo 1991.

Simoes M., and Darbyshire D.P.F., 1991: PETROLOGICAL, GEOCHEMICAL AND GEOCHRONOLOGICAL STUDY OF HERCYNIAN GRANITES AND ASSOCIATED MINERALIZATION IN THE VILA POUCA AGUIAR-JALES REGION, NORTHERN PORTUGAL. Oral presentation, 3rd Brasilian Congress, Sao Paulo 1991.

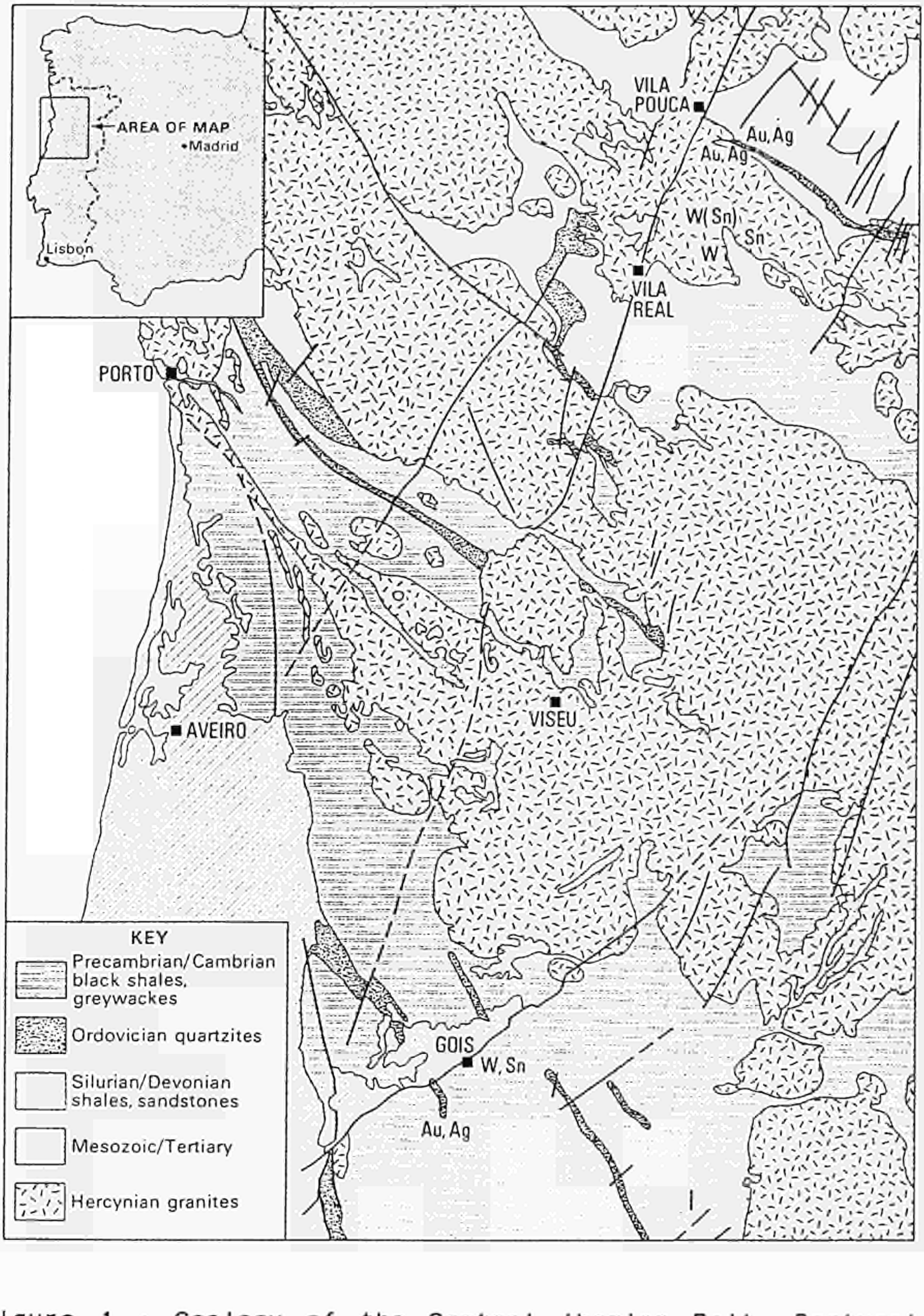


Figure 1 : Geology of the Central Iberian Belt, Portugal showing location of the study areas and principal mineral deposits (1:500,000).

HYDROTHERMAL FLUID ANOMALIES: A NEW STRATEGY FOR GEOCHEMICAL EXPLORATION IN PORTUGAL

Project Leader: J.M.SANTOS OLIVEIRA
Direcçao-Geral de Geologia et Minas (DGGM), Lisbon, Portugal

Contract MA1M-0028-P

1. OBJECTIVES AND INTRODUCTION

This study was part of a 3 year joint project between DGGM and the British Geological Survey (BGS), which was financed by the CEC (contracts MA1M-0027-UK and 0028-P) to develop new exploration strategies for Au and Sn-W deposits. The research has been carried out in some mining districts of Portugal. The methodology for such studies was based on the recognition of hydrothermal fluid anomalies (geochemical, isotopic and mineralogical disturbances in the ores and in the rocks in their vicinity) caused by ore fluid-rock interaction which, as expected, could be used as guides in mineral prospecting.

The principal tasks of this research fell upon the BGS group, taking into account its recognized scientific, technical and technological capabilities to undertake studies on some particular topics that were considered essential to the understanding of this sort of geological and mining problems.

DGGM contributed to this project with i) Geological and structural mapping of previously selected mining areas and one mine; ii) Petrographic studies; iii) Ore mineralogy studies; iv) Chemical analyses; v) Specific mineralogical studies; and vi) Some lithogeochemical studies. The Serviço de Fomento Mineiro (SFM-DGGM) undertook the tasks indicated in i) and the Laboratory (LDGGM) the tasks described in ii), iii), iv), v) and vi).

All these studies carried out by the DGGM tried to converge for the overall goal which aimed to establish new methodologies for the geochemical exploration of sub-surface mineral deposits of gold and tin-tungsten. For this purpose, ore deposits occurring in the following contrasting geological environments of Portugal were selected for study: a) schist-hosted gold and tin-tungsten vein type deposits with no evident link with granite magmatism and b) intragranitic tin-tungsten deposits and gold-silver vein type deposits occurring within or around the margins of granite cupolas.

This report presents the work carried out specifically by DGGM. It adds details to the preceeding article of this volume, which summarizes and draws major conclusions of the work of both organizations involved in the project.

2. MATERIALS AND METHODS

2.1 STUDIED AREAS

Regarding this research two distinct regions of Portugal with mining significance were considered for study: the Gois region, in the centre of the country and the Vila Pouca de Aguiar- Vila Real region, in the north. Geologically, both are included in the geotectonic zone of the Iberian Meseta called Central Iberian Zone (see Fig. 1).

The mining district of Gois, which includes the Escadia Grande Mine (Au) and the Vale de Pião Mine (Sn-W), is located in the tin-tungsten sector of the Central Iberian Zone and close to its boundaries with another geotectonic zone, the Ossa-Morena Zone. The contact between these two zones is a major lineament with shearing (Fig. 2).

The regional geology is actually poorly known in detail due in part to some access difficulties (this region is greatly rugged and badly served by roads). The lithology is dominated by monotonous sequences of metasedimentary rocks of the flyschoid type included in the so-called "Complexo Xisto-Grauváquico" (CXQ), of Cambrian to Infracambrian age, which are mainly formed by series of black phyllites, siltstones, mudstones and greywackes. These lithological units display low grade regional metamorphism in the chlorite zone and, in places, there are evidences of contact metamorphism (occurrence of spotted schists). The stratification, which frequently appears coincident with the schistosity planes, shows a general WNW-ESE strike strongly dipping to NNE (70-80°).

The mining region of Vila Pouca de Aguiar - Vila Real which includes as main ore occurrences with economical importance the gold mine Jales and the tungsten mine of Vale das Gatas, is part of the Hercynian nucleus of the Iberian Peninsula. It is mainly occupied by granites that are in contact on the northeast, west and south with metasediments of the Complexo Xisto-Grauváquico (CXQ), also named Beira Schists (Fig. 3).

According to Brink (1960) the metasedimentary rocks are mainly pelitic and psammitic schists, chloritic and sericitic, affected by metamorphism developed in two stages. However, this region contains in great extent Hercynian granitoids distributed in two main groups: "older" granites, which are rocks with higher contents of SiO_2, Al_2O_3 and even K_2O and "younger" granites, which are rocks enriched in FeO, CaO, MgO and TiO_2. The first are classified as albite two-mica granites and the latter as porphyritic biotite granites. These granite types can be assigned to mesocrustal granites of the S-type and to deeper crustal granites of "mixed" origin respectively, according to modern geotectonic systems of granitoid classification.

In places, some tourmalinic greisens and muscovite granites resulted from metasomatic alterations of the two-mica granites, presumably caused by the intrusion of the later porphyritic biotite granites.

An extensive NNE-SSW fault system, which was developed during the Hercynian and repeatedly became active during a long period of time, affected the geological formations of the study area.

2.2 MATERIALS, METHODS AND TASKS

The studies and works under the responsibility of the DGGM took place in the following mining areas of Portugal:

-	Escadia Grande area (gold)	Gois region
-	Vale de Pião area (tin-tungsten)	
-	Três Minas area (gold)	Vila Pouca de Aguiar-Vila Real region
-	Jales area (gold)	

Having in mind to attain a better understanding of the geochemical-metallogenetical processes that took place in these regions, some geological and structural studies were carried out by the SFM-DGGM. In the Escadia Grande area the surface geological mapping in the proximity of the mine and the mapping of two underground levels, on the 1:2,000 and 1:100 scales, respectively, were carried out (Carvalho, 1988; 1988a). Relatively to the Vale de Pião Mine a number of geological and mining data were extracted from another mining study previously undertaken by the SFM-DGGM on a 1:500 scale which was not, however, integrated in this project (Parra, 1988). The Três Minas area was also mapped on the 1:2,000 scale, with particular emphasis on the lithologic sequence (Farinha, 1990).

Moreover, specific rock sampling was carried out by SFM-DGGM geologists and other skilled technicians, either inside the mines or in their surrounding terrains.

In the LDGGM, tasks related to rock grinding, preparation of thin sections and ore polished sections for microscopic investigation, specific mineralogical and crystallographic studies of schists, and chemical analyses of rocks, were undertaken. Also in this DGGM department, the lithogeochemical interpretation of the analytical data previously obtained in schist and granite terrains (Gois and Vila Pouca de Aguiar-Vila Real regions, respectively) was attempted aiming to contribute to the definition of possible lithogeochemical guides useful in further mineral prospecting.

In the course of the project the following materials were studied and analysed in the DGGM laboratory:

- Mineralogical study of 170 polished sections on 60 ore samples,
- Petrographic study of 110 samples and 260 thin sections of rocks,
- X-ray diffraction study of 80 rock (schist) samples,
- Preparation (grinding) of 400 rock and ore samples for different types of analyses,
- Chemical analysis (major elements) and multielement geochemical analysis of 40 rocks,
- Multielement geochemical analysis (XRF, AA, DCP) of 300 samples of rocks and minerals in a total of some 7,500 chemical determinations.

It must be here underlined the investigation followed in the LDGGM aiming to develop new analytical methods for application in the project. In particular, the following X-ray diffraction techniques on schistous rocks were studied: i) characterization of the occuring phyllosilicates, with determination of the degree of crystallinity of the illite and ii) determination of the graphitization and amount of the carbonaceous material with particular emphasis to the determination of the degree of crystallinity of the graphite (Castro Reis, 1990). These data (particularly requested by the BGS) were aimed at contributing to the interpretation of some geological problems, such as, those related to the metamorphism (low grade) imprinted in the schists.

Some methods of chemical analysis were also investigated in the LDGGM, aiming to guarantee an appropriate analytical support to the project needs: i) Analysis of the major elements in rocks by X-ray fluorescence spectrometry (XRF); and ii) Analysis of a number of selected trace elements in silicate minerals (namely micas) by conductive plasma emission spectrometry (DCP).

The XRF method looks for the determination of Si, Al, Fe, Na, K, Mg, Ca, Ti, P and Mn. The analysis uses a fused bead with metaborate and tetraborate of Li, B_2O_3 and iodine, using as main conditions the alpha correction, variable voltage and suitable crystals according to the elements to be determined.

The Plasma Emission Spectrometry (DCP) was applied to the selective chemical analysis of muscovites. The first step of this study concerned the choice of the most suitable type of chemical attack to be employed in this particular case, taking into account the "refractory" conditions of the micaceous minerals and some problems related to guarantee the accuracy and precision for some "difficult" elements, such as Sn, Nb and B. For example, problems related to sample fusion or unsuitable chemical attack can strongly restrict this analytical method for 22 trace chemical elements on muscovite samples previously grinded at about minus 400 mesh.

In support to the data treatment a number of current computerized (statistical-mathematical) techniques were utilized. Following mainly procedures described by Davis (1973), particular attention was given to some univariate and multivariate techniques such as statistical distribution, tests of significance, element correlations, principal component and discriminant analysis.

3. ANALYSIS OF RESULTS

The main results obtained by DGGM in this project are here presented.

3.1 GEOLOGY

Geological and structural mapping using detailed scales of work was carried out in the auriferous target areas of Escadia Grande and Três Minas.

3.1.1 Escadia Grande Area (from Carvalho, 1988, 1988a)

The mapped area is referred to the CXG formations and is located 1 km to the south of a quartzitic ridge (Silurian) that is placed over flyschoid metasediments. In this area, blocks separated by two dominant systems of fractures (with NNW-SSE and ENE-WSW orientation) were mapped, which put into contact greywacke with schistous lithologies (Fig. 4). Three lithologically well differentiated areas, clearly conditioned by the referred fault systems, were mapped on a local scale :

- a greywacke sector with these rocks interbedded with black and graphitic schists, frequently of siliceous character (these formations mostly contain the gold mineralization);

- an alternating grey greywacke - dark schist sequence occuring to the NW and SE of the former;

- a brown psammitic schist sector with rare intercalations of greywackes, occuring on the west and north zones of the studied area.

The structural control of the mineralization is evident but some control of lithologic type also appears to occur (determinated by the preferential presence of the greywackes as host rock for the mineralization).

The studies developed on a mining scale showed that the mineralization occurs into quartz veins which belong to a multistage set of structures occuring in the area, being constituted mainly by gold + sulphides (arsenopyrite, pyrite, galena, blende and scarce chalcopyrite). It was also concluded that a NW-SE, 45° SW reverse fault (originated by the late compression of the mentioned blocks) controlled the ore deposition, this fracture being used by the hydrothermal fluid circulation. The gold mineralization was deposited in the last stages of that process and it occurs together with some silicification and pyritization which developed in the wallrock. These alterations, however, are only visible to a short distance of the veins.

3.1.2 <u>Três Minas Deposit</u> (from Farinha, 1990)

This area, located 3 kms to the NE of the Jales Mine is geologically covered by Silurian metasedimentary terrains, some of which contain low grade gold mineralization.

The mapping of this area at a 1:2,000 scale (reduced to 1:5,000 scale) outlined the following lithostratigraphic sequence with unknown polarity: black schists (very graphitic) - chloritic schists with sericite and muscovite (this formations generally contains the Au and Ag mineralization) - greyish and brownish schists - strong oxidized greenish schists. Gold mineralization is preferentially concentrated within compact lenses of quartzite and schistoid quartzite or near their contacts, suggesting the possible existence of a paleoplacer (?). It is admitted that mobilization of gold could take place during the subsequent tectonic phases in the area, with ore recrystallization in high silicified schists near shear zones.

3.2 <u>MINERALOGY</u>

3.2.1 <u>Petrography of the granitoids of the Jales area</u> (from Simões, 1989)

The petrography of the regional granitoids of the Jales area together with the petrography of mine granite samples (collected in the 12th and 14th levels) was carried out by the LDGGM in support to the geochronological studies undertaken by the BGS.

In regional terms, the studied granitoids were divided in two groups: a porphyritic biotite granite and a two-mica granite.

The porphyritic biotite granite was described as a rock constituted by microcline, plagioclase, quartz and biotite. The accessory minerals are muscovite, apatite, zircon, alanite, sphene, fluorite, epidote and opaque minerals.

Various alterations of the primary minerals are common: kaolinization (after the microcline); sericitization and saussuritization (after the plagioclase); and chloritization and baueritization (after the biotite).

The two mica granite is essentially constituted by microcline, plagioclase (principally of the albite type), quartz, muscovite and biotite. As accessory minerals, the presence of apatite, zircon, tourmaline, fluorite and opaque minerals is common. Processes of kaolinization and sericitization of the feldspars and of cholorltization of the biotite are visible with more or less intensity as well as the formation, in places, of calcite.

A number of samples of the Jales gold mine granite collected in the contact zone with the mineralization and nearby of the mineralized structures were also studied. This petrographic study revealed the presence of a two mica granite, which is clearly more muscovitic towards the mineralized veins. Some samples contain tourmaline, particularly in the zone of influence of the aplite-pegmatite veins. The hydrothermal alteration (for example, shown by the disappearance of the biotite) and aspects of strong microfracturation are evident in these granites which express the action of the ore fluids and the existence of channels for their circulation.

After granite emplacement and subsequent crystallization of the pegmatite-aplite stage processes of fracturation and alteration occured in these rocks.

From the petrographic study undertaken, it can be said that this rock within the mining environment of Jales is mostly a <u>metasomatic granite</u>.

3.2.2 <u>Petrography of Três Minas drillcores</u> (from Simões, 1989)

The TM6 drillcore, which was obtained from previous drilling in the Três Minas deposit, was studied between 50 and 166 metres.

During the first 15 metres (to 65 metres) a black graphitic schist showing crenulation, microfolding, microfaults, some brecciated aspects and "boudinage" occurs. The graphite distribution follows the microfolds.

From 77 to 114 metres a quartz sericitic and a quartz sericitic chloritic schist with phyllitic zones including some pelitic microquartzitic pockets were observed. Volcanic textural aspects seem to occur, although they are not too conclusive. The sulphide mineralization is more significant in this zone (pyrite, chalcopyrite, sphalerite, arsenopyrite, pyrrhotite, etc.), being visible in the quartz veins that cut the schist and in the schist itself.

Some silicified "clasts" (or macrocrystal relics ?) occur, the sulphides being probably related to this silicification. These sulphides are free of gold.

From the depth of 120 to 129 metres a garnet-bearing graphitic schist occurs again. Till the final depth of the drillcore a quartz sericitic and a quartz sericitic chlorite schist with the same metavolcanic (?) aspects dominate, in which the existence of metamorphosed tuffs is supposed to occur.

3.2.3 Ore Mineralogy of the Jales mine (from Gaspar, 1989)

This study was carried out to give support to the fluid inclusion and isotopic investigation undertaken by the BGS. Broadly speaking, it was aimed to establish the paragenetic and geochronological relationships between the different quartz types and their links to the gold mineralization. The macroscopic and microscopic studies of a number of vein samples collected in some levels of the mine revealed the existence of six different quartz types.

Although the ore paragenesis has been studied by some former authors (Brink, 1960; Neiva, 1986; Ramos, 1983) this topic was also studied here in some detail having in mind the specific objectives of this project. The microscopic study showed the presence of quartz as gangue and a number of ore minerals; arsenopyrite, pyrite, sphalerite galena and chalcopyrite, the first two being largely predominant. The most frequent accessory minerals are gold (mainly in the form of electrum), fahlores, pearceite, marcassite, magnetite, hematite, pyrrhotite and, less frequently, ferberite and scheelite. Among the ordinary supergene minerals common in this type of deposits, the presence of argentite, covellite, cerussite and of some generations of carbonates must be mentioned.

Gold occurs in the following forms: included in the arsenopyrite and pyrite; in veinlets cutting those minerals, particularly associated with galena and sometimes with chalcopyrite and pyrite; in interstitial positions in arsenopyrite and pyrite crystals originating from partial replacements; and finally in rare inclusions within the quartz. From these, the most frequent occurrence of gold is associated with galena. The paragenesis of the Jales ore suggests that the greatest quantity of gold is connected with silver when it occurs with the last generation of galena. It is referred elsewhere (Ramos, 1983) that Hg occurs in the electrum (up to 3.6%) but the analyses may be not representative enough.

Significant hydrothermal alteration associated to the mineralization was observed. For example, the alteration of the biotite, the formation of a new generation of muscovite and aspects of sericitization and chloritization are visible in the granites, while some tourmalinization and the alteration of the biotite (with formation of rutile) are common in the enclosing schists. The presence of talc was noticed sporadically, probably originating from dolomitic carbonates that occur interstitially in the sulphides.

The investigation regarding the chronology of the different quartz generations led to the establishment of five stages of depositon of this mineral during the process of mineralization. The major part of the silica, which is related to the mineralization seems to result mainly from the solubilization of the milky white quartz that crystallized during the first stage of the process.

It is assumed that shearing and variations in the hydraulic pressure of the mineralizing fluids are greatly responsible for the textures imprinted in the veins of the Jales Mine. The mineralization itself seems to follow preferentially the orientation of microfissures which are parallel to the vein walls, and were open during the distensive phases of the process.

3.2.4 Mineralogical studies of schists by XRD (from Castro Reis, 1990)

Aiming to contribute to the study of the low grade metamorphism in schists, some XRD techniques were investigated and subsequently applied to the Gois schistous rocks. The degree of crystallinity of illite (Kübler index) and the amount of carbonaceous matter and its degree of graphitization were determined, as well as the mineralogical composition of the samples and their total silicon contents.

The schist samples are mainly constituted by mica, quartz and chlorite. Kaolinite and, probably, halloysite and smectite are also observed (it was noted that these phyllosilicates may affect the index of illite crystallinity). As accessory minerals, the presence of titanium oxides (rutile), tourmaline, zircon, sphene, garnets and sulphides (pyrite, pyrrhotite and arsenopyrite) may be mentioned. The muscovites are of the phengitic type (silicium-rich). The following polytypes were observed in the micaceous minerals: 2M1 in muscovite; IIb in chlorite; 2M1 in illite.

All the studied samples show values for the illite crystallinity between 0.25° (2t) and 0.42° (2t) which may assign those schists to the anchizone, although some values falling in the limits of the anchizone-epizone and anchizone-diagenesis are also found. Higher crystallinity values correspond to schists with more magnesian chlorites.

Values ranging between 0.7 and 0.9 for the degree of graphitization were determined, which are particularly evident in the more silicified rocks.

From these combined mineralogical-chemical studies it seems that Fe^{2+}, and sulphides are positively correlated with the carbonaceous material contents of the schists. Samples richer in Fe^{3+} are more micaceous.

3.3 LITHOGEOCHEMISTRY

3.3.1 Lithogeochemical studies in schists of the Gois region

A number of metasedimentary rocks from the Gois region, which had been previously collected by the BGS staff, were analysed in the LDGGM for 26 chemical trace and minor elements. Iron, P, Cu, Cr, Ag, B, Zn, Sb, Pb, Ni, V, Mn, Be, Mo, As, Co and Cd were determined by emission plasma spectrometry; and W, Sn, Nb, Ta, Sr, Ba, Rb, Y and Zr by X-ray fluorescence, with analytical precision better than 5%. Ammonium (NH_4) determinations, which were carried out in the BGS laboratories, were also included in the data interpretation. All the elements analysed appear to be lognormally or normally distributed.

The element contents found in the metasedimentary rocks were grouped in a) Escadia Grande and b) Vale de Pião samples each group being splitted according to the two major occuring lithologies - black schists and mudstones - and also grouped in "regional" and "mine" samples. The black schists are of graphitic character, more or less silicified and contain sulphides and iron oxides, while the mudstones are very low metamorphosed metasedimentary rocks showing silty pattern and, in some cases, also containing sulphides and iron oxides.

On a first approach three distinct groups of elements can be selected to assist in the interpretation: i) "lithotype" elements which can show a certain geochemical preference for one of the two analysed lithologies; ii) ore indicator elements, which apparently show geochemical anomalies (positive or negative) in the mineralized zones; and iii) pathfinder elements, which can be probably used to delineate one particular type of mineralization.

From this investigation it appears that Cu, Sr, B and Rb are slightly enriched in the schists while Ba, Zn and V seem to be more concentrated in the mudstone rocks. Antimony, Ag and Cd show significant enrichments in the Escadia Grande samples, the black schists being the preferential concentrator rocks particularly for the two latter, while W, P and Be are enriched in the Vale de Pião area. Other elements, like Co, Mn, Zn, Cd, As, Sr, NH_4 and Ni seem to be enriched in the mine zones but Rb, Cu and Ba exhibit some impoverishment in these places. It is emphasized the behaviour of NH_4, which is supposed to be associated with gold mineralization by replacement of potassium ions in certain aluminosilicates, particularly in zones of fracturation (Appleton et al., 1989).

Some multivariate mathematical analysis applied to the data has confirmed that a number of geochemical differences appear between the samples of the two closely spaced mining areas. Although a relatively high number of mathematical factors is obtained from R-mode factor analysis in both cases, which reveal some complexity in the data distribution, some of those factors can be clearly assigned to specific geological conditions and processes of mineralization. In the Escadia Grande area, a metalogenetic factor characterized by the association Ag-Sb-Zn-As-NH_4-Cd emerges which is related to the style of mineralization. In the Vale de Pião area, another different factor of metalogenetic importance was extracted: the B-Be-Rb-W-As association, probably related to the presence of a granite intrusion beneath the mineralization occuring there.

The somewhat aleatory sampling, low number of samples analysed and criteria of rock classifiction (mainly macroscopic observation) advise some caution in the data interpretation. However, in spite of these limitations, some groups of elements were emphasized which reflect the existence of hydrothermal activity in the Gois area and can differenciate particular styles (and episodes) of mineralization. It appears from this lithogeochemical study that gold and tin-tungsten mineralizations in the Gois area display different geochemical signatures. According to Shepherd et al. (1985) on a study undertaken in England, the fluid evolution may be characterized by a succession of immiscibility events, each one having imprinted its own style of mineralization.

In terms of regional lithogeochemistry for Au-Ag and Sn-W deposits aiming to the selection of targets for further prospection programmes, elements like Co, Ni, Zn, Cd, W, NH_4, P, Sb, As, Ag, Mn and Sn must be analysed. Many of these are also mentioned by other authors (for example, Clarke and Govett, 1990; Govett et al., 1984; Trudel et al., 1989; Newall and Newall, 1989). The distribution of elements that can produce negative anomalies in mineralized areas (Rb, Ba, Cu, B) should also be considered. The lithogeochemistry on a local scale, which can contribute to the definition of the styles of the mineralizing hydrothermal systems, must be supported by the study (with priority) of some pathfinder elements.

From the obtained results it appears that the following classification is admissible:

I) "Lithotype" elements

Ba, Zn, Ni, V - enriched in the mudstone rocks
Cu, Sr, B, Rb - enriched in the black schists

II) Ore indicator elements

Co, Ni, Zn, Cd, W, Sr, NH_4 - enriched in the mineralized zones
P - enriched only in the Vale de Pião area
Sb, As, Ag - enriched only in the Escadia Grande area
Mn, Sn - enriched in both mineralized zones but only in the mudstones
Rb, Ba, Cu, (B), (Y) - impoverished in the mineralized zones

III) Pathfinder elements

Sb, Ag, Zn, Cd, (NH_4) - possibly delineate the Sn-W mineralization of the Vale de Pião Mine

Table 1 furnishes provisional values for a number of selected elements which must be taken into account in further lithogeochemical prospection studies.

Table 1

Provisional anomalous and background values (in ppm) for some pathfinder elements in schists and mudstones surrounding the Escadia Grande and Vale de Piao Mines

ELEMENTS	ORE TYPE	E. GRANDE MINE		V. P. MINE	
		BACK. N=11	ANOM. N=42	BACK. N=10	ANOM. N=18
Ag	Au	0.12	0.63		
Cd	"	0.50	1.00		
Sb	"	10.00	93.79		
Zn	"	72.55	191.81		
Be	Sn-W			2.60	3.44
Rb	"			222.50	175.83
W	"			5.10	5.17
P	"			263.80	775.50

3.3.2 Lithogeochemical studies in granites of the V.P. Aguiar-Vila Real region

Some 100 granite samples were regionally collected over the Vila Pouca de Aguiar-Vila Real region (see fig. 3), following criteria of sample representativity and quality similar to those described by Smales and Wager (1960). The techniques of chemical analysis (plus AA for Li and pyrolysis for F) and data interpretation were the same as those referred in 3.3.1.

From the 25 trace element analyses it appears that only a restricted group provides the distinction between barren and geochemically specialized granites. A number of significant lithogeochemical aureoles were delineated which may be assigned to the different styles of minerlization present over this mining region. So, the gold-silver Jales deposit is characterized by positive Sr, Ba, Mn and Pb anomalies and F, Rb and P negative anomalies. Tin pegmatites occuring to the north of Jales are reflected by clear and extensive positive Sn, Li and B anomalies in the contact granites with the surrounding slates. The tungsten Vale das Gatas deposit, in the south, is defined by northeast-southwest positive aureoles of Ba, F, Zn and Pb and negative Li anomalies. Another type of tungsten and tin mineralization, occuring in the area which is more associated with greisenized and metasomatized muscovitic granites and with quartz stockworks, is well delineated by significant positive Sn, B and Mn anomalies and negative Ba anomalies in the granites.

Table 2 shows the most significant variations found in trace element contents for specialized and barren (regional) granites.

Table 2

Geochemical comparison between regional and specialized two mica granites (Values in ppm)

	REGIONAL GRANITE (N=32)		JALES GRANITE Au-Ag veins (N=10)		FILHAGOSA GRANITE Sn pegmatites (N=10)		JUSTES GRANITE W greisens (N=4)		V.MAÇADA GRANITE Sn greisen;veins (N=8)		V. GATAS GRANITE W veins (N=4)	
	Barren		Au Mineraliz.		Sn Mineraliz.		W(Sn) Mineraliz.		Sn(W) Mineraliz.		W Mineraliz.	
ELEMENTS	MEAN	ST. DEV.	MEAN	ST. DEV.	MEAN	ST. DEV.	MEAN	ST. DEV.	MEAN	ST. DEV.	MEAN	ST. DEV.
Ba	227.39	57.82	338.20	54.71	208.10	82.67	167.75	38.40	223.63	50.62	323.50	72.55
P	1460.75	367.43	1065.50	59.61	1285.00	135.22	1642.75	265.31	1164.36	232.41	664.50	339.51
Cu	5.78	2.64	5.00	0.00	5.00	0.00	6.75	3.50	5.63	1.65	9.00	2.35
Ag	0.12	0.04	0.11	0.03	0.11	0.03	0.25	0.21	0.14	0.07	0.10	0.00
B	24.06	6.51	21.50	5.26	39.50	19.65	53.75	21.15	27.75	5.76	25.25	7.02
Zn	67.25	20.66	50.40	6.86	46.20	10.86	60.75	23.96	49.25	13.02	102.50	11.67
Sb	10.00	0.00	10.00	0.00	10.00	0.00	10.00	0.00	10.00	0.00	10.00	0.00
Pb	28.53	4.67	38.40	5.77	28.20	13.42	28.50	8.20	25.66	9.70	30.50	4.03
Sn	12.41	5.38	10.90	3.08	28.50	12.77	28.00	7.52	24.13	9.76	5.50	4.09
Ni	6.66	2.83	6.10	2.21	6.50	2.29	5.00	0.00	6.25	2.17	6.25	2.17
V	9.19	3.52	11.30	3.72	6.50	2.98	7.25	3.50	8.13	2.42	18.25	2.34
Mn	180.41	46.56	221.50	30.55	243.00	63.92	234.00	51.41	220.38	61.07	175.75	22.54
Be	5.88	2.07	7.40	1.02	7.40	1.91	6.50	1.80	7.63	1.65	4.25	1.09
Mo	1.97	0.81	1.80	0.60	1.90	0.70	1.75	0.83	2.25	0.66	1.75	0.43
As	10.58	3.13	10.00	0.00	10.00	0.00	71.25	106.09	10.00	0.00	10.00	0.00
W	3.97	5.34	2.00	0.00	3.00	3.00	2.00	0.00	2.38	0.99	2.00	0.00
Co	5.88	2.41	5.00	0.00	5.00	0.00	5.00	0.00	5.63	1.65	5.00	0.00
Y	21.34	3.43	22.20	2.14	22.20	2.27	22.75	2.28	20.88	2.37	21.50	2.60
Cd	0.56	0.17	0.55	0.15	0.55	0.15	0.50	0.00	0.50	0.00	0.50	0.00
Nb	17.75	3.01	14.50	1.26	19.00	3.00	17.25	0.83	21.88	1.50	13.00	2.35
F	2520.00	485.43	2006.00	217.75	1275.00	356.82	1755.00	407.09	2247.50	313.73	1701.25	154.51
Li	[illegible]	[illegible]	227.70	61.28	375.40	129.57	206.25	71.04	265.38	56.53	58.50	16.47
Rb	[illegible]	[illegible]	360.50	[illegible]	423.00	36.41	474.00	10.82	464.50	65.03	438.50	[illegible]
Sr	44.75	[illegible]	[illegible]	29.44	45.50	30.35	20.50	6.34	41.13	25.73	71.50	14.72
Zr	[illegible]	[illegible]	[illegible]	13.81	79.70	[illegible]	81.50	44.27	88.00	30.33	156.25	[illegible]

The gold-silver veins of the Jales mine have been recognized in the underground works for a distance of nearly 2 kilometres. However, the extension of some (positive or negative) lithogeochemical anomalies on the surface, particularly for Sr, Ba, F, Rb, Mn, P and Li, along the SSW major fault inferred and supposed to be related to the mineralized structure of Jales by Neiva (1986), as it may be seen in fig. 3, gains relevant importance in terms of mineral prospecting. So, the extension of the mineralization in this direction seems to be possible.

This sort of anomalies related to mineralized hydrothermal systems must be, however, carefully distinguished from others of lithologic character which purely reflect variations in the mineralogical and chemical composition of the granitoid rocks.

The geochemistry of the metasomatized two mica granite of the Jales mine, using a sampling traverse between the two main gold lodes (Campo and Desvio veins), also showed interesting patterns on a mining scale of work. Some analyses of their muscovites and biotites, by means of electron microprobe, expressed some variations in their chemical composition which are mainly due to the fluid circulation that strongly metasomatized the rock near the veins. Enrichments in SiO_2 (muscovites), TiO_2, MgO (biotites) and FeO (biotites) and impoverishments in Na_2O (biotites), K_2O (biotites), MnO (biotites) occur in the contact zone with the ore veins. It is also stressed the behaviour of F, an element significantly impoverished in both minerals.

Meanwhile, some analyses of the metasomatized granite of the mine (whole rock analyses) showed that all the above mentioned pathfinder elements apparently exhibit the same geochemical patterns emphasized in the regional lithogeochemistry. To those elements, Ag must be added in local geochemical studies, as far as it also reveals significant increase near the mineralization.

4. CONCLUSIONS

The participation of the DGGM in this research project was focused, in great extent, on a number of scientific studies - geological, mining, mineralogical, petrographical, analytical - in support to the metallogenetical investigation coordinated by the second partner (BGS). This mainly concerns problems related to the origin, migration and deposition of gold from the hydrothermal solutions, as well as to the definition of signatures of these processes in the surrounding rocks and mineralized systems. At the same time, the DGGM developed some classic lithogeochemical investigations with the same overall objectives, namely aiming to define geochemical parameters and/or guides with application in mineral prospection, taking into account the responsabilities and duties of the DGGM in this country.

A number of conclusions resulted from the studies carried out by the DGGM in two main mining regions of Portugal. They can be emphasized in the following items:

- In terms of mining geology, the studied gold mineralizations are associated with hydrothermal systems of siliceous character, though the possibilities of the occurence of gold (in the Três Minas deposit) related to ancient sedimenary processes (paleoplacers?) cannot be rejected at the present stage of our scientific knowledge.

- The episodes that originated the epigenetic Au-Ag and Sn-W mineralization show some genetic, chronological and spatial independance.

- The structural control of the hydrothermal auriferous mineralization is evident, the fractures being used as channels for the ore fluid circulation.

- The lithogeochemical methods, when applied wisely and supported by suitable statistical-mathematical methods, can contribute positively to the delineation of anomalous areas which, in turn, may indicate the existence of auriferous and tin-tungsten mineralization. This methodology can be used, either on the regional scale, or on the local and mining scales of work.

- The application of the lithogeochemistry to ore prospection in schistous shear terrains (particularly by sampling black schists) seems to give good results in the distinction of Au-Ag mineralized areas (which are mainly anomalous in Sb, Zn, Ag and Cd) from Sn-W areas (enriched in W, Be, Rb and P). This geochemical multielement approach can provide positive information when the analysis of gold is not possible or when the sampling density is lower (Clarke and others, 1990).

- In granitic terrains, distinct groups of trace elements also appear to be useful for the definition of different styles of mineralization. Elements like Ba, Sr, Mn and Pb (positive anomalies) and F, Rb and P (negative anomalies) delineate gold-silver mineralization; Zn, Pb, P and Ba (positive anomalies) and Li (negative anomalies) characterize hydrothermal wolframite mineralization; Sn, Li, and B appear to define areas where pegmatitic-pneumatolytic cassiterite-wolframite mineralization occurs.

- The important gold-silver deposit of Jales is delineated by extensive anomalies with WNW-ESE and NE-SW axis (related to the fracturation) suggesting that the prospection outside the actual limits of the mine should be developed. An area extending for some three kilometres to the SW of the mineralized structure of the Jales Mine is considered as potential.

These promising results, particularly when analysed together with those obtained by the BGS, show that the lithogeochemical methods can furnish a good contribution for the establishment of useful geochemical guides with application in the exploration of gold-tin-tungsten buried mineralization.

5. ADDITIONAL COMMENTS

To some extent this investigation constituted a pilot project whose overall objectives are closely related to the research on the gold (tin-tungsten) mineralizations of Portugal. It was taken into account the importance of this country as a raw materials producer, particularly when put in the perspective of the development strategies of the European Community.

This research being a first appraisal of a problem that presents strong economical implications, it is thought that it must continue in other areas of Portugal (and even in Spain) trying to improve the scientific knowledge on the mineral resources of these countries, as well as to develop new methodologies and techniques for the prospection, discovery and characterization of ore deposits.

6. REFERENCES

Appleton, J.D. et al. (1989): Lithochemical exploration for silver mineralization in Bolivia, Mexico and Peru. Trans. of the Inst. Mining and Metall., V. 98, pp B201-B212.

Brink, A.H. (1960): Petrology and ore geology of the Vila Real-Sabrosa-Vila Pouca de Aguiar region, northern Portugal. Com. Serv. Geol. Portugal, tomo XLIII, 143 pp.

Carvalho, J.H. (1988): Geological and structural mapping of the 835 and 855th levels of the Escadia Grande Mine (in Portuguese). DGGM Internal Report.

Carvalho, J.H. (1988a): Geological mapping of the area surrounding the Escadia Grande Mine (in Portuguese). DGGM Internal Report.

Castro Reis, M.L. (1990): Phyllosilicates as indicators of very low metamorphism and diagenesis. DGGM Internal Report.

Clarke, D.S., Lewis, R.W. and Waldron, H.M. (1990): Geology and trace-element geochemistry of the Umuna gold-silver deposit. Misima Island, Papua New Guinea. Journ. Geoch. Expl., V. 36, pp 201-223.

Clarke, D.S. and Govett, G.J.S. (1990): Southwest Pacific epithermal gold: a rock geochemistry perspective. Journ. Geoch. Expl., V. 35, pp 225-240.

Davis, J. (1973): Statistics and Data Analysis in Geology. John Wiley & sons, Inc., 550 pp.

Farinha, J. (1990): Geology of the Três Minas Deposit (in Portuguese). DGGM Internal Report.

Gaspar, O. (1989): Quartz paragenesis and chronology of the auriferous mineralization of Jales (in Portuguese). DGGM Internal Report.

Govett, G.J.S. et al. (1984): Exploration rock geochemistry for gold, Parkes, New South Wales, Australia. Journ. Geoch. Expl., V. 21, pp 175-191.

Neiva, J.C. (1986): Auriferous mineralizations of Jales - the Campo and Desvio lodes (in Portuguese). Internal Report of the Jales Company, 120 pp.

Newall, P.S. and Newall, G.C. (1989): Use of lithogeochemistry as an exploration tool at Redmoor sheeted-vein complex, east Cornwall, Southwest England. Trans. of the Instit. Mining and Metall. V. 98, pp B162-B174.

Parra, A. (1988): The Vale de Pião tin-tungsten deposit. Geological aspects and preliminary reserve calculation (in Portuguese). DGGM Internal Report.

Ramos, J.M.F. (1983): Some geochemical data on the Jales mineralizations (in Portuguese). DGGM Internal Report.

Shepherd, T.J. et al. (1985): Hydrothermal fluid evolution in relation to mineralization in Southwest England with special reference to the Dartmoor - Bodmin area. In: High Heat Production (HHP) Granites, Hydrothermal Circulation and Ore Genesis. Inst. Mining Metall. Symp. Proc. pp 345-364.

Shouwstra, R.P. and Villiers, J.P.R. (1988): Gold mineralization and associated wallrock alteration in Main Reef Complex at Sheba Mine, South Africa. Appl. Earth Science, Section B, V. 97, pp B158-B170.

Simões, M. (1989): Petrographical Report of the Jales Mine - 14th Level. DGGM Internal Report.

Smales, A.A. and Wager, C.R. (1960): Methods in Geochemistry. Intersc. Publishers, N.Y., London.

Trudel, P. et al. (1989): Géochimie de la minéralisation aurifère à la mine Eldrich, région de Rouyn-Noranda, Québec, Canada. Journ. Geoch. Expl., v. 32, pp 415-428.

7. ORAL COMMUNICATIONS AND PUBLICATIONS

Determination of the graphitization degree of the carbonaceous materials in schists by XRD. Some aspects on the inorganic matrix elimination, by M.L. Castro Reis and M.J. Machado. Submitted to Chemical Geology.

Illite Crystallinity - Problems in the selection of the material to be measured, by M.L. Castro Reis. Conference held at the University of Manchester on Phyllosilicates as indicators of very low grade metamorphism and diagenesis. Manchester, July 1990.

Geological aspects of the Escadia Grande Deposit, by J.H. Carvalho. Report included in the T. Shepherd's communication presented in the International Symposium on Gold 89. Toulouse, France, May 1989.

Geological, mineralogical and lithogeochemical studies in the Gois and Vila Pouca de Aguiar-Vila Real regions, Portugal, by J.M. Santos Oliveira. Communication (with paper) presented in the Contact Group Meeting, France, November 1989.

The role of the lithogeochemistry in the delineation of Au and Sn-W mineralization in schist terrains of the Gois region (Center of Portugal), by J.M. Santos Oliveira. Communication presented at the Symposium of Geochemistry, Lisbon, December 1990.

Contribution to the petrological and geochemical study of the Três Minas gold region, by Margarida Simões. Communication presented to the 3rd Brasilian Congress, S. Paolo, 1991.

8. DGGM STAFF AND CO-WORKERS

Staff involved in the project

Dr. J.M. Santos Oliveira (LDGGM)
Dr. Olando Gaspar (LDGGM)
Eng[a] M. Lourdes Reis (LDGGM)
Dr[a] Margarida Simões (LDGGM)
Dr. J.H. Carvalho (SFM-DGGM)
Dr. João Farinha (SFM-DGGM)

Co-workers

Dr. L. Viegas (SFM-DGGM)
Dr. A. Parra (SFM-DGGM)
Dr. P. Cramez (LDGGM)
Dr^{a} M.J. Machado (LDGGM)
Dr. J. Farinha Ramos (LDGGM)
Eng^{a} M. Eugénia Moreira (LDGGM)
Eng^{a} E. Fernandes (LDGGM)
Eng^{a} M.E. Soares (LDGGM)
Eng^{a} M.R. Afonso (LDGGM)
Eng^{a} M.C. Diogo (LDGGM)
Dr. L. Simões Carvalho (Junior Assistant - LDGGM)

Fig.1 - GEOTECTONIC ZONES OF THE IBERIAN MESETA

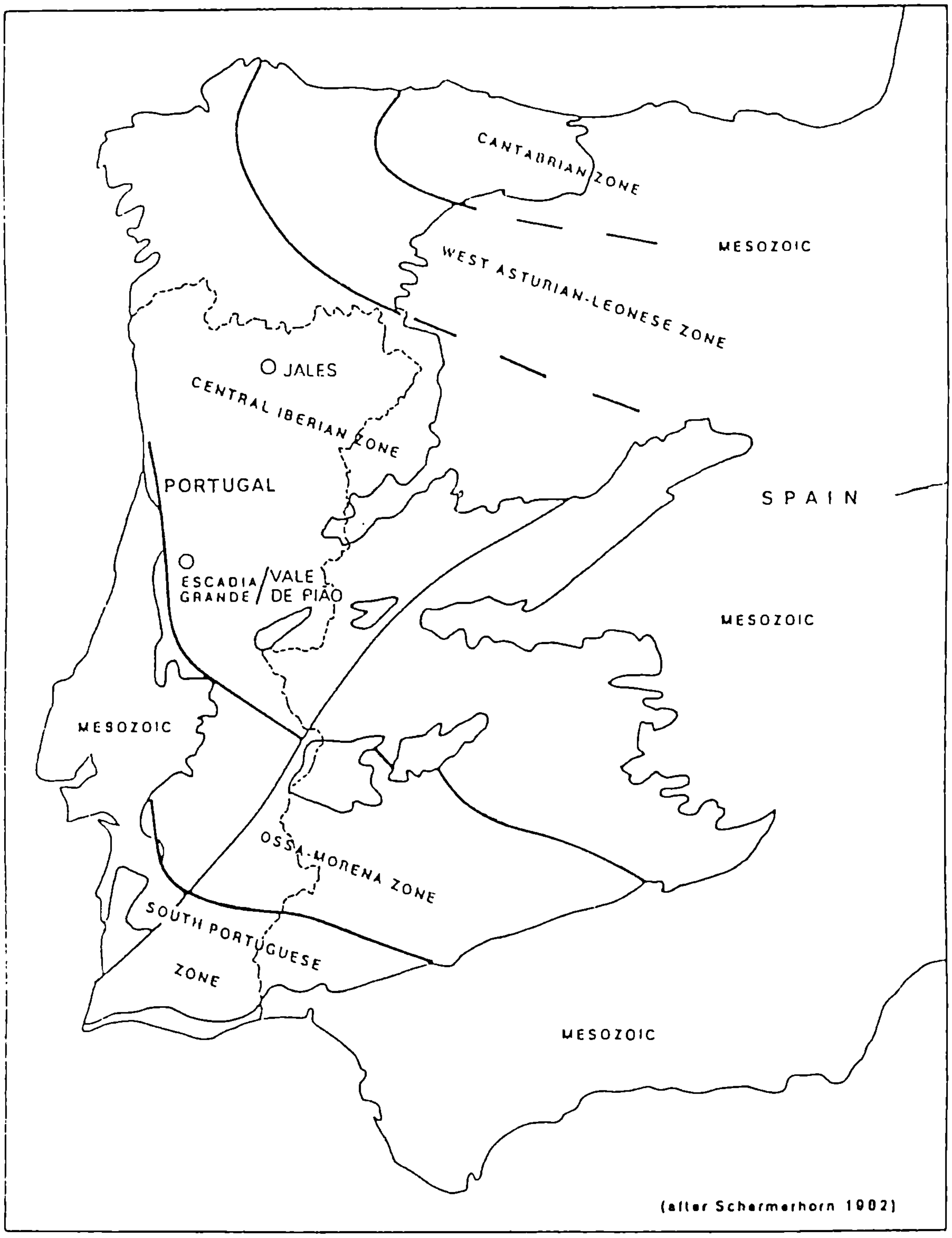
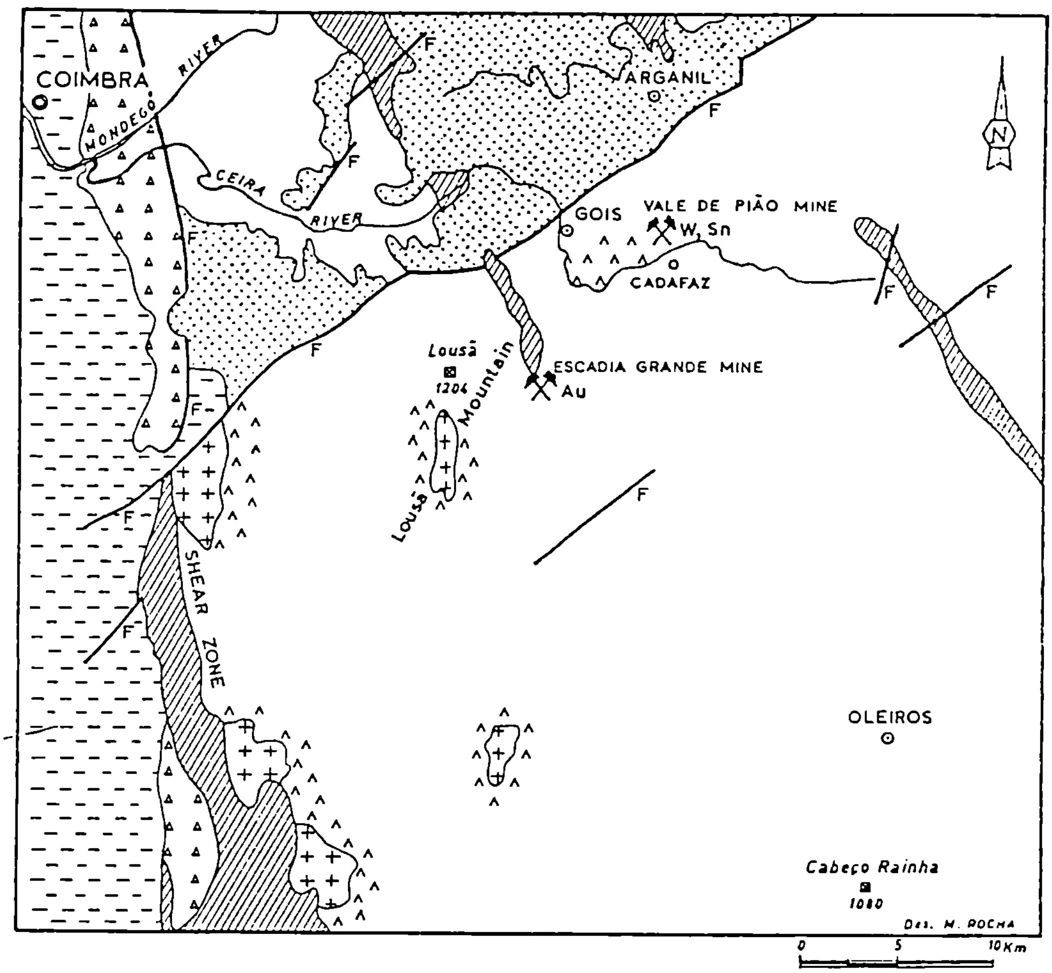


Fig.2-GEOLOGY OF THE GOIS REGION



KEY

- INFRACAMBRIAN METAMORPHIC ROCKS *("Black Sequence")*
- SCHISTS, GREYWACKES *(Pré-Ordovician Xisto - grauváquico complex)*
- QUARTZITES, SLATES *(Ordovician -Silurian)*
- UNDIFFERENTIATED MESOZOIC
- MIOCENE, PLIOCENE AND QUARTENARY FORMATIONS
- ALKALINE GRANITES
- CONTACT METAMORPHIC AUREOLE

EXTRACTED FROM
THE 1:500 000
GEOLOGICAL MAP CARLOS
TEIXEIRA (1972)

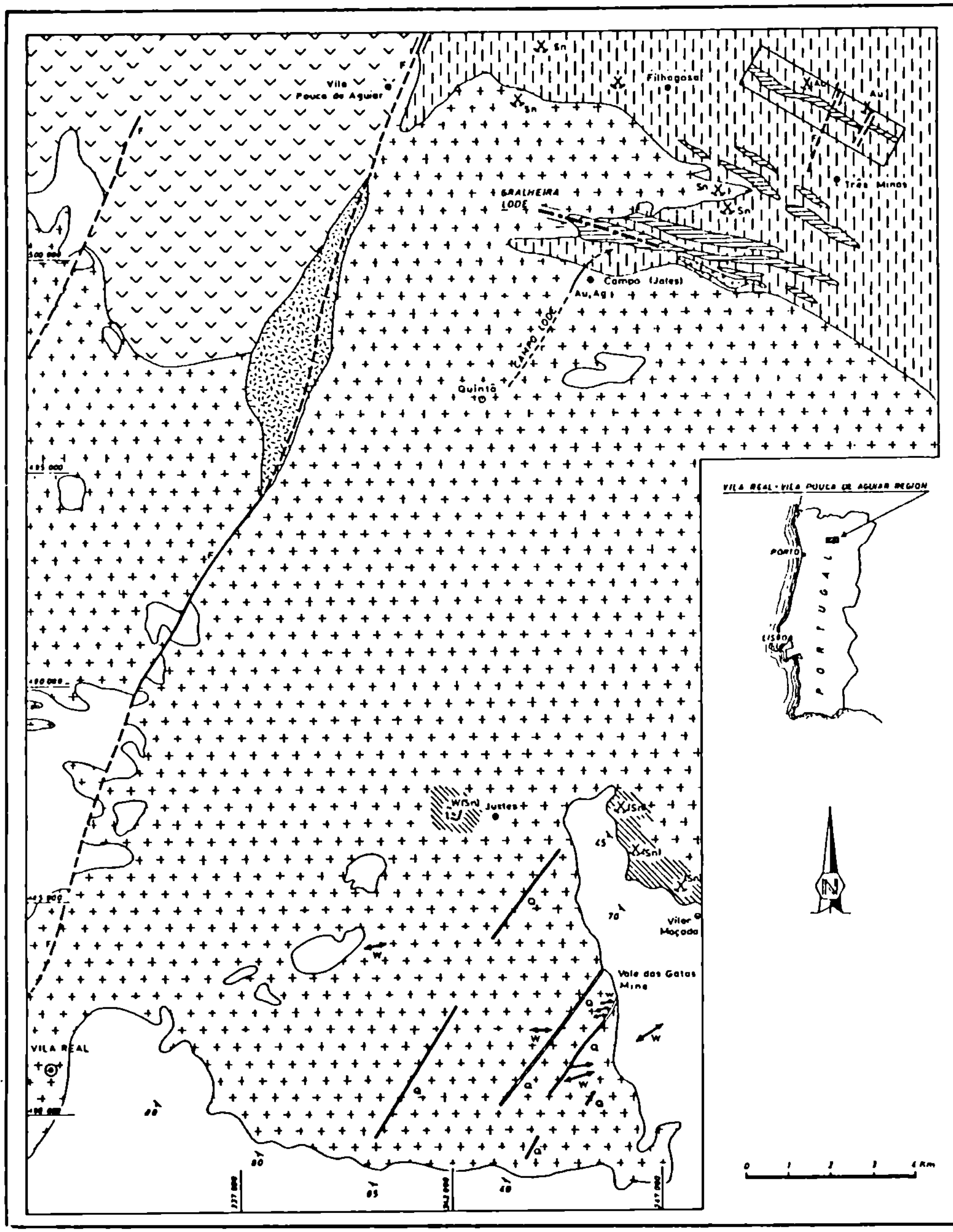
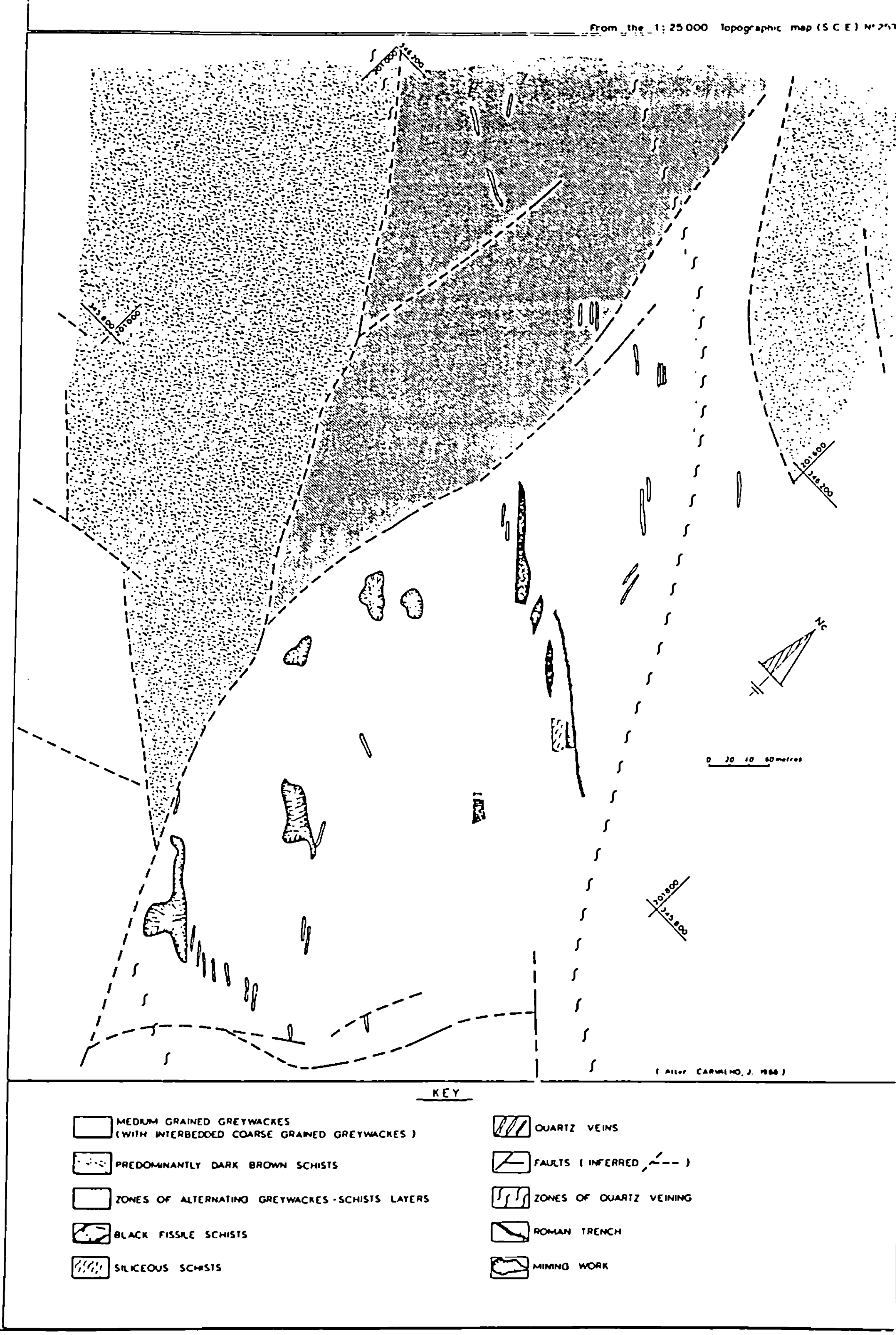


Fig.3-GEOLOGY OF THE
VILA POUCA DE AGUIAR-VILA REAL REGION

- PELITIC AND PSAMMITIC SCHISTS (BEIRA SCHISTS OF THE INFRACAMBRIAN (CAMBRIAN COMPLEX)
- QUARTZITES AND SCHISTS S.L. (ORDOVICIAN-SILURIAN)
- PELITIC ROCKS (SILURIAN PARTICULARY TO THE NORTH OF THE GRALHEIRA LODE)
- ALKALINE TWO MICA GRANITE (HERCYNIAN)
- CALCALKALINE BIOTITE PORPHYRITIC GRANITE (HERCYNIAN)
- LATER APLITE-PEGMATITE
- MUSCOVITE GRANITE AND TURMALINE GREISEN
- ALLUVIUM
- MINERALIZED VEINS
- SULPHIDE-GOLD LODE (GRALHEIRA LODE)
- STOCKWORK OF MINERAL VEINS
- QUARTZ VEINS
- FAULT
- TRÊS MINAS MAPPED AREA

(Geological elements extracted from BRINK, 1960; PORTUGAL FERREIRA et al., 1971; NEIVA, 1986; GARCIA et al., 1985; B.P. INTERNAL REPORT, 1986)

Fig.4-SURFACE GEOLOGICAL MAP OF THE ESCADIA GRANDE MINE



IDENTIFICATION OF DIAGNOSTIC MARKERS OF HIGH-GRADE MASSIVE SULPHIDE DEPOSITS OR OF THEIR ENRICHED ZONES IN FRANCE AND PORTUGAL

Project Leader: J. P. MILESI
Bureau de Recherches Géologiques et Minières (BRGM), Orléans, France

Contract MA1M-0030-F

1. OBJECTIVES OF THE RESEARCH

The aim of the study was to complement conventional massive sulphide prospecting methods by combining volcano-structural analysis, isotopic geochemistry and detailed mineralogy of the alteration phase in order to define distinctive parameters between base and/or precious metal enriched bodies and low-grade deposits. It was anticipated, in the course of such a study, that empirical guides to high-grade ore would be discovered (anomalous amounts of minor and trace elements, or the crystallographic and crystal-chemical characteristics of minerals such as phyllosilicates). It is well known that empirical factors are often more important than theoretical models that are generally formulated only many years later.

2. MATERIAL AND METHODS

The investigation used both theorical and empirical criteria. Genetic models for this class of deposits leave little room for doubt that sulphide precipitation takes place at or near the coeval seafloor. Within the framework of such models several factors determinant in the accumulation of large amounts of base metal sulphides (precious metal bearing) can be envisaged. These include :

a) total amount and rate of supply of mineralizing fluids;

b) composition and physical characteristics of such fluids (e.g. density, temperature, Eh, pH);

c) fluid pathways (fault or pervasive permeability controls on circulation, etc.);

d) chemical reactions leading to ore mineral precipitations;

e) wall rock influence on d);

f) barriers to dispersion of potential ore components (including conditions as diverse as paleotopography and structure, presence of physical, chemical and/or biological barriers to dispersion);

g) post depositional evolution.

Clues to the elucidation of these factors can be found in mineralogical and geochemical studies (including mineral chemistry and lead isotopes geochemistry) of the ores themselves and their host rocks, particularly those affected by hydrothermal alteration. Zonations of various natures and on all scales were sought. Also, correct and detailed reconstructions of the sites of ore accumulations were of utmost importance.

The investigations of the French team were carried out on the Chessy Zn-Cu-Ba orebody and on the Sain-Bel low-grade pyrite bodies (all in the district of Brévenne, eastern Massif Central, France).

The French team comprised : J.P. Milési (project leader), J.L. Lescuyer, Y. Gros, A. Lacomme, B. Lemière, J. Letalenet, E. Marcoux, F. Mathieu (all with BRGM), M. Poupon (University of Paris VI) and M. Lardeau (University of Orléans).

This report presents the results obtained by the French team on the Chessy and Sain-Bel orebodies, as well as a comparison with the south Iberian pyritic belt based upon visits of the French team in Portugal.

The investigations of the Portuguese team (contract MA1M-0029-P) were carried out on the Gaviao (30 Mt) orebody of the Aljustrel area, and aimed at completing earlier detailed work (mapping, mineralogy, geochemistry, drilling) at Feitais (80 Mt) in the same area (Aljustrel).

The Portuguese team comprised : F.J.A.S. Barriga (projet leader), C. Massano, J. Relvas (all with DGFC, University of Lisboa), V. Oliveira (DGGM) and J. Damiao (E.D.M.).

Results obtained by the Portuguese team in the Iberian pyritic belt are presented separately in the next article of this volume (contract MA1M-0029-P).

Exchanges between the French and Portuguese teams enhanced better scientific interpretation of the data.

3. RESULTS

3.1 <u>THE CHESSY Zn-Cu-Ba SULPHIDE DEPOSIT AND THE DEVONIAN BREVENNE VOLCANO-SEDIMENTARY BELT (EASTERN MASSIF CENTRAL, FRANCE) (J.P. MILESI AND J.L. LESCUYER)</u>

The massive sulphide deposits within the volcano-sedimentary belts of the Iberian peninsula and the French Massif Central show, notwithstanding their morphological differences, such as size and number of deposits, several common features that include a Devonian-Carboniferous age and similar mineralization, paleotectonic framework and polyphase litho-structural evolution. These similarities justify comparative studies of the exploration guidelines for high-grade concentrations in the massive sulphides.

For the French part of this study, carried out jointly by BRGM and the Universities of Paris VI and Orléans, results concern the Brévenne district, located about twenty kilometers west of Lyon. They are based on modelling of the anatomy of the polymetallic deposit of Chessy, and on a comparison with the Sain-Bel orebody and the Bernay and Bully showings in the same area.

The mineralization in the Brévenne was emplaced during the late Devonian (360 ± 15 Ma, based on single zircon dating by 207 Pb/206 Pb, Calvez, 1989, pers. comm.), in an ensialic rift within a thinned crust, characterized by a tholeiitic bimodal volcanism.

The lithostructural evolution of this belt commenced with the deposition of a lower, sub-aquatic, acid volcanic pile, hostrock of the massive sulphides and the main occurrences. These rocks, which are at least 300 m thick, were then cut by numerous basic sills and dykes that are locally vesicular. The dykes acted as feeders for locally preserved pillow-basalt flows, associated with hyaloclastites and sediments. Fine-grained detrital sediments, with rare cinerite intercalations, occur away from the volcanic centres. The whole succession was then affected by two tectono-metamorphic phases during early Carboniferous times. These were responsible for the closure of the rift that is now the Brévenne belt and its thrusting over the Monts du Lyonnais basement. During the Middle Carboniferous, granites intruded with succession, which was accompanied by minor Ba-Pb-Ag-vein mineralization.

The Chessy orebody was discovered by BRGM in 1980. It contains 5,8 Mt ore grading 49% pyrite, 22% barite, 2,4% copper, 8,3% zinc, 0,4% lead and 20 g/t silver, hosted by acid volcanic rocks similar to those that enclose the Sain-Bel deposit (20 Mt, mainly pyrite). The Chessy deposit consists of three main facies : massive pyrite ± chalcopyrite ore, termed U1, banded polymetallic ore (pyrite, sphalerite, chalcopyrite, barite ; U2), and barite-sphalerite ore (U3).

Lateral and vertical distribution of the ore facies show that the Chessy deposit is composed of two superimposed sequences :

- The lower barite-rich sequence (U2 to U3), up to 25 m thick, was fed by two sulphide-cemented (U1 to U2) breccia pipes, 400 m apart, which display, from base to top, a dense stockwork that grades to an inner breccia with angular rhyolite blocks, and then to an outer breccia characterized by smoothened and sorted rhyolite fragments.

- The upper sequence was fed by sulphide-bearing stringers that cut both footwall rhyolites and the lower ore sequence ; up to 30 m thick, pyrite-rich (U1 to U2) polymetallic ore grades to the north and west into distal barite-sphalerite (chalcopyrite-galena).

This mineralization was then subjected to the polyphase structural deformation mentioned earlier, as well as to the effects of contact metamorphism. This led to the necessity of "reading" the exploration guidelines through all the transposition that took place after the mineralization was emplaced.

The first metallotect in the exploration for massive sulphides is the acid volcanic pile itself, which was recognized in four lithostructural units (in this case thrust slices), thereby considerably reducing the area to be explored. A few difficulties were, however, encountered, such as the fact that, laterally from the massive sulphides, no exhalative sedimentary deposits were found that could have served as regional guidelines. Furthermore, the rhyolites in the footwall and hanging wall of the ore cannot be distinguished by means of their geochemical signature, which makes them unsuitable as guides. On the other hand, exploration is favoured in the least deformed areas by the fact that the acid volcanic rocks, occurring in "acid strips" of 1 to 2 km width, are only a few hundreds of metres thick.

The second control of the Chessy mineralization is a structural feature. This concerns a NNE-striking paleofracture corridor, up to one kilometer long, 100 to 200 m wide and at least 250 m deep, which acted as a feeder zone for the mineralizing fluids and controlled the formation of the tectonic seafloor depression that trapped the sulphide-barite deposits. The question is now whether this type of paleofracture can be recognized during exploration ; it seems that, at least for the moment, this guideline is difficult to use, in view of the very poor outcrop conditions and the magnitude of the later structural deformations. It is, however, possible to find such paleofractures indirectly, by means of the identification of "hydrothermally altered columns" ; these are characterized by the development of a very particular rock type called "quartz-sericite schist", which may be a few hundreds of meters thick and wide, and a few kilometers long. Another way to find such paleofractures is to search for the oxide mineralization that derived from early stockworks, by means of the textural and geochemical analysis of the various "gossans".

The third guide is deduced from the lithogeochemical signatures observed in the "hydrothermally altered columns" and in the gossans. The hydrothermally altered zones found at Chessy appear to have been formed by several hydrothermal pulsations, as they affect both the footwall and hanging wall of the massive sulphides. In the footwall, two breccia pipes and a siliceous pipe, several hundreds of meters in size, were identified ; in the hangingwall, the hydrothermal envelope of "quartz-sericite schist" is developed over almost 800 m in length and up the 200 m in thikness. At surface the peculiar geochemical signature of this poorly exposed facies can be detected by soil sampling. This point was verified in the framework of this project and then extrapolated to a regional scale. Two particular features derived from this work :

1. External haloes exist with anomalous Zn (200 to 900 ppm) and Hg (50 to 90 ppb) values, regardless of whether they are of early or late (remobilized) origin.

2. Enrichment in K, Ba, Rb, Tl and P (with constant Al-Si) of the "quartz-sericite schist" can be observed ; locally, this rock also contains traces of base metals, and As and Hg. Applying this guideline during the soil geochemical work by BRGM, led to the discovery of several new showings, including that of Bernay.

The detailed analysis of the oxide mineralization found at surface leads to the discrimination of sulphide stockworks within the most hydrothermally altered areas (indicators of the paleofracturing gradient), as well as of gossans derived from stratiform mineralization. Moreover, the composition of such gossans is symptomatic of either the proximal polymetallic or the more distal, baritic (to siliceous) parts. An example of the latter is provided by the small, banded baritic gossan found southwest of Chessy, 300 m from the feeder zone.

Furthermore, lead isotopes analyses were performed on 38 samples from massive and disseminated ore, sulphide and oxide stockworks, and gossans. This made it possible to distinguish between the facies associated with a base metal-rich system, whose fluids are assumed to be of deep origin (206Pb/204Pb less than 18.32), and pyrite-rich disseminations, poor in base metals, whose signature is more radiogenic (206Pb/204Pb > 18.32). The Bernay mineralization, which was thus tested, evidently does not belong to the polymetallic systems of Chessy and Sain-Bel, but presents the signature of the low-grade mineralization found in the hangingwall of Chessy.

The fourth guide is based on the mineralogical and chemical zonations seen in the hydrothermally altered zones of the Chessy orebody. A similar hydrothermal zoning is visible in the altered rhyolites of both the footwall and the hangingwall, despite subsequent recrystallization caused by the late Hercynian granite intrusion. Ba-muscovite, K-feldspar and andalusite (after quartz and muscovite), gahnite (after sphalerite and muscovite), quartz, rutile, apatite, and sulphides, all mark the inner zone along the paleofracture described under the second metallotect. The outer, less altered zone is characterized by biotite-phlogopite (after Fe- and Mg-chlorite), quartz, rare andalusite and muscovite, and relics of magmatic minerals, such as albite and ilmenite. Changes in the mineral composition of these mineral assemblages are noted from the outer to the inner zones ; they are shown by a decrease of the FM (Fe/Fe+Mg) ratio in phyllites, an increase of the Ba content in muscovite (up to 3.7% BaO) and of K-feldspar, and a decrease of Fe content in andalusite. At Sain-Bel (Saint-Antoine quarry), a similar evolution in the FM ratio of chlorite and in the Ba content of muscovite is observed from the outer zone to the inner altered zone.

The chemical composition of the mineral phases, deriving from the early hydrothermal activity, makes it possible to rank the hydrothermally altered columns and to focus exploration on the "fertile" pathways. This approach has been applied to the major hydrothermally altered areas of Bernay and Bully. In the former, the alteration gradients are slight and the low base metal content was confirmed by drilling ; in the latter, the intense alteration (4% BaO in muscovite) is similar to that of the hydrothermally altered columns at Chessy.

Finally, concerning geophysical exploration methods, the latest interpretation work has led to the conclusion that no gravimetric or electromagnetic signatures are directly related to the massive sulphide mineralization found at Chessy. As concerns resistivity and magnetics, in view of the geological and structural complexity of the area, only a few, low resistivity anomalies could be related to the altered hangingwall ; the strong N-S magnetic anomaly is probably due to a chilled margin effect at the contact between the basic intrusive rocks and the western, distal part of the orebody.

The introduction, in an otherwise conventional mineral exploration procedure, of specific guidelines related to the zonation of the ore facies and of the hydrothermally altered columns, should increase the chances of finding Chessy-type massive sulphide deposits of the Brévenne type in other volcanic belts.

Certain of the methods tested and described here, such as lead isotopes geochemistry, composition of hydrothermal marker minerals, and rock geochemistry of outcropping mineralization, make it possible to select at an early stage those systems that might host deposits that are rich in base metals. This, in turn, allows to be much more selective than hitherto possible, when drilling a district with a multitude of hydrothermal manifestations.

3.2. <u>INITIAL COMPARISON BETWEEN THE BREVENNE BELT(FRANCE) AND THE PORTUGUESE PART OF THE SOUTH IBERIAN PYRITE BELT</u>

3.2.1. FIELD WORK IN THE IBERIAN PYRITE BELT (SOUTH PORTUGAL)

The best geological section of the area is provided by the Pomarao anticline, the NW termination of a very large anticlinorium mostly developed in Spain (Puebla de Guzman Anticlinorium), where it hosts the famous Tharsis massive sulphide deposits.

Furthermore, hydrothermal effects in the area are perhaps less intense and varied than in most other exposures in the belt, enabling better recognition of original features. We had extremely enlightening discussions on the field criteria for distinction between dust tuffs, tuffites and pelitic sediments, and for the recognition of base surges and lahars.

Surface work in the Aljustrel area provided further opportunity for inspection of the various lithologies, especially those characteristic of Aljustrel : megacryst tuffs, green tuffs and felsites. Several new volcanological observations were made, such as the recognition of centimetric beds of dust tuffs (fall tuffs) intercalated in the Quartz-Eye Tuff (QET) Formation (near the Algares iron cap, and later also observed in Gaviao drillcores), as well as the interpretation of some of the fragments in this unit as fragments of more or less vesiculated and plastic lava, at the time of deposition. These fragments are often angular, and have dimensions up to 10 cm, attesting modest transport, what implies a proximal character for the QET. There was also opportunity for discussions on the significance of the felsites, abundant in the Mine Tuff Formation. The criteria for ash flow versus ash fall tuffs were also debated. According to J.P. Milési, the QET Formation may correspond to a thick unit of ash flow tuffs. Hydrothermal effects were also observed, including spectacular multi-phase alteration in the QET. Lithological observations were completed with inspection of drillcores of the Gaviao area, one of the main objects of study in the framework of the present research contract, and also during an underground visit to the Moinho orebody. Here structural complications were apparent. Massive sulphide ore was observed in situ, and contrasted with the observations made in Chessy (far greater size, but much lower grades and finer granularity).

The area of the old S. Domingos mine (exhausted) was also visited. From the volcanological point of view, there are important peculiarities in the area, especially the greater than usual abundance of lavas, including glassy domes. Massive sulphide mineralization was here subvertical, at the contact between felsic and mafic volcanics.

One of the highlights of this session of joint field work was obviously the visit to the spectacular Neves-Corvo Mines, fundamental for the research contract, in view of the extremely high copper (and tin) grades in several types of ore. Demonstrated reserves of copper ore (8,5 % Cu) amount to 33 Mt, including 14 Mt of measured reserves with 11% Cu, 2 Mt of which carry > 1% Sn. Polymetallic ore (demonstrated) amounts to 33 Mt with 8% Zn equivalent and 30 g/t Ag.

The Neves-Corvo orebodies lie in a gentle anticline oriented NW-SE. Four main sulphide lenses are already known (Neves, Corvo, Zambujal and Graça - the latter on the SW flank of the anticline). Two further targets are currently under evaluation (Algaré and A de Pires). The geology of the Neves-Corvo area is not yet fully understood, in view of a unique lithostratigraphic sequence, in which turbidites occur intercalated in the Volcanic-Siliceous Complex, and several VS rocks and ores are unusual and/or occur in unusual positions (e.g. sheared stringer copper ore - "rubané" ore - at the hanging wall or the massive lenses). Other intriguing features are for example the nature and significance of abundant "black schists" : at least some of these may correspond to extreme chloritic alteration of volcanics. The distribution of volcanic facies is also peculiar. These and other aspects deserve study, and are extremely important in the context of the present research contract.

3.2.2 COMPARISON BETWEEN THE BREVENNE AND THE IBERIAN PYRITE BELT SULPHIDE DEPOSITS

Throughout our visit to the Brévenne district there was ample opportunity to compare the mineral deposits visited with those of the Iberian Pyrite Belt.

In both provinces mineralisations are related to important episodes of felsic volcanism. However, in the Brévenne district lava flows are largely dominant, whereas in the Iberian Pyrite Belt volcanism was mostly explosive. Consequently, hydrothermal circulation in the Iberian province was certainly far more pervasive, given much higher "porous" permeabilities, and thus metal leaching from the rocks was greatly facilitated. This may have been an important factor in the large size of orebodies in the Iberian Pyrite Belt. On the other hand, the temperature of the volcanic rocks at the time of deposition is likely to have been higher in the Brévenne, with consequent differences in the conditions of water-rock interaction. This may have had bearing on the grade of the deposits, althought post-depositional events (deformation, contact metamorphism) must also have been very important.

The effect of the emplacement of thick (and hot) lava flows on top of sulphide mineralisations still forming (given the lack of sediments) in the Brévenne may also have been of importance, in phenomena such as mineral zonations and granularity variations.

Other differences between the Brévenne district and the Iberian Pyrite Belt are (a) the zonation of stockwork alteration, with sericitic cores and chloritic rims in the Brévenne district, and exactly the opposite in the Iberian Pyrite Belt ; (b) the intriguing absence of even traces of volcanogenic hydrothermal sediments in the Brévenne district, such as jaspers and manganese concentrations, so common elsewhere (including in the Iberian Pyrite Belt) ; (c) the abundance of barium in the Brévenne deposits, certainly related with anomalous background values, but possibly also reflecting the physico-chemical conditions of ore deposition.

Exploration in the Iberian Pyrite Belt is greatly facilitated by the fact that the mineralized horizons are easily discernible, whereas in the Brévenne the lack of volcanogenic sediments at the favourable horizons (other than the ores themselves), and the great similarity between footwall and hanging wall volcanics, make mapping of the "favourable horizons" next to impossible. Geochemical investigations of the volcanic rocks, particularly oriented to the understanding of hydrothermal activity, may prove to be a powerful tool in distinguishing footwall and hanging wall rocks. Determination of the oxidation state of iron and stable isotope studies are especially promising.

Exploration techniques for massive sulphide deposits in the Brévenne district include, among others, the determination of the abundances of K_2O and SiO_2 on soils. In the Iberian Pyrite Belt the most used methods have been gravimetry, electrical methods, magnetometry and soil geochemistry. The latter has never been performed for K_2O and SiO_2, and available data have not been particularly useful. In the Brévenne district, given that sulphide mineralisation is accompanied by quartz-sericite alteration, soil analysis of K_2O and SiO_2 enables quantification of the degree of hydrothermal alteration of the volcanic rocks hosting mineralisation. It is therefore possible to define zonalities with respect to increased concentration of sulphides.

The Cercal-Odemira area of the Iberian Pyrite Belt depicts very interesting similarities with the Brévenne district, namely greater than usual abundance of lavas, comparatively few jaspers, and abundant barium. A few sulphide occurrences are known in the area, notably Salgadinho. This deposit is accompanied by intense quartz-sericite alteration. Soil samples of the area are available, on a 100x100 m grid (obtained by Servico de Fomento Mineiro), and preliminary tests could be run on these samples, and be subsequently extended to other sectors of the Cercal-Odemira area, sulphide bearing and barren.

4. CONCLUSIONS

The multidisciplinary studies conducted on the Chessy orebody and other volcanosedimentary mineral deposits in the Late Devonian Brévenne metamorphic belt have determined the main characteristics of the mineralization and of its setting, thus providing additional guides for regional exploration of base metal-rich concentrations. Specific characteristics of the Brévenne volcanic-hosted sulphide deposits can be summarized as follows :

- Location of the orebodies within a thick felsic pile which was emitted during the first stage of ensialic rifting.

- Sulphide deposition during short breaks in the submarine volcanic activity, which was proximal and effusive (scarcity of sedimentary and pyroclastic intercalations between rhyolitic flows).

- Absence of regional stratigraphic marker laterally to the massive sulphide deposits.

- Homogeneous lead isotope signatures of the main (usually base metal-rich) mineralizing event indicating similar deep-seated sources, and probably contemporaneous hydrothermal systems, for the Chessy and Sain-Bel deposits; distinct, more radiogenic lead isotope signatures characterize the last, base metal-poor mineralizing event (hanging wall of Chessy, Bernay).

- Typical zonation of the hydrothermal systems which display, after metamorphic crystallizations, an outer chlorite/biotite zone and an inner muscovite (phlogopite, andalusite, K-feldspar, sulphides) zone; progressive Ba enrichment of muscovite and decreasing of the FM ratio of phyllites is noted towards the inner zone (i.e. the feeder zone), which is characterized by whole-rock K-Ba-Rb-Ti-P (Fe-Cu-Zn-As-Hg) enrichment.

- Concentration of the most intense hydrothermal transformations (with sulphide impregnation and stockworks) along highly deformed (quartz-sericite schists), kilometer-long corridors which correspond to former N-S paleofractures; two or three successive stages of hydrothermal activity along the same paleofracturation zone have been demonstrated at Chessy.

- Concentration of base metals, barite and precious metals (Sain-Bel) in stratiform massive sulphide bodies or layers which were deposited in local paleodepressions around the feeder zones (higher permeability of fractures); mineral and chemical ore zonation, well demonstrated at Chessy, displays a classical arrangement from proximal pyrite ore (U1 facies) passing through polymetallic (U2), then distal barite-sphalerite ore (U3); two zoned ore sequences are locally superimposed (Chessy); stockwork ore, breccia ore (Chessy) or massive pyritic lenses of ill-defined type (Saint-Pierre-la-Palud mine at Sain-Bel) have no economic base or precious metal contents.

Diagnostic markers for base metal-rich concentrations in Brévenne or similar volcanosedimentary series (Violay-Ternand area, Beaujolais, Fig. 2) are therefore paleo-alteration zones within the lower acid volcanic rocks which have typical textures, mineralogy and geochemical composition. Where not outcropping, these zones can be detected by specific multi-element geochemical signatures in residual soils. Focusing on the most intensely altered parts of the former hydrothermal system, i.e. on the paleofracturation zone which acted as channelway for the mineralizing fluids, can be made through mineral chemistry of the hydrothermal paragenesis. Once the inner part of the alteration column is defined, lead isotope geochemistry of sulphides (oxidized or not), which are usually present in this central zone, can be used by reference with the Chessy model : radiogenic signatures, typical of the last hydrothermal event of Chessy, will indicate a possible base metal concentration at a lower stratigraphic level of the felsic pile; less radiogenic signatures, similar to that of the Chessy and Sain-Bel main mineralizing event, should orientate the exploration towards orebodies deposited laterally, if the analyzed mineral occurrence is stratiform (e.g. the baritic gossan of Chessy or the sulphide-bearing chert of Bully), or at an higher stratigraphic level, if the analyzed sulphides were deposited as stockworks or stringers.

In each case, a detailed structural analysis is necessary to determine the primary layering of the volcanic sequence (S_O) and the effects of the successive deformation stages (shearing, folding, late faulting) on the geometry of a possible stratiform concentration. Re-interpretation of all geophysical data is also essential before reconnaissance drilling of the most favourable targets.

This multidisciplinary methodology of exploration, which combines classical prospection tools with specific methods, such as mineral chemistry, structural analysis or isotope geochemistry, is not directly transposable to other volcanosedimentary belts.

Comparisons with the Iberian pyrite belt, which was studied by our Portuguese colleagues in the joint EEC project and visited by our team, show that disparities in the geological environment (more abundant sediments and pyroclastic rocks) enable to select different exploration guides : proximity of paleovolcanic centres, geochemical composition of lateral exhalites, regional metallic zonation, etc. On the other hand, differences in fluid compositions are marked by a reverse hydrothermal zonation in the Aljustrel area (inner chlorite zone, outer sericite zone) compared to the Brévenne mineralizing systems. Even if geochemical markers are specific to a given area or district, similar methods are used to focus exploration towards the inner parts of the hydrothermal system (alteration gradients, early stockwork density), in order to best define the feeder zones and the paleostructural traps which control the ore deposition and the base metals zonation.

In conclusion, the general approach which progressively prevails for the prospection of still undetected rich concentrations in old mining districts can be summarized as follows : to acquire a complete knowledge of the geological and structural evolution, to reconstruct the regional models of ore deposition in their paleogeographic setting, then to infer the specific markers of mineral concentrations which will be searched for using the most accurate scientific methods and exploration tools.

5. LIST OF PUBLICATIONS

LACOMME A., MILESI J.P. and GROS Y. (1987). L'amas sulfuré à Cu-Zn de Chessy (Rhône). Evolution historique des recherches, état actuel des connaissances sur le gisement et son environnement. Chron. rech. min., no 489, pp. 3-21.

POUPON M., MILESI J.P. and FONTEILLES M. (1988) - Les zonations hydrothermales associées aux amas sulfurés de Chessy et de Sain Bel (Paléozoïque, série de la Brévenne, Massif Central français). C.R. Acad. Sci. Paris, v. 397, pp. 595-601.

LARDEAU M. (1989) - Minéralogie et pétrogenèse du minerai sulfuré du gisement volcano-sédimentaire à Zn-Cu-Ba (Pb-Ag) de Chessy-les-Mines (Rhône) - Thesis (3e cycle), Université d'Orléans, document BRGM no 166, 180 p.

MILESI J.P. and LESCUYER J.L. (1989) - The Chessy Zn-Cu-Ba massive sulphide deposit and the Devonian Brevenne volcanosedimentary belt (Eastern Massif Central, France). Final report, CEC Contract MA1M-0030-F (D) - BRGM Report 89 DAM 010 DEX, 51 p, 8 appendix.

POUPON M., 1990 - Les altérations hydrothermales associées aux amas sulfurés de Chessy et de Sain Bel (Paléozoïque, série de la Brévenne, Massif Central Français). Thesis (3e cycle), Université Paris VI, document BRGM no 177, 215 p.

MARCOUX E., LESCUYER J.L. and MILESI J.P. (1990) - Géochimie isotopique du plomb du gisement de Chessy et des minéralisations volcanosédimentaires de la série de la Brévenne (Massif Central). Implications metallogéniques et conséquences pour l'exploration. Chron. rech. min., no 501, pp. 3-11.

6. POSTER PRESENTATION

LAGNY Ph., LESCUYER J.L., MILESI J.P. and AUTRAN A. - (1990). Les gisements de demain plus profonds plus difficiles à trouver. Poster présenté au colloque "Terre notre planète, voir, mesurer, modéliser", Strasbourg, France (3-5 July 1990).

7. ORAL COMMUNICATION

LESCUYER J.L. (1989). The Chessy Zn, Cu, Ba massive sulphide deposit. Congrès Cardiff, 11-12 Déc. 1989. Abstract published in "Mineral Study Group" (Geo. Soc. London, The society of Economic Geologists), Abstracts, pp. 3-4.

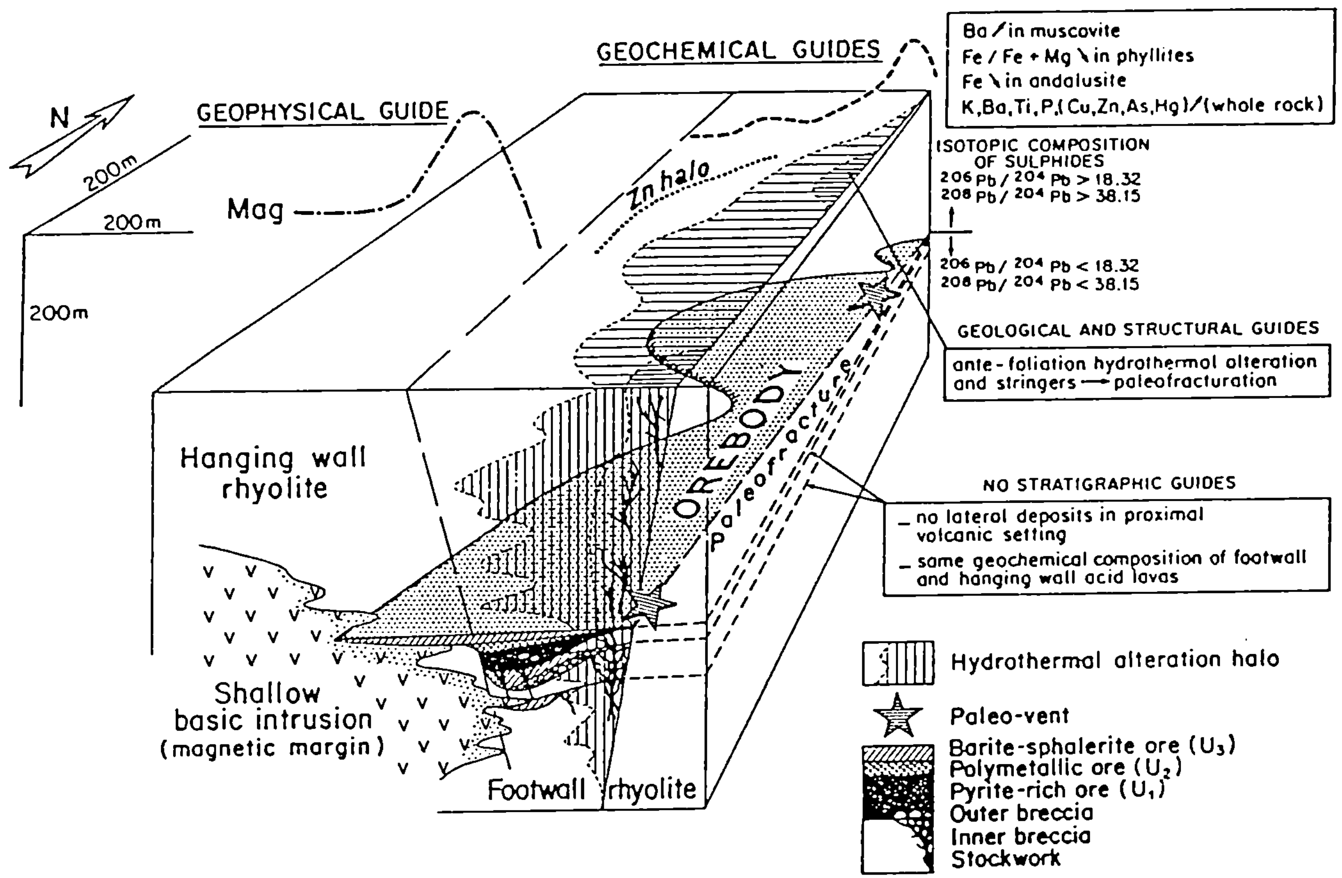


Fig. 1: The Chessy metallogenic model: guides of exploration

IDENTIFICATION OF DIAGNOSTIC MARKERS OF HIGH-GRADE MASSIVE SULPHIDE DEPOSITS OR OF THEIR ENRICHED ZONES IN FRANCE AND PORTUGAL

Project Leader: Fernando J.A.S. BARRIGA
Departamento de Geologia da Faculdade de Ciências
da Universidade de Lisboa, Portugal

Contract MA1M-0029-P

1. INTRODUCTION

The Iberian Pyrite Belt (IPB) of southern Portugal and southwestern Spain is western Europe's largest stock of base metals, with massive ore reserves of the order of 700 Mt (million metric tonnes). Since the early sixties exploration for massive sulphide deposits in the IPB has been quite successful, once detailed geophysical surveys were performed on target areas selected on the basis of sound geological knowledge. This exploration practice is powerful enough for the discovery of blind deposits, as evidenced by many discoveries, including the Neves-Corvo deposits, famous for their size and extremely high copper and tin grades. However, it has two drawbacks: 1) in several cases, very promising targets have been abandoned after drilling that neither intersects ore nor explains the favourable data (geophysical anomalies, etc.); and 2) no known tools capable of distinguishing low and high grade ore are used yet. The objective of the present research contract was to contribute to solution of both problems, with new exploration tools to be added to the methodologies currently in use. Such new tools should preferably be of more general use, outside the IPB. A Portuguese team (University of Lisbon, Serviço de Fomento Mineiro, and Empresa de Desenvolvimento Mineiro), studying the IPB, did so in association with a French team (BRGM and University Pierre and Marie Curie, Paris) studying the Brévenne province of the French Massif Central.

Studies in the IPB were focused on detailed characterisation of the ore-related phenomena around the Gavião massive sulphide deposits (Aljustrel area), and application to actual exploration targets (Brejo near Lousal, and Durianas near Panóias).

1.1. REGIONAL GEOLOGY

In the Iberian Pyrite Belt sulphide mineralisation occurs in association with the waning stages of felsic explosive volcanism which took place in early Carboniferous times, on a phyllite - quartzite shelf facies conformable basement (PQ Formation). Subordinate mafic volcanism accompanied the felsic volcanic activity, producing a bimodal association in which the two types of igneous rocks are not related by magmatic differentiation. Volcanic rocks were affected by widespread seawater hydrothermal metamorphism responsible for the present spilitic and quartz-keratophyric compositions of the rocks, for the massive sulphide deposits and also for abundant volcanogenic sediments such as Mn accumulations (with or without barite), Fe-Mn cherts, and purple and red slates.

Volcanism occurred along lineaments of discrete volcanic centres in a framework of detrital, biogenic and chemical sediments, generating a lithologically variable (ore hosting), volcanic-siliceous (or -sedimentary) complex (VS). The lithostratigraphic columns of the VS complex are widely variable, and their correlation is a misleading exercise. After volcanism the area experienced pronounced subsidence, with deposition of a conformable, several kilometers thick flysch group, the Baixo Altentejo Flysch Group (base of Visean to Westphalian). During the time of flysch deposition large scale synsedimentary deformation took place, enhanced by probably continuous, subsequent tectonic compression. The result is, at the present erosion level, a typical imbricate structure (in "piggy-back" sequence) characterised by overturned, frequently isoclinal folds, with thrusted reverse limbs, with VS anticlines and flysch synclines. The presence of pre-cleavage overthrusts complicates this basic pattern. Generally speaking, the whole region consists of a "thin - skinned" tectonic belt in the SW segment of the Iberian Hercynian orogen. Deformation was accompanied (and followed) by low grade (zeolite - lower greenschist facies) and low pressure regional metamorphism of essentially isochemical nature.

Mostly during the eighties the understanding of ore genesis has greatly improved. Thus it has been shown that ore fluids were generated during hydrothermal metamorphism of host rocks, especially felsic volcanics, from seawater derived hydrothermal fluids (perhaps with contributions from other sources). Several types of hydrothermal alteration of host rocks have been detected and characterised (e.g. regional alteration versus ore zone alteration).

2. THE GAVIÃO PROPERTY (ALJUSTREL AREA)

Here two orebodies were intersected by drilling in 1970, on the basis of geology backed up by geophysics (mostly gravimetry). One of the orebodies (Gavião NE) is an extension of other well known mineralisation in Aljustrel (S. João, Moinho and Algares), and is composed of ore low in Cu-Au. On the other hand, Gavião SW depicts the highest Cu grades of the whole Aljustrel camp. There are obvious exploration implications.

Gavião NE is included in the reverse limb of a Central Anticline. It is tightly folded, and disrupted by early thrust faults and wrench faults. It rests on top of volcanic rocks (Mine Tuff Formation). The immediate hanging wall is composed of a discontinuous jasper layer. Evidence from elsewhere (Moinho mine, Aljustrel, Pomarão, etc.) suggests that the jasper may have been originally bedded (continuous) and later disrupted during deformation (boudinage and perhaps soft sediment deformation).

Gavião SW is included in the reverse limb of another major anticline (SW Anticline). This is less deformed than Gavião NE, although equally affected by folding, thrusting and wrench faulting. The stratigraphic position of the orebody is nearly the same as for Gavião NE, but here a thin layer (up to a few metres) of hanging wall volcanics (mine tuffs) is often found between the sulphides and the jasper.

In the Gavião area there are two formations of felsic volcanic rocks (previously identified and characterised in the Aljustrel area), at least partly laterally equivalent. These are the lowermost units exposed in the area, and are the Mine Tuff (MT) (ore host), and Quartz-eye Tuff (QET) formations. Physical volcanology (debated in the field with our French partners) indicates that the QET is essentially a thick ash-flow tuff, with very thin and rare ash-fall crystal tuff intercalations. The MT is more heterogeneous, better banded, and includes prominent felsites, some of which are possibly former lavas.

2.1. ALTERATION TYPES

The predominant alteration type found in Gavião volcanic rocks (both MT and QET formations) is green facies regional alteration (mostly very strong development of aggregates). Whole rock geochemistry shows that chlorite is often more abundant than estimated optically, given MgO abundances up to 5.3% MgO and H_2O are covariant, implying that MgO fixation and hydration are related phenomena.

Ore zone alteration is also widespread. Type 1 (chlorite-quartz-sulphides) is rare. Type 2 (sericite-quartz-sulphides) is the dominant alteration in many samples, overprinted on green facies regional alteration. It is characterised by complete replacement of igneous feldspars by K-sericite (see below), abundant hydrothermal quartz and sulphides, vein-controlled alteration, very low $Na_2O/(Na_2O+K_2O)$, very constant $(K_2O + BaO)/Al_2O_3$ between 0.2 and 0.3, and generally high total Fe (and Fe^{2+}/total Fe), particularly towards the cores of the hydrothermal systems. Type 2 ore zone alteration is surrounded, in the sense of greater distance to sulphide mineralisation, by an external alteration halo, type 3 alteration, described here for the first time. It is much subtler than the others (as it corresponds to weaker alteration), but affects a very large volume of volcanic rocks, and is of particular importance in exploration, given its ultraperipheral situation with respect to ore. Regional alteration (earlier) predominates in samples where type 3 alteration can be detected by a)presence of hydrothermal quartz; b)sporadic occurrence of deformed (pre-tectonic) veins with quartz ± sericite ± chlorite ± sulphides surrounded by alteration halos; c)disseminated sulphides in rock matrix; d)presence of Na-bearing sericites replacing regional sericite, sometimes nearly pure paragonite; e)Fe^{2+}/total Fe shifted towards reduction (values near 1) in rocks otherwise similar to green facies regional alteration, (i.e. reduced rocks rich in Mg and Fe); f)high whole rock values of $Na_2O/(Na_2O + K_2O) > 0.5$, and $(K_2O + BaO)/Al_2O_3 < 0.14$.

Figure 1 depicts the variation of Na/Na+K in ore zone alteration sericites, projected as a function of horizontal distance to the axes of massive sulphide mineralisation and type 1 alteration, respectively (thus essentially a map view). It is apparent that type 2 alteration, generally identifiable in hand specimen (or easily seen in cursory thin section inspection), is present more than 500 metres beyond the axis of the SW orebody. Type 3 alteration persists up to 1000 metres, and can be detected without difficulty by means well within reach during exploration.

2.2. PRE-TECTONIC RELATIONSHIPS IN THE GAVIÃO AREA

Detailed knowledge of the alteration and its zonation, coupled with structural reinterpretation enabled reconstruction of the pretectonic relationships between the various host rocks, and sulphide ores and associated alteration halos around the Gavião orebodies. Figure 2 depicts the pre-tectonic relationships among the various rock types, ores, and alteration types, taking the jasper unit as horizontal reference level. This figure is particularly interesting as it is not a simple schematic representation, but a reasonably accurate tridimensional map instead.

3. APPLICATION TO OTHER SITUATIONS

The findings concerning the Gavião area are already being tested outside the Aljustrel area. A first exploration target under study is the Brejo prospect, near the Lousal mine. In an area covered by a few tens of metres of Tertiary sediments (Sado basin), there is a marked gravity anomaly that cannot be explained by basement relief alone (0.4 mGal Bouguer residual anomaly). Several shallow and two deep drillholes have already been made, providing geological data and samples. The area is structurally complex, and there are uncertainties concerning the significance of some rock types and possible tectonic accidents. Hydrothermal alteration is very prominent. Strongly chloritised quartzwackes, thick (tens of metres) zones of nearly massive sericite after pelitic material (probably volcanics), and zones of intense pyritisation (sometimes as metric intersections of nearly massive pyrite) are all highly favourable indicators of ore proximity. Ore zone alteration similar to that of the Aljustrel/Gavião area is present in Brejo, although there are significant differences. For example, carbonate (siderite) alteration is here far more important than at Aljustrel, and cherts and jaspers are rare.

Near Cerro de Durianas (Aldeia dos Elvas, Panóias), in an area with very little outcrop, manganese ore and bluish-gray chert occur probably immediately above felsic volcanic rocks. Geochemical study of the cherts indicates a hydrothermal origin. There is a nearby gravity anomaly that may correspond to massive sulphide ore.

Lithogeochemical work is being performed as part of actual exploration in the areas.

4. REFERENCES

Barriga F.J.A.S., coord., 1988: Identification of Diagnostic Markers of High Grade Massive Sulphide Deposits or of their Enriched Zones in Portugal (MA1M-0029-P). First Meeting of the Contact Group "Geochemical Methods in Exploration", EEC DGXX-C5, Padova, Italy.

Barriga F.J.A.S., 1990: Metallogenesis in the Iberian Pyrite Belt. In: Martinez-Garcia E., R.D. Dallmeyer, eds., Pre-Mesozoic Geology of Iberia, Springer-Verlag. In press.

Barriga F.J.A.S., P. Carvalho, A. Ferreira, D. Richards, 1990: Geology of the Neves-Corvo Volcanogenic Cu-Sn-Zn Sulfide Deposits, Beja District, South Portugal. Invited paper for Symposium SEC II, GSA Annual Meeting, Dallas, USA (abs., in press).

Barriga F.J.A.S., W.S. Fyfe, 1988: Giant pyritic base-metal deposits: the example of Feitais (Aljustrel, Portugal). Chem. Geol. 69: 331-343.

Relvas J.M.R.S., 1990: Estudo Geológico e Metalogenético da area de Gavião, Baixo Alentejo. M.Sc. Thesis, University of Lisbon.

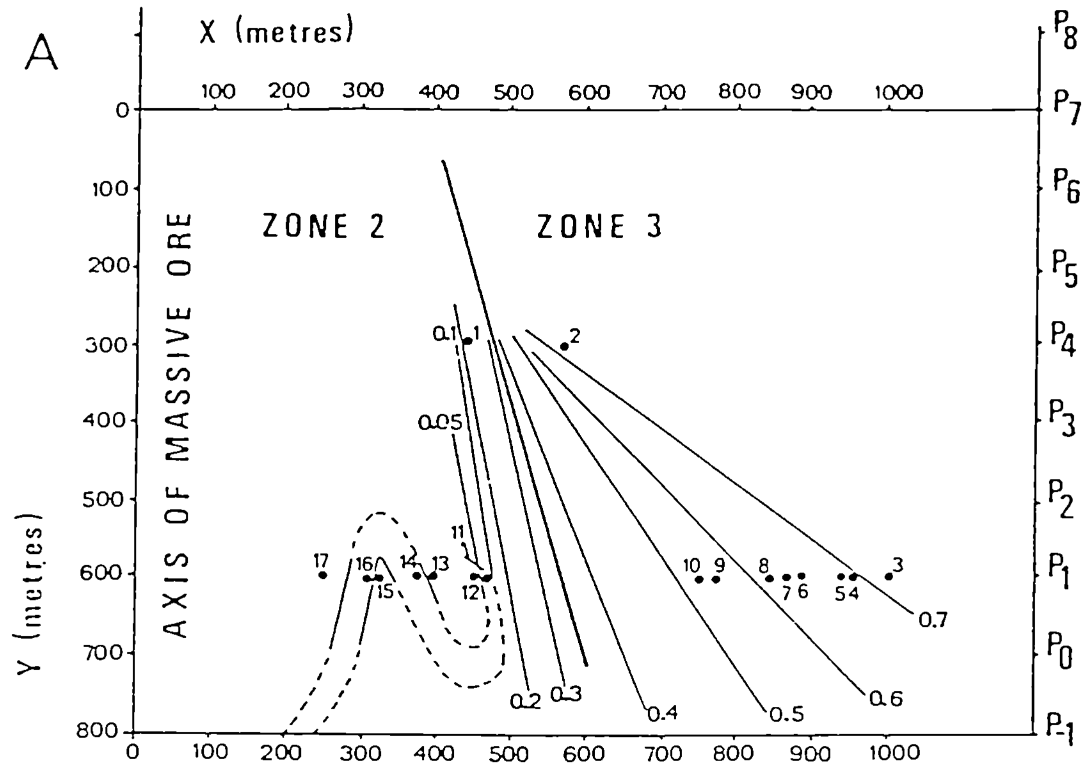
Relvas J.M.R.S., C.M.R. Massano, F.J.A.S. Barriga, V. Oliveira, J. Damião, 1990: Lithogeochemical Exploration in the Iberian Pyrite Belt. In preparation.

Figure Captions

Figure 1: Plan view of the variation of Na/Na+K in ore zone alteration sericites (average by sample). X: lateral distance to longer axis of massive sulphide mineralisation; Y: distance (normal to X) to the centre of ore zone (stockwork) alteration. A: SW Gavião orebody; B: NE Gavião orebody.

Figure 2: Tridimensional approximate reconstruction of the predeformation spatial relationships in the Gavião area, using the Jasper unit as a horizontal reference level. P-1 to P8, position of drilling cross-sections. Ore-zone alteration zones 1, 2 and 3, type 1, 2 and 3 alteration, respectively. Regional alteration not represented. See text.

A


X (metres)
Y (metres)
AXIS OF MASSIVE ORE
ZONE 2
ZONE 3
P8
P7
P6
P5
P4
P3
P2
P1
P0
P-1

B

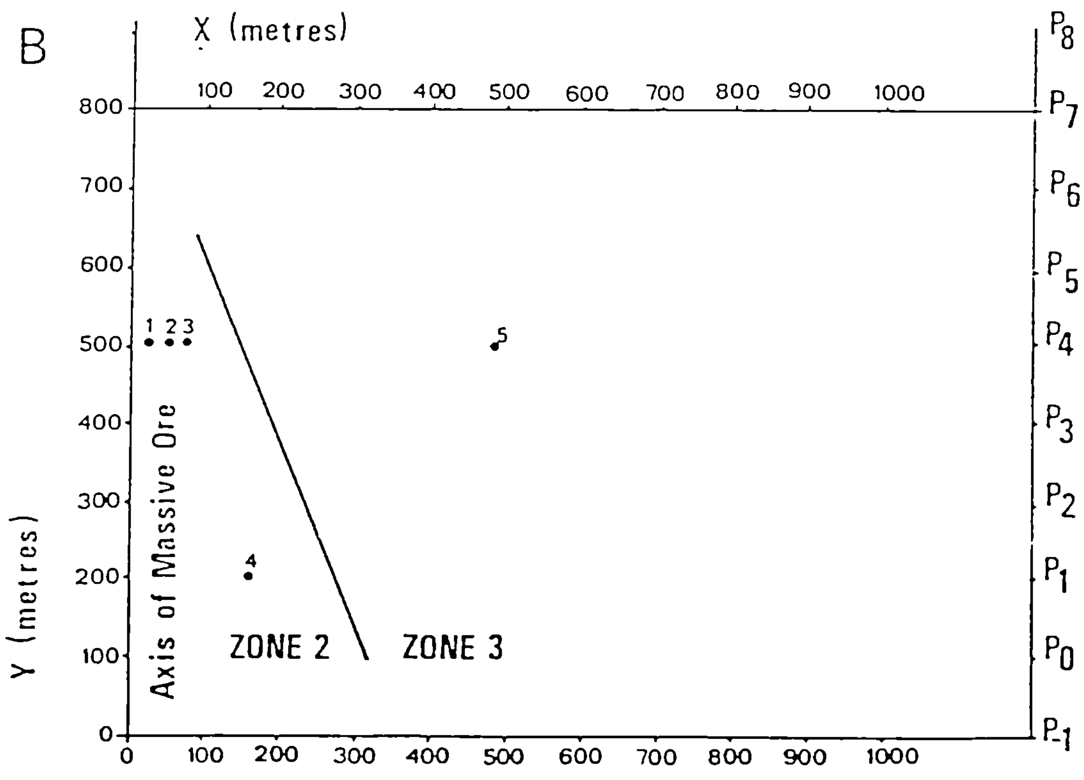

X (metres)
Y (metres)
Axis of Massive Ore
ZONE 2
ZONE 3
P8
P7
P6
P5
P4
P3
P2
P1
P0
P-1

Figure 1

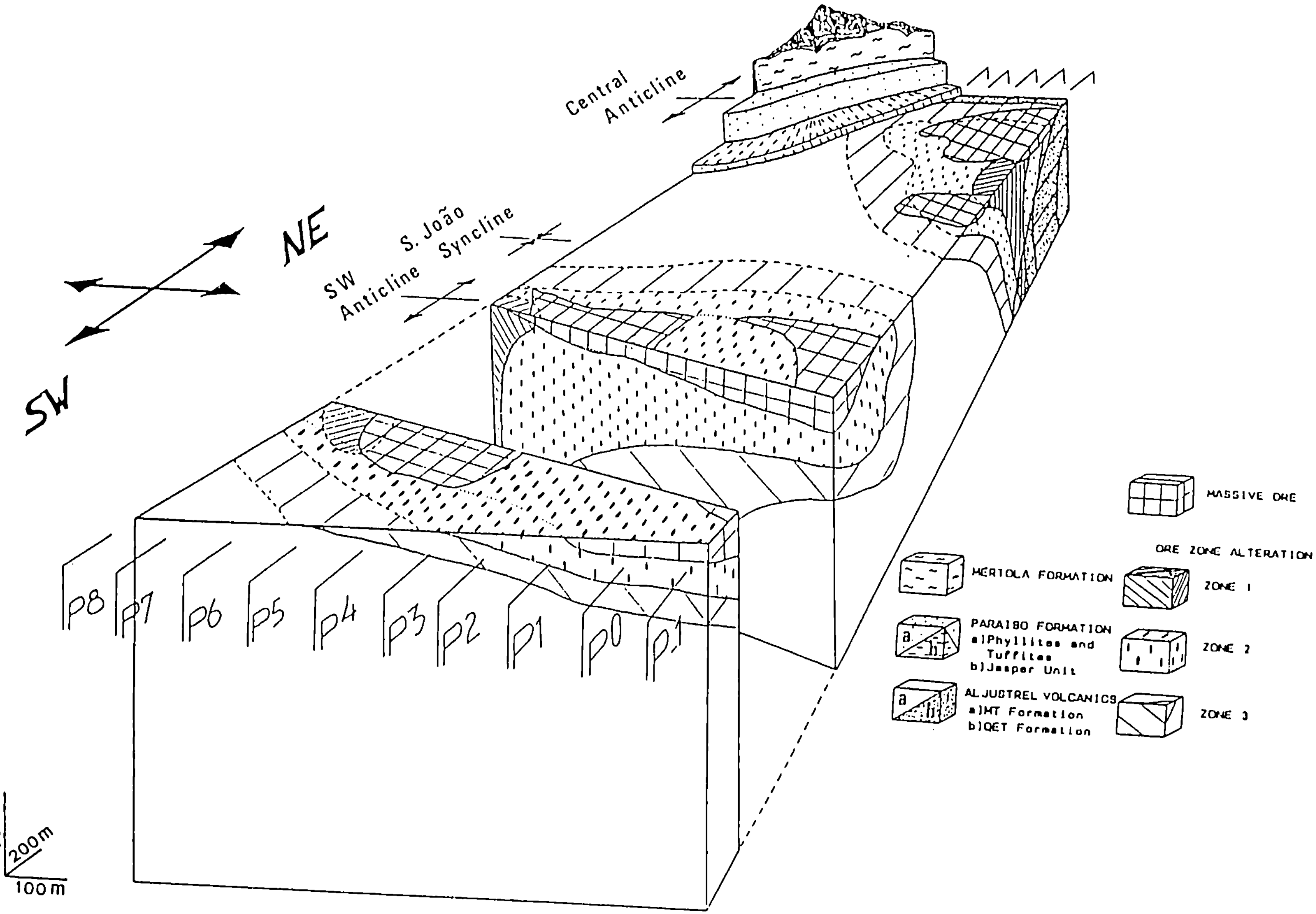

Central Anticline
S. João Syncline
SW Anticline
SW
NE
P8
P7
P6
P5
P4
P3
P2
P1
P0
P1
100 m
200 m
100 m
MASSIVE ORE
ORE ZONE ALTERATION
MERTOLA FORMATION
ZONE 1
PARAIBO FORMATION
a)Phyllites and Tuffites
b)Jasper Unit
ZONE 2
ALJUSTREL VOLCANICS
a)MT Formation
b)QET Formation
ZONE 3

Figure 2

DEVELOPMENT OF NEW MULTI-DISCIPLINARY TECHNIQUES FOR MINERAL EXPLORATION IN SEVERAL AREAS OF THE WESTERN IBERIAN PENINSULA - PART 1

Project Leader: P. GUMIEL
Instituto Tecnologico GeoMinero de España (ITGE), Madrid, Spain

Contract MA1M-0032-C(A)

1. OBJECTIVE

This report outlines the findings of a research and development project involving the ITGE (Spain), ENUSA (Spain), ENU (Portugal), Salamanca University (Spain) and Southampton University (U.K.). The fundamental aim of the project is to develop new mineral exploration strategies applicable within the Iberian Peninsula for a variety of elements, including Sn, W, Nb, Ta, Li, Sb, Au and U.

It is ambitious in that it involved government, industry and university groups of three nationalities, with a wide variety of techniques and expertise, attempting to tackle several areas of considerable mineral potential. The logistical support of ITGE has been particularly important in the coordination of these participating institutions.

Finally, the most important aspect of this venture has been the final report. The intention has been to produce a common report in which an attempt has been made to integrate the data and provide a summary of relevant results. This final report has been divided in two volumes. Volume 1 presents the results of the collaboration between ITGE (Spain) and the University of Southampton (U.K.) which focused on an area of gold mineralisation, the La Codosera area, within the Extremadura region of SW Spain.

The present investigation commenced in the Autumn of 1987 and utilised the initial work of the ITGE who have contributed significantly to the current knowledge of the area through several mineral exploration projects in the "State Reserva of La Codosera". Extensive fieldwork periods were undertaken in the initial stages to establish a "Geological Framework" within which the more sophisticated geochemical and remotely sensed data could be interpreted.

Ten chapters are presented outlining the results of the various techniques employed (structural geology, geochemistry, remote sensing, gravity, etc.) and which clearly reflect the multidisciplinary nature of the project. Most importantly, the key findings of each contribution are then drawn together in the final chapter to provide new exploration targets within the region and relevant to future exploration in the Community.

Volume 2 presents the results of the collaboration between ITGE and other partners ENUSA (Spain), ENU (Portugal), Salamanca University (Spain) and Southampton University (U.K.) in which the other substances (uranium and tungsten) have been grouped together by working areas.

The logistical support of ENUSA in the most important Iberian uranium mine (Fe mine, Ciudad Rodrigo) and ENU in Azere and Nisa (Portugal) has been particularly important.

Thirteen chapters are presented outlining the results of the various techniques employed, from structural geology, airbone geophysics-a combined helicopter-borne magnetic, electromagnetic and VLF- gravity, remote sensing-Landsat TM imagery-, lithogeochemistry, to stable isotopes in Fe mine in order to improve the current knowledge of the uranium mineralization in Spain and Portugal which represent the most important uranium potential within the Community.

2. ANALYSIS OF RESULTS

2.1. SUMMARY OF MAIN FINDINGS IN LA CODOSERA AREA

2.1.1. Tectonic setting

The La Codosera area is located within the Central Iberian zone immediately north of the Badajoz Shear Zone (Fig. 1a). The rocks can be correlated with similar sequences elsewhere in Central Spain and comprise a Precambrian (CEG) sequence overlain unconformably by alternations of quartzite and slates ranging from Lower Ordovician to Devonian in age. The latter hosts most of the gold-antimony mineralization.

The Precambrian rocks were subject to Pre-Ordovician tilting and open folding, accompanied by local faulting and veining, but no cleavage. These, together with overlying Ordovician-Devonian rocks were subsequently affected by Hercynian ductile deformation, which produced steeply inclined folds, cleavage and faulting. Intense left-lateral shearing on the southern limb of the La Codosera Syncline produced augen, shear bands, sub- horizontal stretching lineation, boudinage, variably oriented folds and steep faults, whereas the northern limb of the syncline is characterised by folding and thrusting in a transpressional regime, with limited net northward transport.

The geometry of the structures in the La Codosera area, and their spatial and temporal variations indicate the importance of left-lateral transpression throughout much of the Hercynian deformation. The greatest strike-slip component is localized within the Badajoz-Cordoba Shear Zone. Thus early folding and thrusting within the Central Iberian Zone became increasingly transpressive towards its southern margin, producing a progressive change from thrust to strike-slip tectonics across the La Codosera area. D2 deformation was more localized, but maintained a left-lateral component. Late Hercynian faulting produced N-S and NE-SW faults which overprint the early structures and granites. These rotate to a NW-SE trend and increase in right-lateral displacement as a result of domino or bookshelf faulting which can be attributed to continued left-lateral motion along the Badajoz Shear Zone (Fig.1b).

2.1.2. Gold exploration

ITGE's gold exploration programme has involved geological mapping at various scales, soil and stream sediment geochemical surveys and lithogeochemistry of specific formations. Within the anomalous gold zones, ITGE has re-opened old workings, trenched and diamond drilled specific targets. Los Algarbes represents one of the most interesting areas, where mapping at a scale of 1:5000, complemented by soil sampling, has indicated three major anomalies (La Portilla, Brena and Mataslete) with Au values higher than 0.3ppm in soils. Furthermore lithogeochemical studies of host lithologies from drill holes suggest that specific horizons where quartz veining is widespread carry significant gold (e.g. Lower Devonian Quartzite 0.49 ppm, iron -rich sandstones 0.013 ppm).

The most significant gold prospects are located on a series of steep quartz veins trending 040°, which show grades of up to 10g/t Au, over a maximum thickness of 1.5 m, and are generally restricted to the Devonian black slates. These veins are developed on extension faults which post-date the main S1 cleavage. The veins show little visible wall-rock alteration in the field and conform to the commonly described "gold only" veins with a restricted mineralogy of pyrite and arsenopyrite.

2.1.3. Geochemistry

Geochemical analyses indicate that the auriferous veins of the La Codosera area resulted from the passage of dilute, CO_2-rich fluids at temperatures of 350°C and depths of c.10km. The fluid contains appreciable amounts of methane (up to 20 mole %). The common association of mineralized veins within black slates suggests the reaction of fluid with carbonaceous wall-rock plays an important role in gold precipitation. The dilute nature of the fluid and the connectivity of veins to the Badajoz Shear Zone suggests a shear zone origin for the fluid. Beta-autoradiography indicates the gold is most likely lattice bound within the arsenopyrite structure.

2.1.4. Gravity

The gravity survey has demonstrated that the major source of density variation in the upper crust can be attributed to granites such as the Alburquerque Batholith. Some N-S trending profiles (eg. X660R) show additional gravity lows. The interpretation of this particular profile suggests the existence of a lower density body (granite) below the La Codosera syncline, separated from the main body of the Albuquerque batholith by an extension fault. In addition a significant negative anomaly of some -7.5 mgal (Fig.2), occurs to the west of La Codosera, extending beneath the Algarbes area.

2.1.5. Landsat TM

Digital classification of Landsat TM data has discriminated two spectrally contrasting soils within the contact aureole of the Alburquerque Batholith. The resulting classification delimits the metamorphic aureole of the granite. Extending this classification over a wider area outlines an area, west of La Codosera, where soils, derived from Devonian slates, show a spectral classification similar to those found within the contact aureole of the granite.

Comparison of the TM classification with aeroradiometric data, using a G.I.S. system, showed the coincidence of a moderate $K_{(e)}$ anomaly in the same sector as the anomalous soil classification west of La Codosera. These data in association with the observed gravity low and presence of spotted slates over the same area strongly suggest the presence of a granite cupola at depth (Fig.2).

2.1.6. Lineament Analysis

Using the Landsat data, combined with the ground structure, air photograph interpretation and gravity data, a clear picture of the fracture system has emerged. Three major sets of lineaments trend 045°, 135° and N-S and these correlate with extensional fractures, including those at known mineral prospects. In addition Landsat lineaments correlate with known faults in many parts of the area, thus providing a useful dataset with which to augment the regional structural studies.

Known U-P mineralization is largely confined to large 045° fractures with evidence that these veins form in arrays along 030° and 065° lineaments, many of which may be identified from Landsat. Sn, W and Li mineralization mainly occurs along both 135° and 045° fractures in the aureole of the Alburquerque granite, particularly where lineaments of these trends dominate.

Several E-W lineaments cut the Central Ridge and appear to correspond with known gold prospects of this trend. In the Southern Ridge, where the bulk of the prospects are located on quartz veins within Devonian quartzites and slates, a clear relationship between the mineralization and Landsat lineament pattern has been established.

2.2. USE OF GIS TO INTEGRATE EXPLORATION

The multidisciplinary nature of the project has generated a wide range of different spatial data, which can best be integrated and compared using a geographical information system (GIS). Geological maps, gravity, aeroradiometric data, and Landsat TM classification were analyzed using the GRASS software at ITGE. The resulting maps, discussed in Chapter 9, (Vol.1) illustrate the great potential of GIS within exploration programmes.

Not only can different data sets be superimposed quickly and accurately, but these data can be readily updated in response to further exploration and drilling. This has been particularly valuable in the intensively investigated area to the west of La Codosera. Fig. 2 shows the numerous gold occurrences (yellow triangles) and the drill holes (white spots) carried out by ITGE, superposed on the geological map. In addition selected anomalies are also displayed, these include moderate $K_{(e)}$ values (blue), the TM contact metamorphic soils (red) and the Bouguer gravity contours (white). The resulting coincidence of the negative gravity anomaly, moderate $K_{(e)}$ radiation and TM classified contact soils, suggestive of an intrusive body at depth, is clear.

2.3. STRUCTURAL CONTROL OF GOLD MINERALIZATION IN THE LA CODOSERA AREA

In the Los Algarbes area, the main prospects lie on steep N-S to NE-SW veins developed as extensional fractures with some left-lateral reactivation, sited at the terminations of the larger NE-SW faults. These major fracture zones (lineaments) provide connectivity between the shear zone and the Southern Ridge of Palaeozoic rocks which host the main Au-Sb mineralization.

Based on detailed observation of the structural setting of veins and investigation of their geochemistry and fluid characteristics, a number of prospective settings have been recognised (Fig.3). The gold-bearing veins generally occupy N-S to NE-SW trending extension fractures developed at the terminations (Fig.3(A)) or offsets (Fig.3(B)) of major NW-SE trending faults or where dilation was produced at intersections of these with their conjugate (NE-SW) set (Fig.3(C)).

The NW-SE faults have a right-lateral component of slip and form part of an extensive "bookshelf" or "domino" system linking the Southern Ridge to the Badajoz Shear Zone. Maximum dilation will occur where the domino faults change orientation or have large displacement. It is significant that the main area of old Au workings at Los Algarbes occurs at the northwestern end of the main change in orientation of the domino faults and that the San Antonio antimony mine occurs at the NW extension of a large displacement fault (Fig.4). Using the known structural controls, the lineament map provides a basis from which to identify new target areas which show abundant N-S to NE-SW fracturing in a similar structural setting (Fig.4).

The current drilling programme at Los Algarbes (Section 4.3, Vol.1) is within one of the proposed target areas and confirms that the gold is associated with NNE trending extension veins, possibly developed as pinnates to a NE-SW fault, conjugate to the main NW-SE "feeder" faults (Fig.5).

The spatial association of the Los Algarbes area with a gravity low, anomalous $K_{(e)}$ radiation and TM signatures characteristic of known contact metamorphic soils suggest the presence of a buried pluton (Fig.2). The fluid chemistry of auriferous veins, however, supports a shear zone source; the methane content possibly reflecting interaction with carbonaceous shales. In addition we note the presence of auriferous quartz veins in areas such as the Central Ridge, which are not underlain by granites. Thus, the role of the buried plutons may be to act as stress concentrators, promoting fracturation, or they may control and enhance pore fluid circulation.

This study has demonstrated a strong structural control to the mineralization of the La Codosera area. An understanding of the kinematics of these structures and the nature of the mineralizing fluid then allows exploration models to be developed. Remotely sensed data from Landsat TM, when combined with a good ground control can then be used to systematically define prospective targets.

2.4. SUMMARY OF MAIN FINDINGS IN THE URANIFEROUS AREAS OF CIUDAD RODRIGO (SPAIN) AND AZERE & NISA (PORTUGAL).

Fe mine is structurally organized by WSW-ENE trending fractures set which distribute the area in blocks. This fracture zones have been picked up in the field and also by other exploration methods such as airborne geophysics, gravity and remote sensing which have been integrated in a GIS available at ITGE. These fracture zones are brittle-ductile shear zones acting from Hercynian to Tertiary and showing different reactivations. Most of the uranium occurrences are set up in these or around these structures.

The Landsat lineaments study has demonstrated that remotely sensed data combined with air photography can be used to map the fracture pattern in the Fe mine area. These fractures exert a structural control on the mineralization, as at Fe mine itself where mineralization occurs along faults. The kinematics of these structures involves reactivation under at least two different stress systems, but uranium mineralization cannot be linked to particular phases of movement. Thus mapping of lineaments from Landsat may be of use in following out local anomalies.

Based on the current geological knowledge of the Fe mine area and on the integration of different data sets generated in this project (TM imagery, gravity and structural geology - Fig. 6), the WSW-ENE trending fracture zones may be considered as "structural corridors". The role of these corridors could favour granite emplacement existing near granitic basement below the CEG rocks around Fe mine.

Based on the strong structural control of the Fe mineralization at different scales, the application and combination of several geophysical methods at various scales is an important tool in mineral exploration in the area, delineating structures hosting uranium mineralization. Particularly, the airborne geophysics -a combined helicopter borne, magnetic, electromagnetic and VLF- gives interesting information about lithologies and structures. The information obtained from these methods is comparative to that coming from ground surveys, the latter being restricted to specific targets.

To further develop structural models would require detailed integration of field data and remote sensing work. Firstly, it is necessary to establish local uranium anomalies and to link these to particular structures (faults). Then these could be linked to specific lineaments based on their directional, spatial and temporal relationships. Once this is established the Landsat imagery may be used as an aid to map specific lineaments or zones of particular pattern. Only when kinematics are understood can models be developed which relate the structural control of the various types of mineralization to specific locations, providing exploration targets.

The lithogeochemical study carried out on CEG shows that carbonaceous slates have high U content (U > 10 ppm) $U_{(tot)}-C_{(org)}$ being correlated in unfractured rocks. The influence of these carbonaceous rocks as potential source of the U-mineralization may be of major importance. But the enrichment and concentration of the mineralization is fracture-controlled, particularly reactivations of faults mainly in the Alpine Cycle. These data are supported by the radiometric age of the pitchblende (35 $\pm$2M.a, see chap. 9, vol. 2).

Based on fluid inclusion and stable isotope (O, C, & S) data on the Fe mineralization, the most appropriate model for the origin of the deposit is that of a hydrothermal system operating in response to Alpine tectonic activity in the lower to middle Tertiary. Extensive, steeply-dipping faults permitted the deep penetration of meteoric water which became heated and reacted with the metasedimentary rocks. Uranium and other components of the mineralization, such as Mg, Ca, K, Fe, Mn, C and S were derived by leaching from metasediments. The hydrothermal system , as suggested by Arribas (1985), may have been driven by seismic pumping processes.

The portuguese uranium deposits (Iberian type) show an spatial distribution related to some U-bearing, post-kinematics Hercynian granites. As the uranium deposits in Spain, the mineralizations in Portugal (Azere and Nisa) are structurally controlled. The fracture zones, particularly reactivations of faults, provide fluid flow and sites for uranium concentration. Some specific lithologies may be considered as a target.

The integration of different techniques aids to mineral exploration in both uraniferous areas in Spain and Portugal providing new strategies for discovering potential areas.

In the Azere region the blocks architecture (horst and grabens) is a differentiation criterion delineating potential areas.

Based on the combination of remotely sensed data from Landsat TM, air photography and ground structural work, in the Nisa area, the main results concern the possible significance of major NW-SE lineaments. These fractures may control fluid flow and mineralization in the granite. Precipitation and concentration are associated with N-S extension fractures locating the vein style mineralization. It may be significant that such structures were not recognised in the Alburquerque part of the Batholith, which contains significantly less uranium mineralization.

2.4.1. Potential for gold mineralization in the Nisa region (Portugal)

There are no significant records of gold in the Nisa area, and this project was not concerned with this element in this region. It might, however, be worth pointing out that the structural style of lineaments in the Nisa area resembles closely that at La Codosera (see vol.1). There, the main prospects, such as Los Algarbes and La Portilla, lie on steep N-S to NE-SW veins, which appear to be developed as extensional fractures, with some left-lateral reactivation, sited at the terminations of the larger NW-SE faults (Fig.4). Using the known structural controls, the lineament map provides a basis from which to identify new target areas which show abundant N-S to NE-SW fracturing adjacent to large NW-SE lineaments; precisely the situation for many of the quartz veins to the east of Nisa.

The findings of this study have already proven of sufficient interest to warrant a series of presentations and in scientific publications which are outlined below.

3. PRESENTATIONS AT MEETINGS

Roberts S., Sanderson D.J., Nesbitt R.W. & Ashworth K.
MULTI-DISCIPLINARY TECHNIQUES FOR MINERAL EXPLORATION IN SEVERAL AREAS OF THE WESTERN IBERIAN PENINSULA
First meeting of the contact group : Geochemical methods in exploration. Padova. September 1988.

Gumiel P.
DEVELOPMENT OF NEW MULTIDISCIPLINARY TECHNIQUES FOR MINERAL EXPLORATION IN SEVERAL AREAS OF THE WESTERN IBERIAN PENINSULA
First meeting of the contact group : Geochemical methods in exploration. Padova. September 1988.

Roberts S. & Ashworth K.
TECTONIC AND FLUID EVOLUTION OF AURIFEROUS QUARTZ VEINS, LA CODOSERA AREA, SOUTHWEST SPAIN"
IMM Commodity meeting, London, December 1988.

Sanderson D.J., Roberts S. & Gumiel P.
HERCYNIAN THRUST/STRIKE-SLIP TECTONICS AT THE SOUTHERN MARGIN OF THE CENTRAL IBERIAN ZONE, WEST SPAIN
Tectonics Studies Group Meeting, Cambridge University, December 1988.

Anton-Pacheco C. & Sanderson D.J.
USE OF LANDSAT TM DATA IN MINERAL EXPLORATION, ALBURQUERQUE-LA CODOSERA AREA, SOUTHWEST SPAIN
Invited contribution, EUG meeting, Strasbourg, March 1989.

Anton-Pacheco C.
CARTOGRAFIA DIGITAL DE ROCAS EN EL AREA DE ALBURQUERQUE-LA CODOSERA, UTILIZANDO IMAGENES LANDSAT THEMATIC MAPPER
In III Reunion Cientifica del Grupo de Trabajo en Teledeteccion, Madrid, 17-19 Octubre 1989. Ministerio de Industria y Energia.

Sanderson D.J.
APPLICATION OF REMOTE SENSING IN TECTONICS AND MINERAL EXPLORATION
In III Reunion Cientifica del Grupo de Trabajo en Teledeteccion, Madrid, 17-19 Octubre 1989. Ministerio de Industria y Energia.

Perez Cerdan F., Garcia P., Anton-Pacheco C. & Gumiel J.C.
APLICACIONES DE UN SISTEMA DE INFORMACION GEOGRAFICO (S.I.G.) EN INVESTIGACION GEOLOGICA
In III Reunion Cientifica del Grupo de Trabajo en Teledeteccion, Madrid, 17-19 Octubre 1989. Ministerio de Industria y Energia.

Gumiel P., Anton-Pacheco C., Campos R. & Perez-Cerdan F.
DEVELOPMENT OF NEW MULTIDISCIPLINARY TECHNIQUES FOR MINERAL EXPLORATION IN SEVERAL AREAS OF THE WESTERN IBERIAN PENINSULA
EEC Meeting Paris 21-23 November 1989.

Anton-Pacheco C.
DIGITAL MAPPING OF ROCKS IN THE ALBURQUERQUE-LA CODOSERA AREA,EXTREMADURA, SPAIN USING LANDSAT TM DATA
In 2nd Meeting of the WEGS Working Group Remote Sensing. 7-8 March, 1990.BGR.Hannover FRG.

4. PUBLICATIONS

Campos R. & Gumiel P.
1990 ESTUDIO GRAVIMETRICO EN EXTREMADURA, (ZONAS DE LA CODOSERA-ALBURQUERQUE Y ALBALA) Y SU APLICACION A LA EXPLORACION DE YACIMIENTOS MINERALES
Bol.Geol.Min.vol 101-1 pp 122-134.

Roberts S., Sanderson D.J., Gumiel P. & Dee S.
TECTONIC AND FLUID EVOLUTION OF AURIFEROUS QUARTZ VEINS FROM THE LA CODOSERA AREA, SW SPAIN
In Prep. Economic Geology.

Sanderson D.J., Roberts S., Gumiel P. & Mcgowan J.
HERCYNIAN THRUST/STRIKE-SLIP TECTONICS AT THE SOUTHERN MARGIN OF THE CENTRAL IBERIAN ZONE, WEST SPAIN
Submitted to J. Geol.Soc.London.

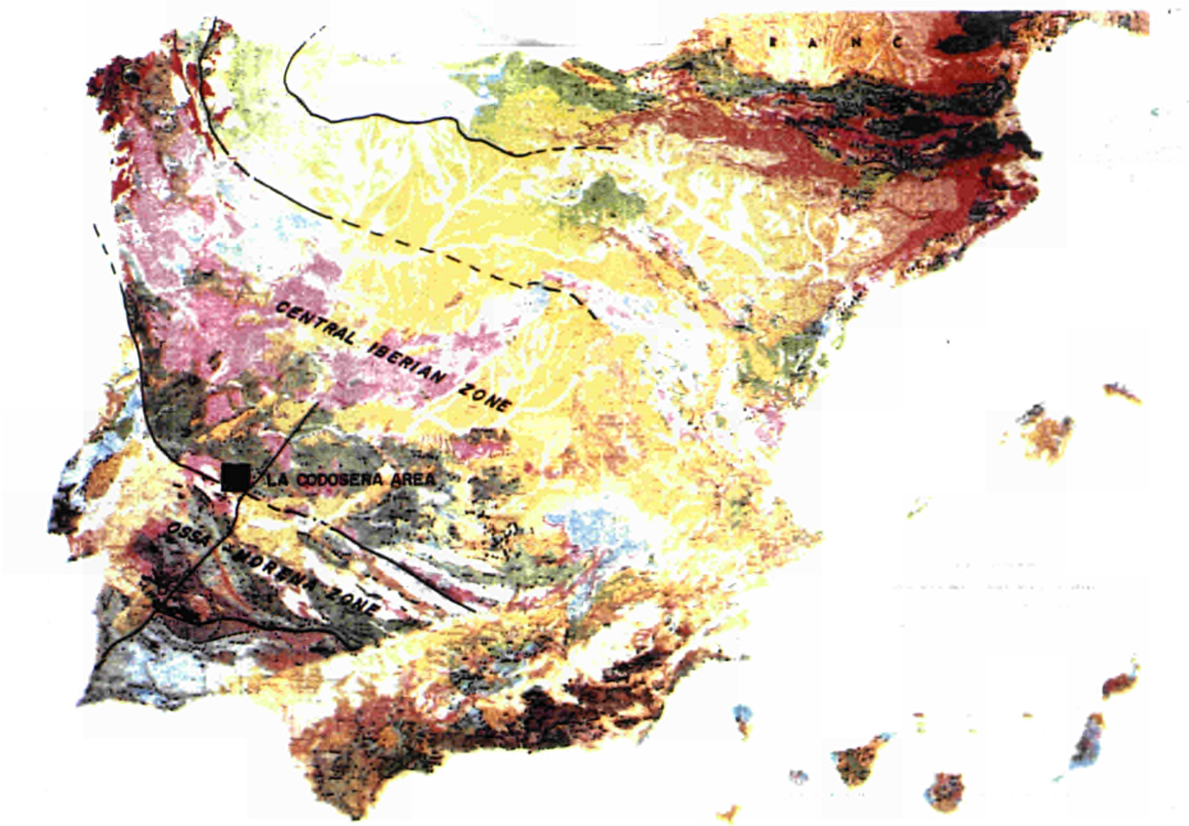


FIG. 1a - LOCATION OF THE LA CODOSERA AREA IN RELATION TO MAJOR HERCYNIAN ZONES.

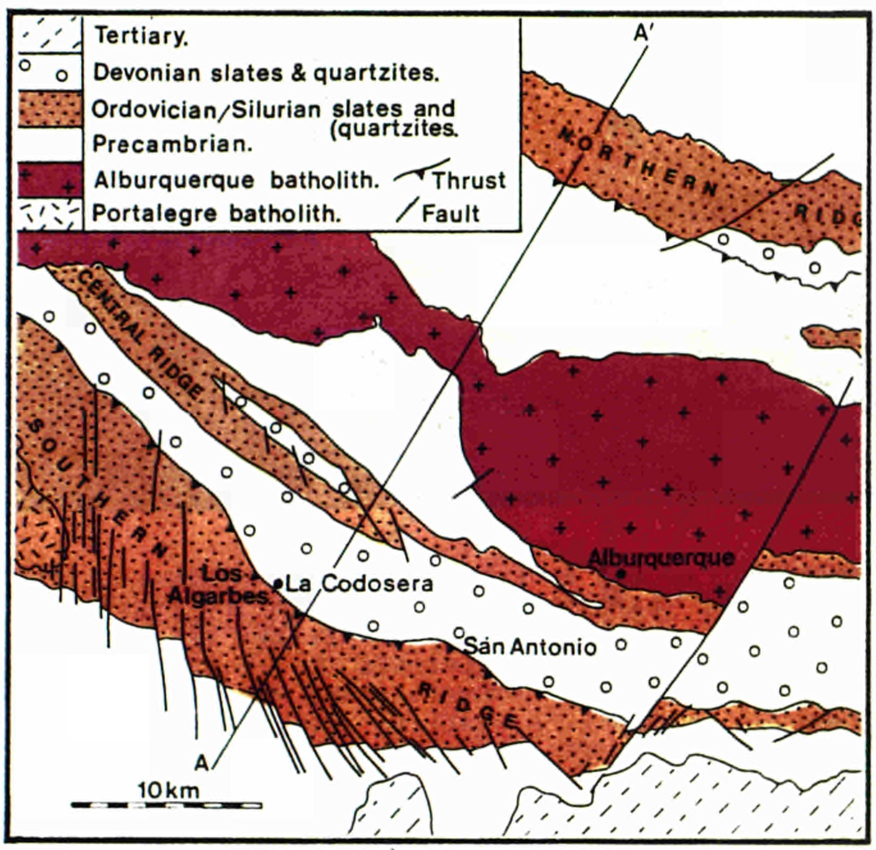


FIG. 1b - OUTLINE GEOLOGY OF THE LA CODOSERA AREA.

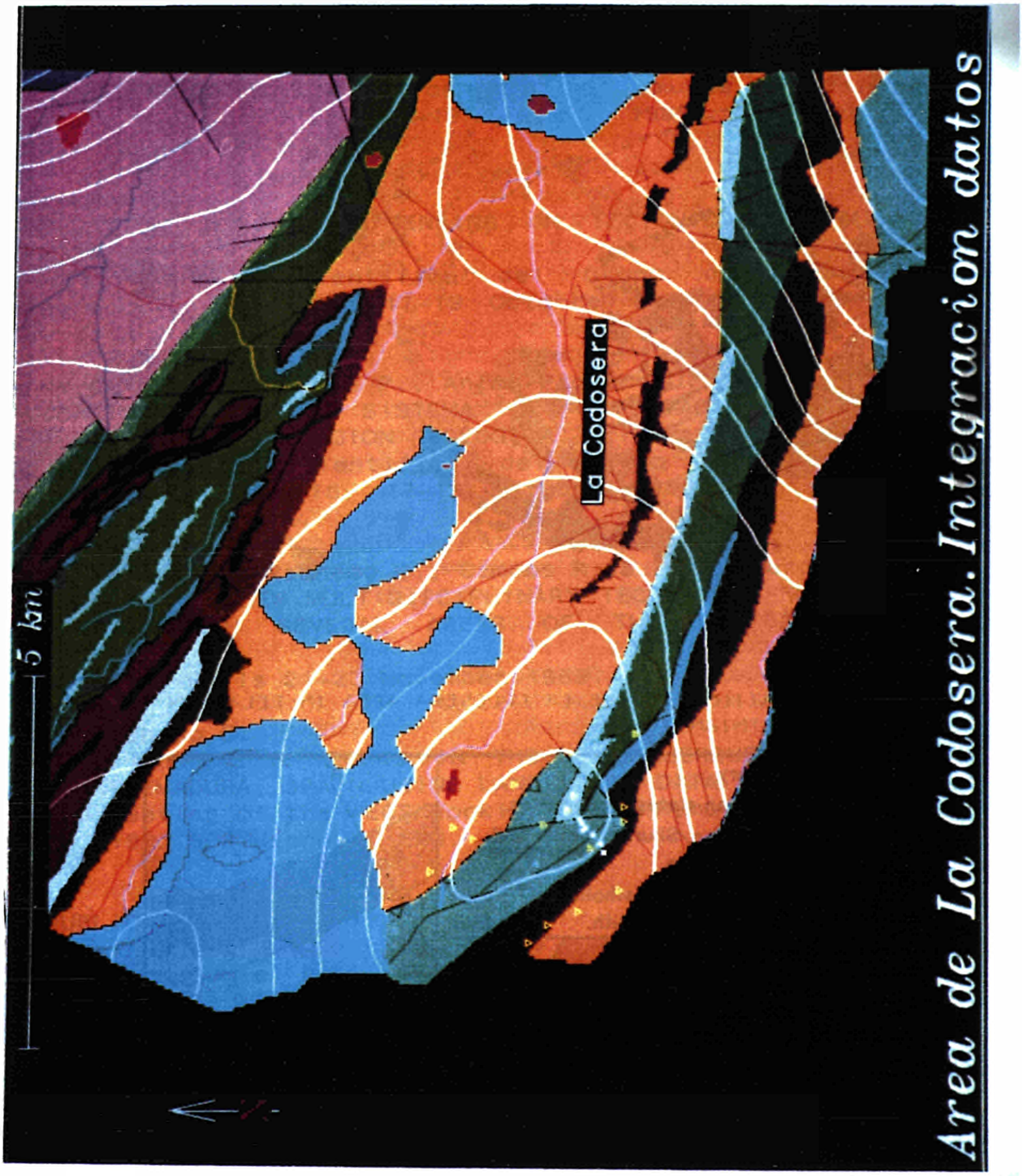


FIG 2 - POTENTIAL OF GIS IN CONNECTION WITH MINERAL EXPLORATION. INTEGRATED DATA SETS IN AN AREA TO THE WEST OF LA CODOSERA. GOLD OCCURRENCES (YELLOW TRIANGLES). DRILL-HOLES (WHITE SPOTS) SUPERPOSED ON THE GEOLOGICAL MAP. IN ADDITION SELECTED ANOMALIES ARE ALSO DISPLAYED. THESE INCLUDE MODERATE K VALUES (BLUE), THE TM CONTACT METAMORPHIC SOILS (RED) AND THE BOUGUER GRAVITY CONTOURS (WHITE).

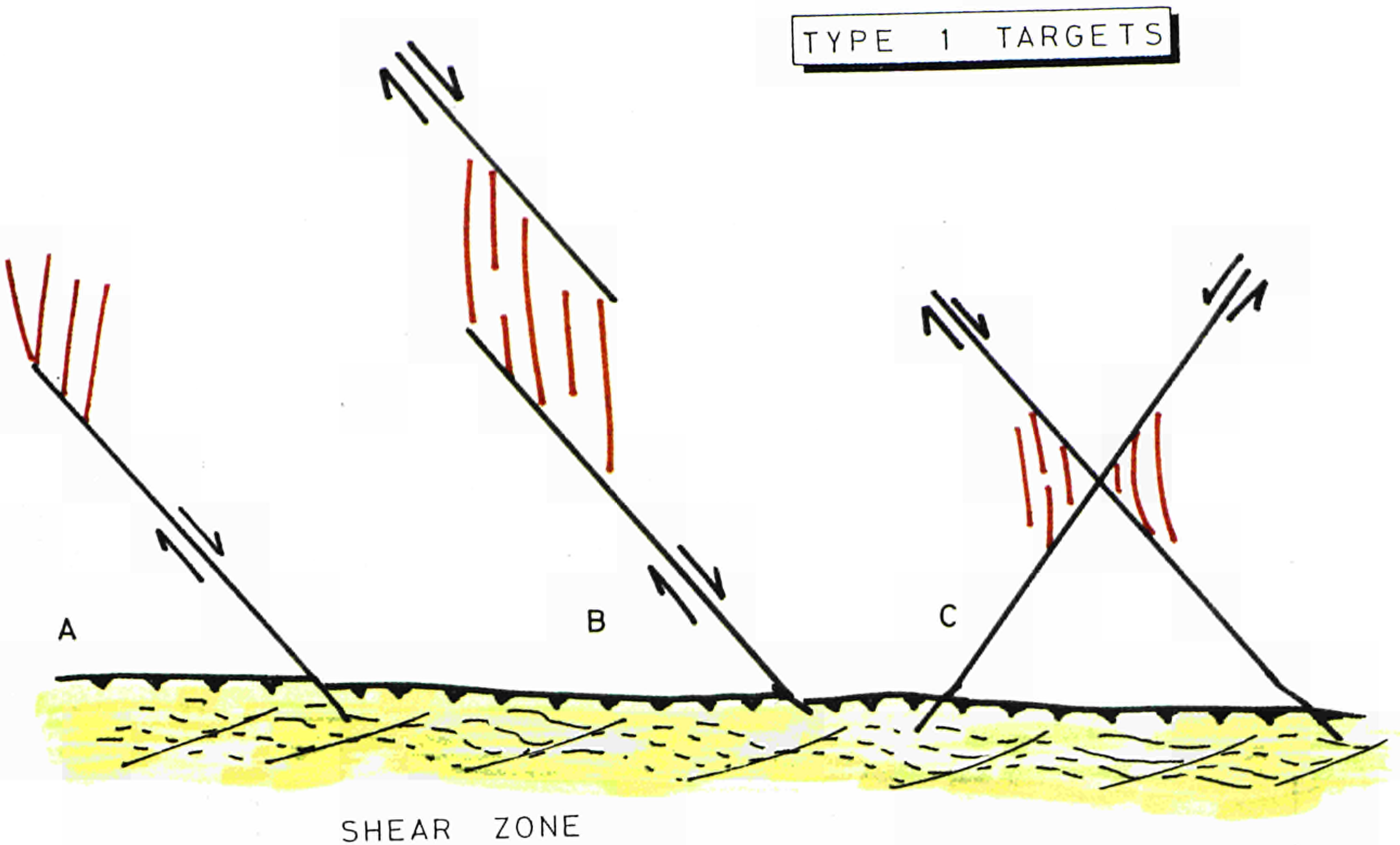


FIG 3 - TARGET TYPES RECOGNISED IN THE SOUTHERN RIDGE AT (A) TERMINATIONS AND (B) OFFSETS OF NW SE FAULTS AND (C) AT DILATIONAL AREAS OF INTERSECTING FAULTS.

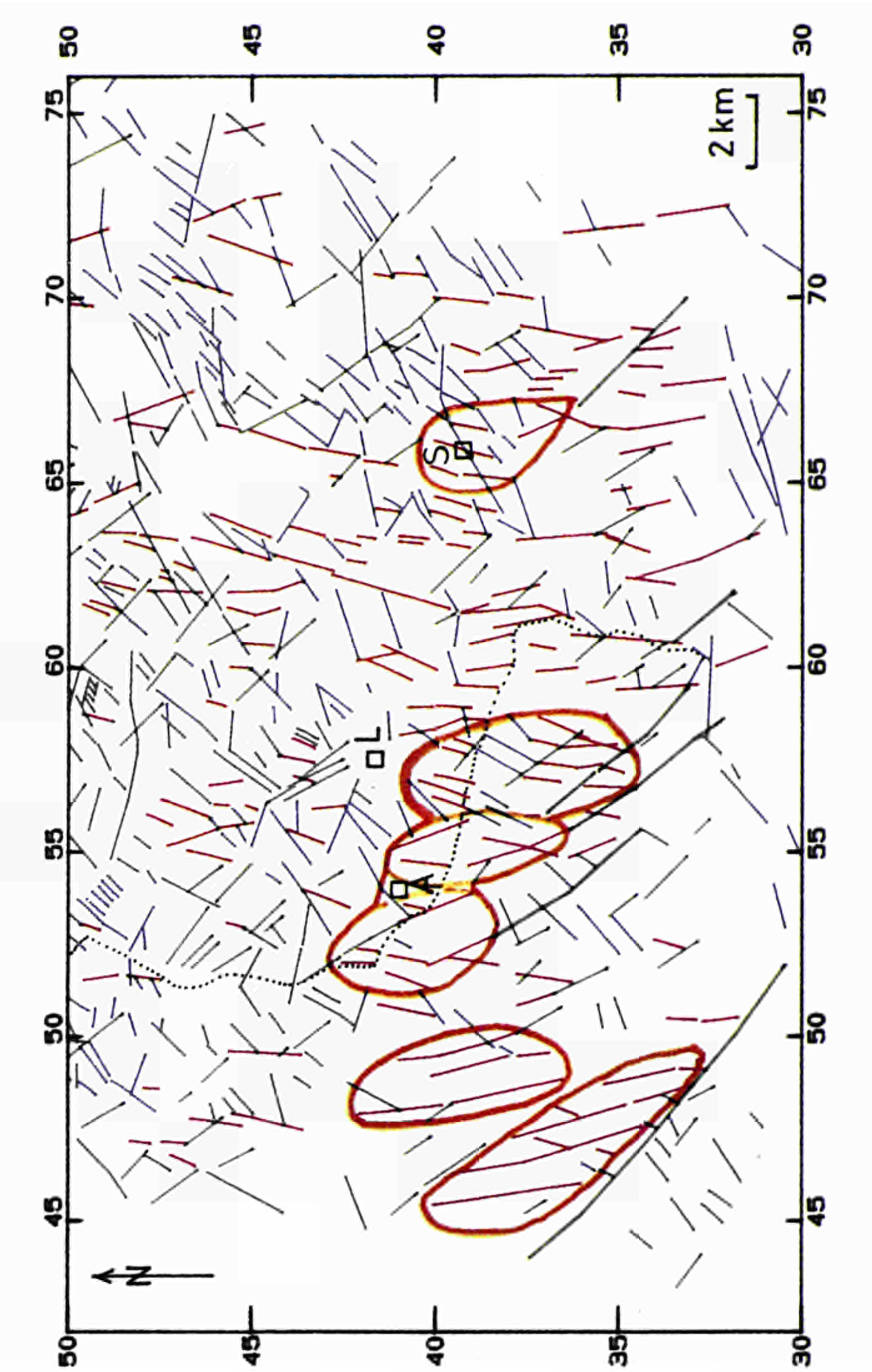
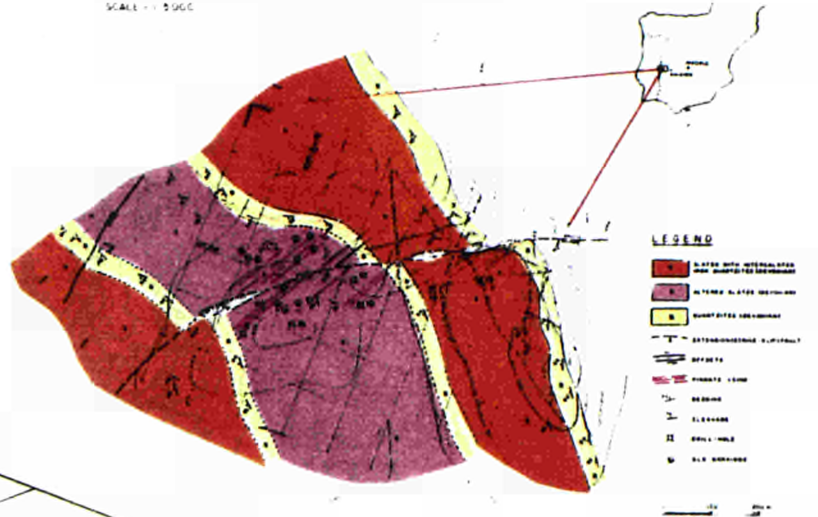


FIG 4 - LANDSAT TM LINEAMENT MAP OF THE SOUTHERN PART OF THE LA CODOSERA AREA. LARGE NW-SE LINEAMENTS (GREEN) REPRESENT FAULTS CONNECTING THE SOUTHERN RIDGE TO THE BADAJOZ SHEAR ZONE, WHICH FEED N-S EXTENSION FRACTURES (RED). TARGET AREAS BASED ON THE PATTERNS IN FIG. 11.2 ARE IDENTIFIED IN ORANGE.

GEOLOGICAL MAP OF "LOS ALGARBES" GOLD PROSPECT
(FROM FIELD WORK AND DRILL-HOLES DATA)



THREE-DIMENSIONAL MODEL OF "LOS ALGARBES"-GOLD DEPOSIT
FROM DRILL-HOLES DATA LA CODOSERA, BADAJOZ (SPAIN)

SCALE : 1:2.000

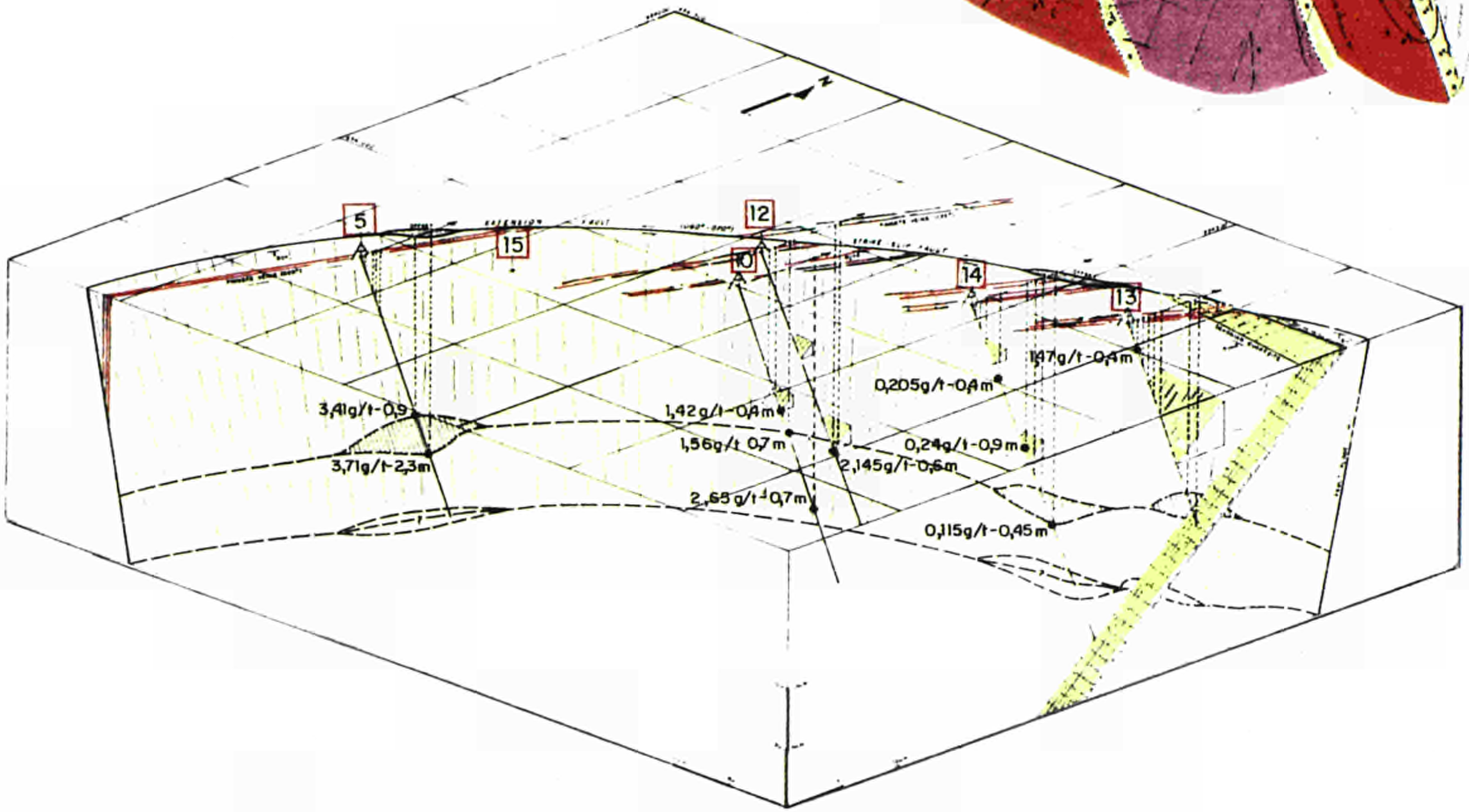
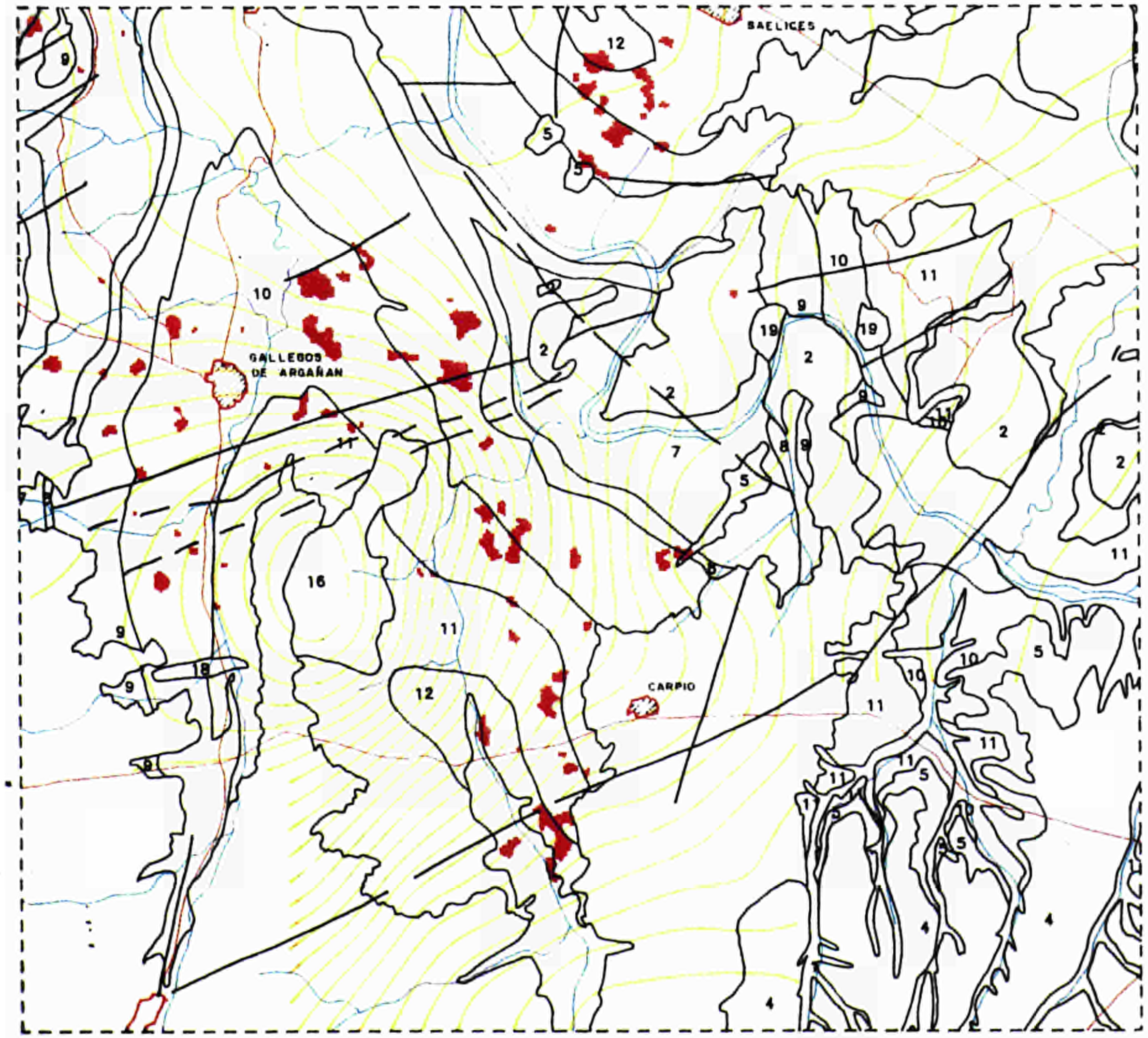


FIG. .5 - THREE-DIMENSIONAL MODEL OF LOS ALGARBES GOLD PROSPECT FROM DRILL-HOLES DATA.

Area de Ciudad Rodrigo

I.T.G.E. – S.I.G.



Coordenadas:

Norte: 4505001
Sur: 4493000
Este: 705000
Oeste: 692000

Escala 1: 60000

0 .5 1 Km

Cl.TM.
Gravimetri
Carretera
Poblacion
Drenaje
Falla
Contacto

FIGURA 6 - MAPA DE INTEGRACION DE DATOS DE LA ZONA DE GALLEGOS DE ARGANAN.

DEVELOPMENT OF NEW MULTI-DISCIPLINARY TECHNIQUES FOR MINERAL EXPLORATION IN SEVERAL AREAS OF THE WESTERN IBERIAN PENINSULA - PART 2

Project Leader: R.W. NESBITT
D.J. Sanderson, S. Roberts
Department of Geology, The University, Southampton, United Kingdom

Contract MA1M-0032-C

1. INTRODUCTION

This report outlines the contribution of the Department of Geology, Southampton University to the EEC contract "Development of new multi-disciplinary techniques for mineral exploration in several areas of the Western Iberian Peninsula" (see previous article of this volume). It focuses on the results more directly attributable to the Southampton part of the research although it should be emphasised that much of the work was done in the spirit of the EEC and is thus of a collaborative nature. Therefore, we must acknowledge in particular the assistance of the project leader Dr. Pablo Gumiel in the completion of this work.

2. OBJECTIVES

The aim of this project was the development of exploration guidelines for mineralization, in particular gold, within the central and west Iberian peninsula. Research activity by Southampton University and ITGE focused on regional structural studies, Landsat interpretation and geochemical analysis of the fluids deemed responsible for the mineralisation.

The following sections outline the main findings of each of the individual aims of the project. These findings are then drawn together in the production of a new exploration model for the region.

2.1 TECTONIC SETTING

The La Codosera area is located within the Central Iberian zone immediately north of the Badajoz Shear Zone (Fig. 1). The rocks can be correlated with similar sequences elsewhere in Central Spain and comprise a Precambrian (CEG) sequence overlain unconformably by alternations of quartzite and slates ranging from Lower Ordovician to Devonian in age. The latter host most of the gold-antimony mineralization.

The Precambrian rocks were subject to Pre-Ordovician tilting and open folding, accompanied by local faulting and veining, but no cleavage. These, together with overlying Ordovician-Devonian rocks were subsequently affected by Hercynian ductile deformation, which produced steeply inclined folds, cleavage and faulting. Intense left-lateral shearing on the southern limb of the La Codosera Syncline produced augen, shear bands, sub-horizontal stretching lineation, boudinage, variably oriented folds and steep faults, whereas the northern limb of the syncline is characterised by folding and thrusting in a transpressional regime, with limited net northward transport (Fig. 2).

The geometry of the structures in the La Codosera area, and their spatial and temporal variations indicate the importance of left-lateral transpression throughout much of the Hercynian deformation.

The greatest strike-slip component is localized within the Badajoz-Cordoba Shear Zone. Thus early folding and thrusting within the Central Iberian Zone became increasingly transpressive towards its southern margin, producing a progressive change from thrust to strike-slip tectonics across the La Codosera area. D2 deformation was more localized, but maintained a left-lateral component. Late Hercynian faulting produced N-S and NE-SW faults which overprint the early structures and granites. These rotate to a NW-SE trend and increase in right-lateral displacement as a result of domino or bookshelf faulting which can be attributed to continued left-lateral motion along the Badajoz Shear Zone.

2.2 GOLD PROSPECTS

The most significant gold prospects are located on a series of steep quartz veins trending 040°, which show grades of up to 10 gm/t Au, over a maximum thickness of 1.5 m, and are generally restricted to the Devonian black slates. These veins are developed on extension faults which post-date the main S1 cleavage (Fig. 3).

The veins show little visible wall-rock alteration in the field and conform to the commonly described "gold only" veins with a restricted mineralogy of pyrite and arsenopyrite.

2.3 GEOCHEMISTRY

Geochemical analyses indicate that the auriferous veins of the La Codosera area resulted from the passage of dilute, CO_2-rich fluids at temperatures of 350°C and depths of c.10 km. Bulk volatile and Raman analysis indicate that the fluid contains appreciable amounts of methane & nitrogen (combined total up to 20 mole %). The common association of mineralized veins within black slates and increase volatile component (Fig. 4) suggest the reaction of fluid with carbonaceous wall - rock plays an important role in gold precipitation.

The dilute nature of the fluid and the connectivity of veins to the Badajoz Shear Zone suggest a shear zone origin for the fluid. Beta-autoradiography indicates the gold is most likely lattice bound within the arsenopyrite structure.

2.4 LINEAMENT ANALYSIS

Using the Landsat data, combined with the ground structure, air photograph interpretation and gravity data, a clear picture of the fracture system has emerged.

Three major sets of lineaments trend 045°, 135° and N-S correlate with extensional fractures, including those at known mineral prospects. In addition Landsat lineaments correlate with known faults in many parts of the area, thus providing a useful dataset with which to augment the regional structural studies.

Known U - P mineralization is largely confined to large 045° fractures, with evidence that these veins form in arrays along 030° and 065° lineaments, many of which may be identified from Landsat. Sn, W and Li mineralization mainly occurs along both 135° and 045° fractures in the aureole of the Albuquerque granite, particularly where lineaments of these trends dominate.

Several E - W lineaments cut the Central Ridge and appear to correspond with known gold prospects of this trend. In the Southern Ridge, where the bulk of the prospects are located on quartz veins within Devonian quartzites and slates, a clear relationship between the mineralization and Landsat lineament pattern has been established (summarized below).

3. CONCLUSIONS

3.1 A NEW STRUCTURALLY BASED EXPLORATION MODEL FOR GOLD MINERALIZATION IN THE LA CODOSERA AREA, W. SPAIN.

In the Los Algarbes area, the main prospects lie on steep N-S to NE-SW veins developed as extensional fractures with some left-lateral reactivation, sited at the terminations of the larger NE-SW faults. These major fracture zones (lineaments) provide connectivity between the shear zone and the Southern Ridge of Palaeozoic rocks which host the main Au-Sb mineralization.

Based on detailed observation of the structural setting of veins and investigation of their geochemistry and fluid characteristics, we have recognised a number of prospective settings (Fig. 5). The gold-bearing veins generally occupy N-S to NE-SW trending extension fractures developed at the terminations (Fig. 5a) or offsets (Fig. 5b) of major NW-SW trending faults or where dilation was produced at intersections of these with their conjugate (NE-SW) set.

The NW-SW faults have a right-lateral component of slip and form part of an extensive "bookshelf" or "domino" system linking the Southern Ridge to the Badajoz Shear Zone (Fig. 6). Maximum dilation will occur where the domino faults change orientation or have large displacement. It is significant that the main area of old Au workings at Los Argarbes occurs at the northwestern end of the main change in orientation of the domino faults and that the San Antonio antimony mine occurs at the NW extension of a large displacement faults. **Using the known structural controls, the lineament map provides a basis from which to identify new target area which show abundant N-S to NE-SW fracturing in a similar structural setting (Fig. 7).**

The current drilling programme at Los Algarbes is within one of the proposed target areas and confirms that the gold is associated with NNE trending extension veins, possibly developed as pinnates to a NE-SW fault, conjugate to the main NW-SW "feeder" faults.

The spatial association of the Los Algarbes area with a gravity low, anomalous K radiation and TM signatures characteristic of known contact metamorphic soils suggest the presence of a buried pluton. The fluid chemistry of auriferous veins, however, supports a shear zone source; the methane content possibly reflecting interaction with carbonaceous shales. In addition we note the presence of auriferous quartz veins in areas such as the Central Ridge, which are not underlain by granites. Thus, the role of the buried plutons may be to act as stress concentrators, promoting fracturing, or they may control and enhance pore fluid circulation.

This study has demonstrated a strong structural control to the mineralization of the La Codosera area. **An understanding of the kinematics of these structures and the nature of the mineralizing fluid then allows exploration models to be developed.** Remotely sensed data from Landsat TM, when combined with a good ground control can then be used to systematically define prospective targets.

4. PRESENTATIONS

During the Contractual Period of the report the following presentations were made by members of the Southampton University research group :

Roberts S., Sanderson, D.J., Nesbitt, R.W. & Ashworth, K. "Multi-disciplinary techniques for mineral exploration in several areas of the Western Iberian Peninsula". EEC Contact Group Meeting, Padova, September, 1988.

Roberts S. & Ashworth, K. "Tectonic setting and fluid evolution of auriferous quartz veins, La Codosera area southwestern Spain". Institute of Mining & Metallurgy Commodity meeting, London, December, 1988.

Anton-Pacheco C. & Sanderson, D.J. "Use of Landsat TM data in mineral exploration, Albuquerque - La Codosera area, southwest Spain". Invited contribution, EUG meeting, Strasbourg, March, 1989.

Sanderson D.J. "Application of remote sensing in Tectonics and mineral exploration". In III Reunion Cientifica del Group de Trabajo en Teledeteccion, Madrid, October, 1989.

Roberts S. & Sanderson D.J. An exploration model for auriferous gold veins in the La Codosera area SW Spain. EEC Seminar on Exploration, Paris, November, 1989.

Roberts S. & Dee S. Tectonic and fluid evolution of auriferous quartz veins from the La Codosera area, SW Spain. Mineral Deposits Studies Group, Geological Society London, Cardiff, December, 1989.

5. PUBLICATIONS

Sanderson, D.J. & Chinn, C. 1990. Analysis of Landsat lineaments : an example applied to the structural control of mineralization at La Codosera, Extremadura, Spain. III Reunion Cientifica del Grupo de Trabajo en Teledeccion. 133 - 149..

Sanderson, D.J., Roberts S., Gumiel, P. and McGowan J. 1991. Hercynian strike - slip tectonics at the southern margin of the Central Iberian Zone, west Spain. 1991.
Journal of the Geological Society, London. v. 147.

Roberts S., Sanderson D.J. Gumiel, P. and Dee. S. (In Press) Tectonic and fluid evolution of auriferous quartz veins from the La Codosera area, SW Spain. Economic Geology.

EEC Final Report. 1991. Development of new multi-disciplinary techniques for mineral exploration in several areas of the western Iberian peninsula. Ed. P. Gumiel et al., 2 Volumes. 397p.

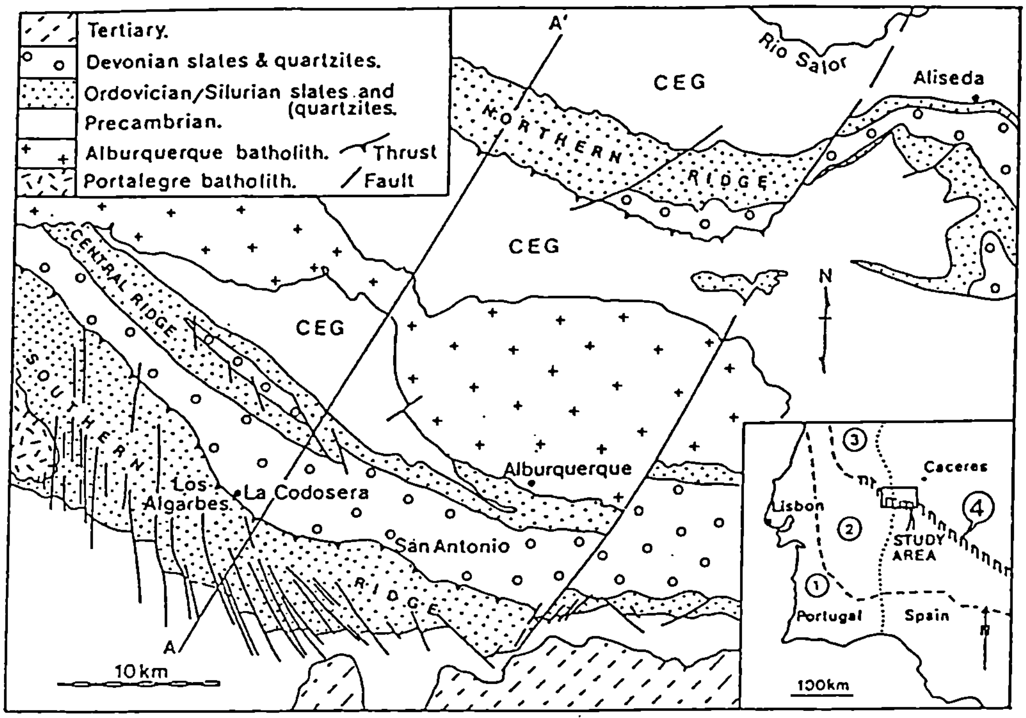


Figure 1. a) Location Map of the La Codosera area. 1, South Portuguese zone; 2, Ossa Morena zone; 3, Central Iberian zone; 4, Badajoz shear zone. b) Outline geological map of the La Codosera area. CEG, Complejo Equisto – Grauvaquico. A – A', line of section in Fig. 2.

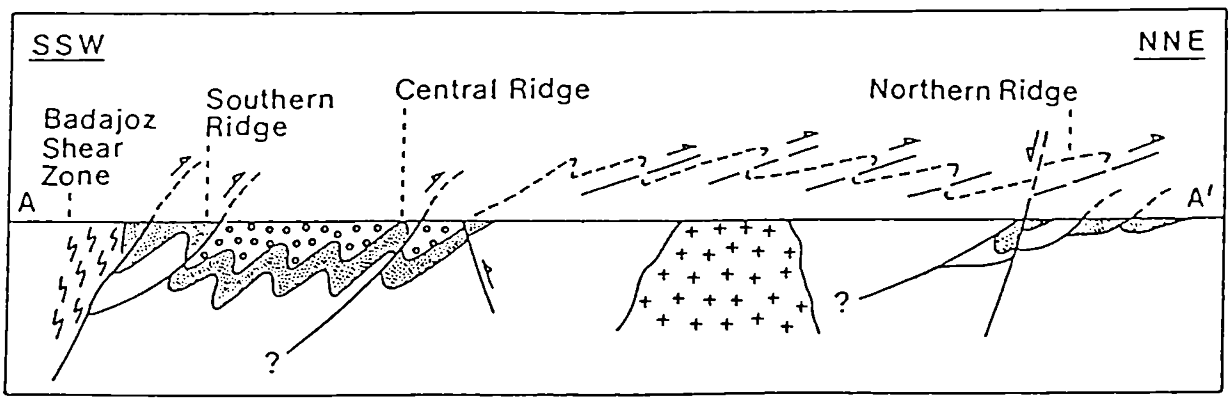


Figure 2. Simplified cross – section of the La Codosera area.

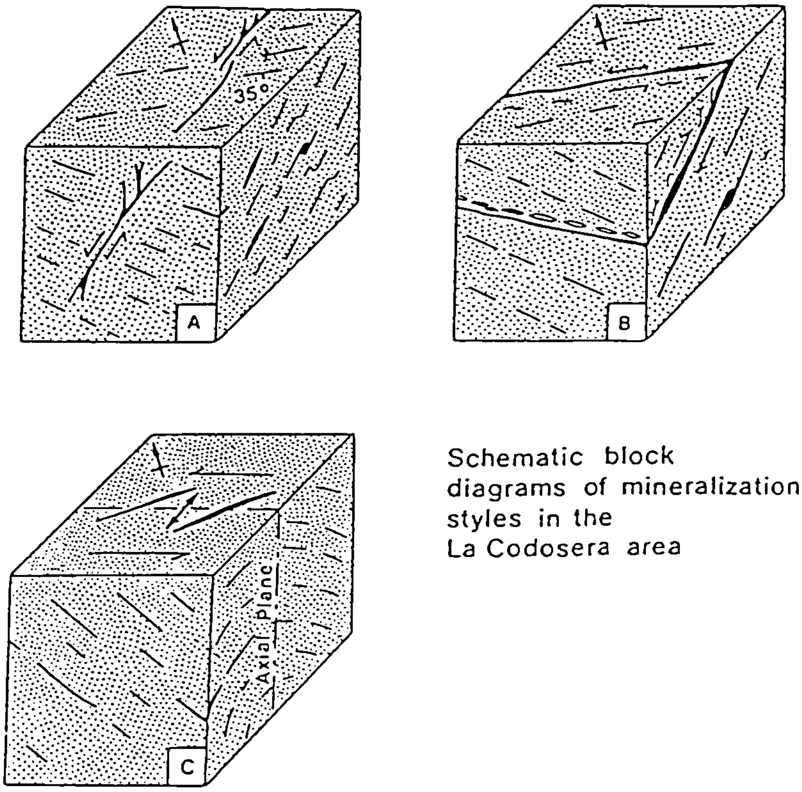


Figure 3. Schematic block diagram of the gold prospects; not to scale. a) High angle veins, typical of the geometry of mineralised localities of the Southern Ridge. The veins are at a high angle to the S1 fabric which is indicated by dashed lines. b) Strike parallel veins, commonly forming on minor detachment surfaces present in both ridges. c) E – W veins common within the core of the Central Ridge anticline.

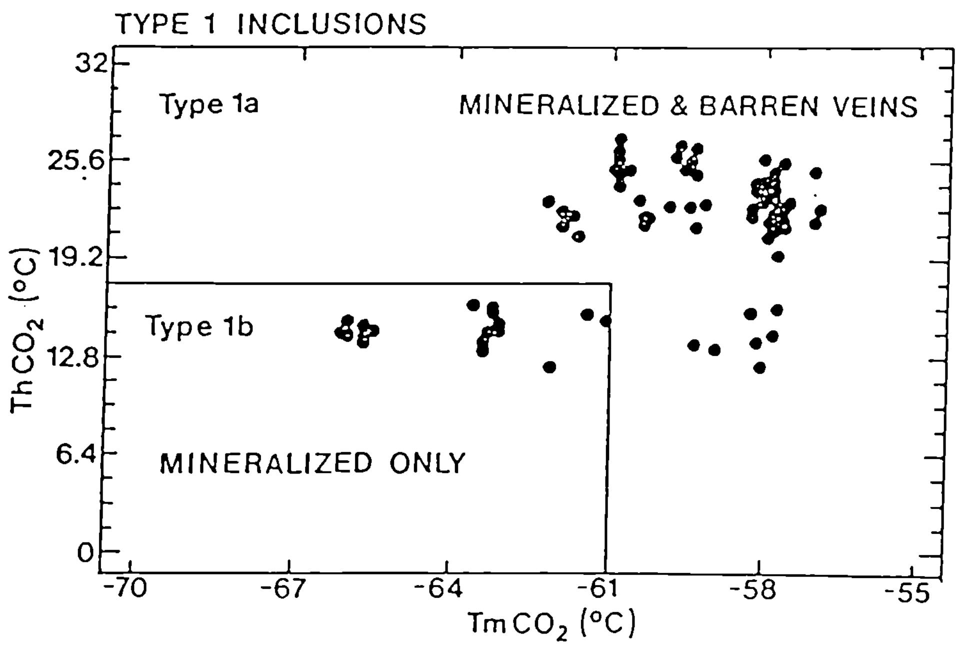


Figure 4. $TmCO_2$ v $ThCO_2$ for type 1 inclusions. Mineralized veins show lower $TmCO_2 - ThCO_2$ values.

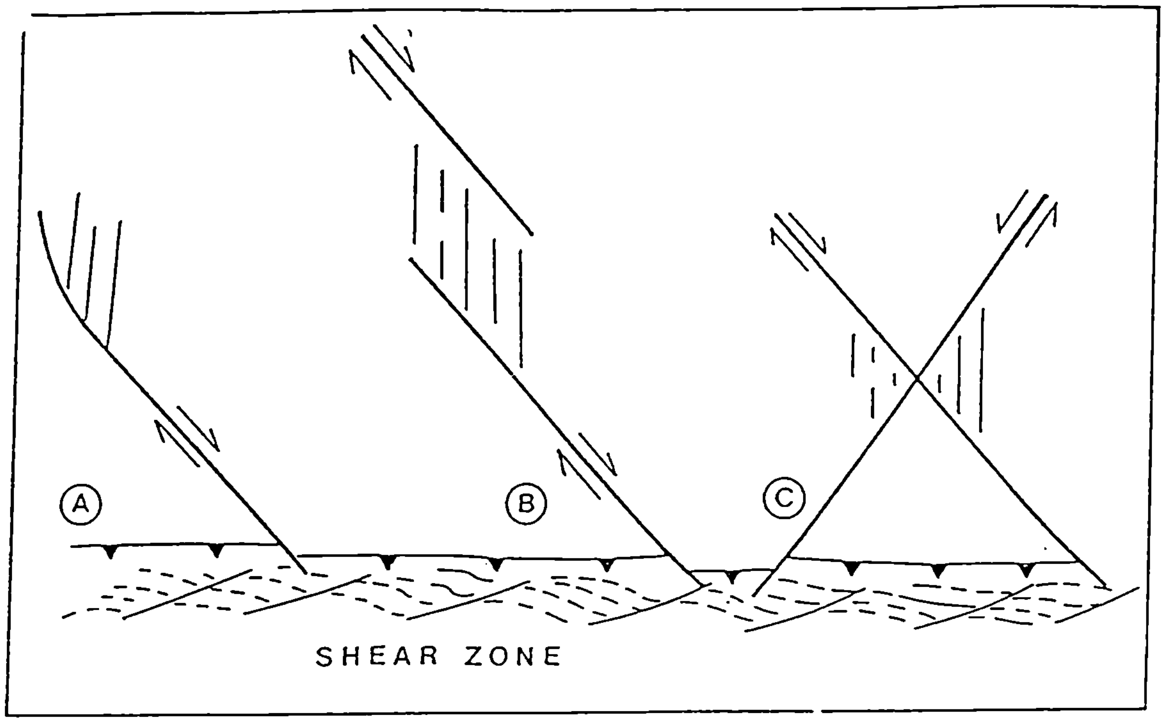


Figure 5. Target types recognised within the Southern Ridge; a) terminations, b) offsets of NW-SE faults, C) dilation at intersecting faults.

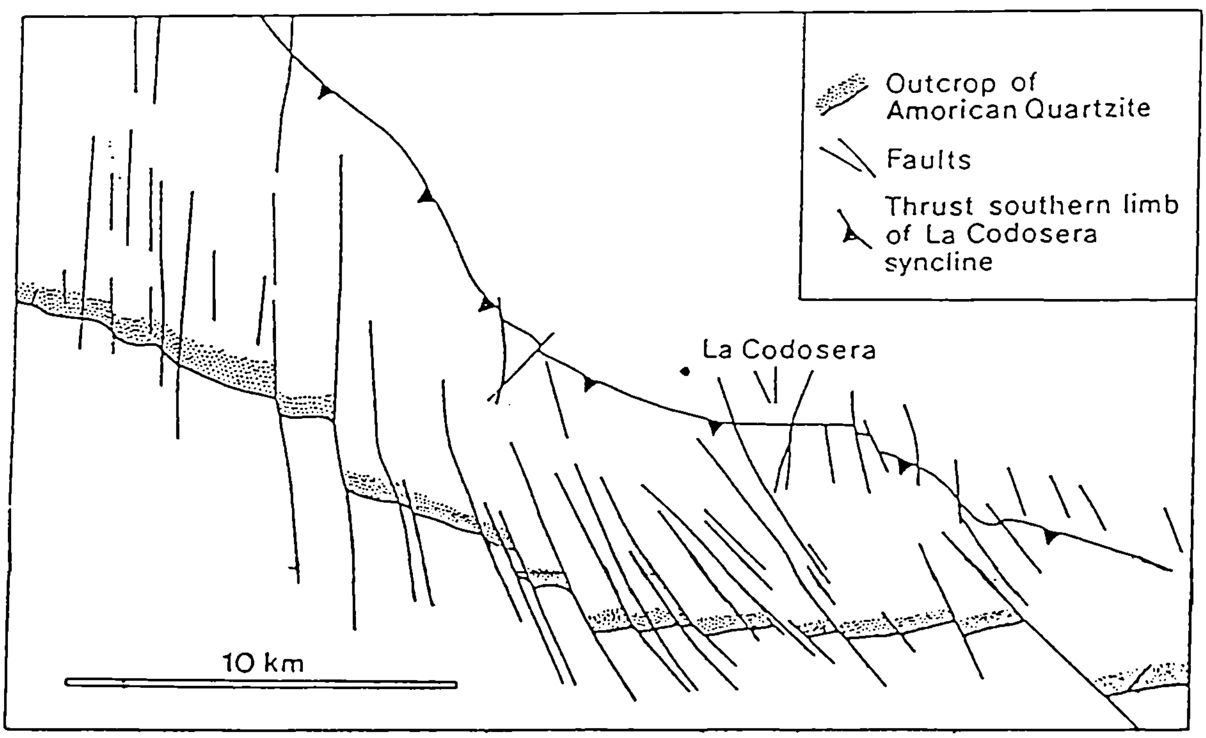


Figure 6. Simplified map of faulting in the Southern Ridge, showing progressive rotation of faults to the south and east of La Codosera (based on published maps of the geological survey's of Spain and Portugal).

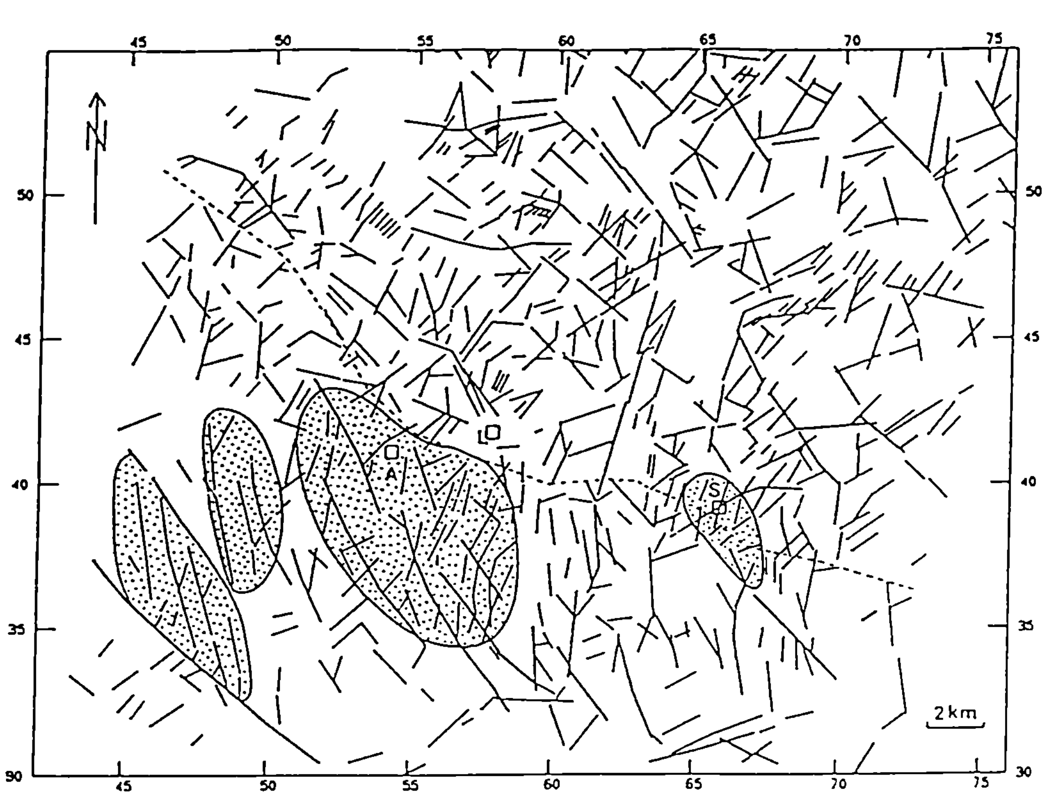


Figure 7. Lineament map of the La Codosera area, with prospect location and "new targets" indicated; L – La Codosera, A – Los Algarbes, S – San Antonio Mine.

RESEARCH AREA 1.3

METHODS OF GEOPHYSICAL PROSPECTING

DEVELOPMENT AND IMPROVING OF GEORADAR SYSTEM AS A GEOPHYSICAL METHOD FOR MINING EXPLORATION

Project Leader: Mauro PICCOLO
IDROGEO S.r.l., Trieste, Italia

Contract MA1M-0012-I

1. OBJECTIVE

IDROGEO started the use of G.P.R. techniques in the early 80's. According to the EEC programme aiming at developing and improving both field instruments and methods for mining exploration, it was looked at the possibility of employing G.P.R. method on the basis of the very useful data obtained in some investigation sites and of the low costs for ore prospecting and mining.

The objectives of the research were the following:

a) to improve the geophysical equipment to increase the signal/noise ratio, the precision, handling and the reliability of the instruments,

b) to improve the techniques for field data acquisition and processing system,

c) to improve data interpretation and target modelling,

d) to develop prospecting methods related to data and results in comparison to other geophysical methods,

e) to improve prospecting and mapping techniques for a more detailed description of disseminated ores.

2. MATERIALS AND METHODS

The research was carried out by a GSSI SIR 8 Radar System with several transducers:

100 MHz mono and bi-static
300 MHz
500 MHz
900 MHz

The system was completed by a digital tape recorder Mod. DT 6000, a Video Display Unit Mod. VDU 38 with colour portable monitor and a DAT digital tape recorder.

Data were processed by means of a GSSI built RADAN package (Release I & II) plugged on a HP computer completed by many peripherals and a streamer memory for data storage.

The field equipment was mounted on a 4x4 vehicle (Land Rover 90) or other vehicles suitable for use inside mine tunnels. Data from other geophysical methods were collected by IP instruments.

The research was carried out through the following five phases:

1) Analysis of radar reflected signals and improvement of field data collection.

2) Construction of an ore deposit model.

3) Field survey in different mines and ore deposits.

4) Improvement of processing methods and software. Improvement of instruments reliability in difficult conditions.

5) Survey velocity and cost/benefits comparison in respect to other geophysical methods.

3. ANALYSIS OF THE RESULTS

Results obtained from the ore deposit model confirmed the applicability of the G.P.R. method for ore prospecting in alluvial deposits.

The quick surveys typical of this technique make wide areas or regional reconstructions possible without long waiting times and high costs, also allowing a wider survey or the possibility of testing low promising areas.

The capability of the method to discriminate ore bodies is, at this stage, limited to some centimetres thick layers.

Structural reconstructions are always possible and precise. To follow a checked horizon and to discriminate the filling sediments is quick and easy. This type of interpretation allows the operator to reconstruct the transport energy of the stream with the consequent knowledge of the potential deposit areas.

The capability of detecting fractures, unconformities and cavities was confirmed. Mineralized cavities were easily detected (Drama mine, Greece). The limiting factor, in limestone, is the red beds thickness. Several dozens of metres of investigation depth can be reached in good conditions with low frequency transducers.

Mine tests confirmed the capability of the method to be successfully employed for ore prospecting.

The G.P.R. techniques were able to detect mineralized faults in a sphalerite-galena mine.

Investigation depth was about a maximum of 40-50 meters with a 100 MHz transducer in bi-static mode. The variation both in reflection and in absorption of the signal can be used, after a careful processing, for trying to discriminate the mineralized parts of the faults from the sterile ones.

4. CONCLUSIONS

The G.P.R. method is a valid technique for ore prospecting in many types of mineralized environments. The limitations of the method are mainly related to the penetration depth and the characters of the transducers. The hardware requests some modifications for routine work inside a mine.

Existing data processing packages are too multi-purpose and it is thought that a finalised software could greatly improve the signal/noise ratio or speed the data processing phase. Good results are obtained with a signal processing path similar to those used for seismic data.

Many software manufacturers suggested to try a signal processing approach to improve the directivity and resolution of the transducer. This technique, known as S.A.R. (Synthetic Aperture Radar) is already used in military, satellite an meteorological surveys.

An European Radar system can not only find a good place on the instrument market but also become a practical and useful tool in ore prospecting.

5. MEETINGS, LIST OF PUBLICATIONS AND ORAL COMMUNICATIONS

5.1. MEETINGS

05-14/09/88	Hudson (USA)	G.S.S.I. factory
16/09/88	Padova (Italy)	Rare earths
20/09/88	Madrid (Spain)	Geophysical methods in exploration
22-23/11/88	Athens (Greece)	I.G.M.E.
25/04/89	Hannover (Germany)	Meeting on EM and gravity methods
15-30/05/89	Drama (Greece)	I.G.M.E.

22-23/09/89	Paris (France)	Seminar on mineral exploration
14-18/05/90	Denver (USA)	3rd international conference on G.P.R.

5.2. PUBLICATIONS

Reports and case-histories (Madrid - Paris EEC meetings)

5.3. SEMESTRIAL REPORTS

10/04/88	Software and radar data collecting. Conventional geophysical data bank for future test sites.
01/10/88	First tests in the field: granite and limestone. Comparison of survey velocities in respect to conventional methods.
01/04/89	Model build-up. First mine tests (Raibl, Italy), first model tests.
01/10/89	Drama tests (Greece), other Raibl tests, Drama data interpretation. Other model tests.
01/04/90	Software tests, data analysis, final interpretation and processing.
19/09/90	Final report and conclusions.

UV LASER PROSPECTING - FIELD TEST OF PREUSSAG'S CLOSE RANGE SYSTEM

Project Leader: H.L. BROICHER
Preussag AG Metall, Goslar, Germany

Contract MA1M-0013-D

1. OBJECTIVES

Preussag AG Metall and the Commission of the European Communities developed a mobile fluorosensor system for the prospecting of fluorescent minerals and related deposits, which was tested in 1987 in Turkey.

The tested fluorosensor system is a truck mounted (Mercedes Unimog 1300 L) container hosted laser system in close range application, with the ability of a continuous survey in the driven path, for the detection of fluorescent minerals, i.e. scheelite, hydrozincite, fluorite and bastnaesite.

The objective of the test was to obtain data on the systems reliability under field conditions and to establish a firm cost and logistic structure.

2. FIELD SURVEY

A fluorosensor survey through four main areas in Turkey:

- northwest-coast
- northwest Anatolia
- Central Anatolia and
- south coast

was laid out with the available data on mineral occurrences of scheelite and base metal (table 1).

A second system channel in the near ultraviolet light range for REE-prospecting was tested in a joint work programme with the universities of Trento, Italy and Munich (TU), Germany, in the Kizilçaören area (Central Anatolia) which includes a fluorite-baryte-bastnaesite deposit (see contract MA1M-0014-D).

Only 56 of the planned 120 days (table 2) of field survey were realised due to several failures of the carrier truck and system difficulties with an unexpected high albedo level.

The 68 taken samples breakdown to 38% scheelite, 7% hydrozincite and 5% fluorite which adds up to 50% found minerals with an economic value and 19% calcite, 26% feldspar and 5% anthropogenic contamination which makes up an equal proportion of luminescent minerals of non economic interest.

The near ultraviolet REE test failed due to a weak optic system and the extreme fine grained bastnaesite in the Kizilçaören deposit.

3. CONCLUSIONS

The mobile Preussag Close Range Fluorosensor is a fully operable system for the prospecting of fluorescent minerals with a priority on scheelite.

The method is very selective with a low number of samples needed, most of them only for checking a mineralogy and grade. The survey enables a team to step from the first detection of a mineral as float to follow up work until final localisation of the occurrence.

Nevertheless, the fluorosensor system has shortcomings against other reconnaissance methods due to:

- a random survey (driveable path)
- preconditions of mineral occurrences as:
    - minerals have to be on surface
    - should be fresh and
    - have to show a minimum fluorescent plane (detection limit)
- random conditions of activated fluorescent minerals which are influenced by ions acting as killers and quenches of fluorescence and a saturation phenomenon.

Performance and costs are related to the driven kilometres per day, i.e. depend on favourable field conditions. The fluorosensor method is open for further development and applications in a broader wavelength range.

Table 1: Field Survey and Samples

Survey Areas Turkey 1987	Survey Kilometers	Number of samples	Detected fluorescent minerals
1) Çanakkale (Northwest coast)	563	13	Calcite, Feldspar
2) Bursa (Northwest Turkey)	33	4	Calcite, Feldspar, Scheelite
3) Nidge (South Turkey)	45	20	<u>Scheelite</u>,Feldspar
4) Yozgat (Central Anatolia)	138	1	Fluorite
5) Sivrihisar (Central Anatolia)	218	8	<u>Scheelite</u>,Feldspar
6) Ankara (Central Anatolia)	428	19	Calcite, Feldspar Hydrozincite, Scheelite,Fluorite
7) Antalya/Alanya	105	2	Hydrozincite
8) Kizilçaören -UV Prospecting- (Central Anatolia)	43	1	Fluorite
Total Turkey 1987	1573	68	

Table 2: Fluorosensor Performance Field Test Turkey 1987

	Result Turkey 1987 7 months	Plan 7 months	Revised Plan (Base: Turkey)
Survey Days	56	120	120
Survey Kilometers	1573	6000	3700
Survey Kilometers per day	28	50	31
Kilometers per sample	23	5	37
Number of samples	68	1200	100
Availability of system	28%	60%	60%
Cost per kilometer	222DM	92DM	154DM

RESEARCH AREA 1.4

REMOTE SENSING
Including "integrated" studies

DEVELOPMENT AND TESTING OF NEW TECHNIQUES FOR MINERAL EXPLORATION BASED ON REMOTE SENSING, IMAGE PROCESSING METHODS AND MULTIVARIATE ANALYSIS

Project Leader: E. ORTEGA
Minas de Almadén y Arrayanes, S.A., Madrid, Spain

Contract MA1M-0010-E

PREFACE

Research under Contract MA1M-0010-E was carried out as part of a joint project with Gesellschaft für Angewandte Fernerkundung mbH (GAF) and DLR, German Aerospace Research Establishment (MA1M-0009-D), Technical University of Denmark (MA1M-0015-DK), and Trinity College of Dublin (MA1M-0011-IRE). The joint research was coordinated by the MAYASA team.

1. OBJECTIVE

The main purpose of this project has been to develop a practical and useful tool to be applied in mineral exploration. Research focused on the following points:

- offering a fast and inexpensive technique for exploration;
- contributing to the acquisition of more detailed knowledge of the surface geology;
- supporting georeferred databases, where all the geological information can be stored, thus facilitating the interactive integration of multisource datasets.

2. INTRODUCTION

The responsibility of the MAYASA team has been centred on the following points:

- Geological background of the project area.
- Georeferred database elaboration.
- Data integration and interpretation.
- Field-checking of the integration and processing results. Prospecting models elaboration.

- Coordination of all research activities.

In the following, the basis of the developed methodology will be described.

3. MATERIAL AND METHODS

The project has been performed using the geological knowledge and the data available on a wide area of more than 15,000 km^2 around the Almadén mercury deposit, located approximately in the centre of the southern part of Spain (300 km south of Madrid).

From the regional geology point of view, the area lies in the Centro-Iberian zone (Julivert et al., 1972), near the boundary of the Ossa Morena Zone. Upper Precambrian, Paleozoic and Caenozoic rocks are outcropping. The Hercynian deformation (Upper Carboniferous) is the main tectonic event, although some Precambrian deformation can be recognized.

The main mineralisations in this area are the following:

- Sedimentary phosphate deposits near the Precambrian-Cambrian boundary.

- Mercury deposits in relationship with a Silurian basic volcanic episode.

- Lead/zinc/silver veins, structurally controlled and in relationship with a late-Hercynian shear deformation phase.

- Tin-tungsten/arsenic/gold mineralisations related to late-Hercynian granitic bodies.

The available geological and exploration data covering this zone are:

- Geological maps at 1:50.000 scale.

- Old mine works inventories.

- Stream sediment geochemistry with an average sampling density of 4 samples per square kilometre. Each sample has been analysed for 26 elements.

- Heavy minerals prospecting (panning), with an average sampling density of 1 sample per 2,5 square kilometres.

- Gamma-spectrometric and magnetic airborne data with an average of 1 kilometre distance between the flight lines. The survey includes five different datasets: potassium, uranium, thorium, total count and residual magnetic field.

- Landsat-TM images (winter and summer scenes) with 7 bands.

All the information described above has been stored in image format and georeferred to the same coordinate system.

The main purpose of building up this database is to have an organization system giving easy access to information and where all the data are in compatible formate to facilitate overlaying.

This database offers the following advantages:

- To digitize the information enables any change in the scale representation or in coordinate system to be made automatically and immediately.

- The data access is very easy, very fast and the compatibility is absolute if all the information is referred to the same coordinate system.

- It is very easy to overlay the information (or better, to integrate it graphically) on the screen using the multichannel screen facilities, or even to generate more sophisticated representations such as IHS or SSS.

- The exact numeric value of the original data is preserved and can be recovered at any moment by positioning the screen cursor in the appropriate position.

- Any change due to resampling, reinterpretation or other causes can be easily introduced and processed.

- It is possible to change interactively on the screen the contouring or threshold values, as well as to stretch or to distinguish between the values ranges in order to enhance the graphic representation.

- It is possible to perform arithmetical or logical operations between two or more images, increasing the integration data possibilities, and also in some cases to define empirical equations to infer the probabilities about the existence of a type of ore deposit.

The database has been build up in an image processing system, and a scale of 1:50.000 has been chosen for the individual sheets as a basic cell for this database.

For each of these sheets, more than 45 images or layers of information have been created from the original data:

- Digitized geological map (boundaries between lithologies) (1 layer).

- Digitized faults from the geological maps (1 layer).

- Digitized lineaments from Landsat image (1 layer).

- Distribution of structural parameters, mainly bedding and cleavage, incorporated into an already existing structural database (usually 2 layers).

- Inventory of old mine works, with different images representing several parameters such as paragenesis, host rock, vein direction, genetic type and size (3 layers).

- Gamma spectrometric data (U, K, Th, T.C.) (4 layers).

- Aeromagnetic data (residual magnetic field) (1 layer).

- Stream sediments geochemical data (P, As, Sb, Sn, Pb, B, Zn, Cd, Hg, Cu, Ag, Ni, Co, Fe, Mn, Cr, Mo, W, V, Nb, Y, Be, Ba, Al, Mg and Ti) (26 layers).

- Landsat TM, with the seven bands subsampled from the original scene and adjusted to the sheet boundaries (7 layers).

- Gravimetry (when available) with representation of the Bouguer anomaly and the first and second derivatives (3 layers).

4. ANALYSIS OF RESULTS

The advantage in the use and application of this kind of data base can be easily illustrated with two practical examples:

4.1 APPLICATION TO A SINGLE DATA SET: STREAM GEOCHEMICAL DATA

The stream sediment geochemistry is one of the most usual techniques in mineral exploration. The results obtained with this technique in general are good. Nevertheless, there are always a number of practical problems during processing and interpretation. The most important of these problems can be summarized as follows:

- Even using computing facilities, most of the statistical techniques applied to geochemistry interpretation cause losses in the spatial information.

- The analytical results obtained are influenced by numerous external factors such as contamination coming from old mining works or different background values caused by the differences in lithology.

- There are technical limitations to displaying all this necessary information on the generated interpretation products (automatically or manually plotted maps).

- The statistical techniques applied to the processing and interpretation of geochemical campaigns are really powerful statistical tools (e.g. factorial analysis), but in many cases they appear inadequate to this task because they have a tendency to typify behaviour of the statistical majority population, rather than the anomalous population which is the true target for geochemical exploration.

The proposed methodology (Artieda & Ortega, 1988) using the image processing system overcomes these difficulties in the following ways:

- The time necessary for the data interpretation is sharply reduced.

- The spatial information is preserved.

- There is no limit to display and to control all the necessary information and external factors.

- The results obtained by overlaying or integrating graphically several elements are not disturbed by the multivariable statistical relationship of the background.

Besides the above-mentioned points, there are additional advantages besides other methods of interpretation:

- It is possible to access very quickly and very easily to a large amount of information (14 Kb per square kilometre).

- It is not a "rigid" way to process the data, in other words the results are not generated automatically or the anomalies selected according to fixed rules. On the contrary the method is open and interactive, so that geological field information plays an important role in the selection of anomalous areas.

- It is possible to generate automatically (by printer) documents (maps or images) including all the necessary information to check directly the interesting anomalies on the fields.

- It permits an increase in the performance of the information available.

A similar approach can be performed (and has actually been performed within this project) over each single dataset, determining the real behaviour of each type of information with respect to the exploration target.

4.2 APPLICATION TO A MULTIDATA SET

In principle, the basic philosophy to be applied in multidata integration is similar to that described in the above chapter. In practice, the main difference is the larger number of data to be used, generating a very large number of potential combinations. It is then very important to have a clear idea on what information is being sought and on what is to be discriminated, in order to avoid computer time and work as consequence of useless combinations.

Between the different types of orebodies present in the project area, the Sn/W/As/Au mineralisations related with granitic bodies have been chosen as an example, as being possibly the most illustrative of the methodology's capabilities.

If a fertile granitic cupola is located at a shallow depth below the topographic surface, the richest mineralised zone can still be preserved.

According to this information, our targets can be defined as not outcropping and mineralized granitic cupolas, located at shallow depth, a primary condition in order to be minable.

After definition of the target and with a clear idea of the geological situation which is sought, the next step consists of a revision of the useful information available in the database, and to elaborate the prospecting model.

The most important practical rules acquired during this process can be expressed by the following points:

- The aeromagnetic information is very reliable for detecting such kinds of structure. It does not mean that any magnetic low should be interpreted as a granitic cupola, but when a cupola has been detected a magnetic low is always present.

- A similar pattern occurs with the gravimetric information. There is a gravimetric low related to the granitic cupolas, but every low does not signify the existence of a buried granite.

- The use of the geochemical information has been essential to confirm the interest of the preliminary target areas selected by other methods. As expressed above, not every aeromagnetic or gravimetric low can be interpreted as a cupola, and moreover we may suppose also that not every cupola is mineralized. It is necessary at least to find some geochemical evidence supporting the existence of an orebody.

- The structural information has been very useful to delineate the more favourable zones at regional scales.

- The remote sensing data are very interesting, mainly from the economic point of view. Data acquisition and processing are very cheap and very fast compared to other techniques. From the structural point of view, it is possible to detect large structures (lineaments) too big to be recognized by other means (e.g. aerial photography). This has been very useful in understanding the regional distribution of the most favourable areas.

  The main application of remote sensing has been to locate contact metamorphic aureoles based on the infrared spectral response. The project leader, GAF, jointly with DLR (Volk & Lehmann, 1988, and this volume) developed a very sensitive methodology based on the spectral field/laboratory measurements and image processing. This methodology has been applied to the whole project area with very good results in general, although there are some vegetation interferences giving rise to apparent anomalies, which may be easily eliminated by field checking.

- The significance of gamma spectrometric data and the old mining works inventory varies, being strongly controlled by their relationships with the other data sets. As in the case of the structural information, it is not possible to select a target area exclusively on this information.

As a consequence of all these practical considerations and having in mind the reliability, costs and time consumed by each dataset, the following steps for the exploration of this type of target are proposed:

1. Scanning all the area to be investigated by using Landsat TM data, looking for the spectral response of thermal metamorphism. Preliminary target selection.

2. Interactive comparison on the computer screen between the selected targets and the aeromagnetic (and gravimetric when available) data. Elimination of the areas not related with gravimetric or magnetic lows. Field checking to verify the spectral anomaly in relationship with vegetation cover interference.

3. Comparison of the remaining selected target areas with geochemical information. Verification of the geochemical halo and zonation around the targets, using the techniques described in chapter 4. Selection of the interesting anomalies.

4. Comparison of the regional structural data within the selected zones in order to estimate the regional pattern for the chosen areas. Restudy of the eliminated zones included in these chosen areas and evaluation of the potential interference parameters (Quaternary sediments, vegetation, etc.).

5. Inside the definitively selected areas, interactive data integration using all layers of information, selection in detail of the most interesting zones for mineralisation and determination of the granite depth/geometry as support to the investigation survey (soil geochemistry, drillings, etc.).

The systematic application of this methodology over all the project area has permitted to select five target areas. Three of these areas have already been drilled, and in all the cases, previously unknown mineralisations associated to granitic bodies have been discovered. Even though the economic interest of these deposits is still being evaluated, it is important to emphasize the reliability of this technique, able to pick out areas which do not appear significantly anomalous from each of the individual data sets. Only by integration processes the anomaly is well visible.

It is important to remark that this kind of exploration model can easily be developed for other types of deposits in other geological contexts.

5. CONCLUSIONS

The more important feature of this methodology is the "open" character of the system, being possible to introduce any new scientific improvement or any new idea derived from geological field observations. The data integration and interpretation processes are always controlled by the geological criteria coming from the exploration field experience.

During the project development, and more specifically the performing of this technique, other improvements over the single datasets have been reached:

- Evaluation of the ratio costs/reliability for each type of data.

- Improvement of the evolution of infrared spectral responses for these kinds of deposits.

- Testing of new statistical approaches for the multivariate analysis and image processing.

- Elaboration of new data representation and display techniques.

It is very important to remark (for its economic implications) that all the methodology can be supported by a personal computer.

In summary, the proposed methodology aims to enhance the usual techniques in mineral exploration:

- It is a very flexible, rapid and economic system to manage and to interprete exploration datasets, in particular when data are numerous.

- It increases sharply the amount and quality of information provided by the original data. In some cases interesting anomalous areas not found by conventional methodologies have been detected.

- It is not a rigid system and all the processing and interpretation are strongly controlled by the geological knowledge and field criteria.

In addition to scientific progress there are numerous economic implications:

- It is possible to cover large areas during an exploration project with a comparatively small team, thereby reducing the cost of manpower.

- It is possible to perform a fast, reliable and cheap exploration, reducing time consumed in data processing and unnecessary fieldwork.

- It is possible to reinterpretate data from previous exploration campaigns, with a very small rate of additional fieldwork.

6. REFERENCES

ARTIEDA, J. & ORTEGA, E. (1988)
Técnicas de proceso de imagenes para la interpretación de campanas de explotación geoquímica. VIII Congreso Internacional de Minería y Metalúrgia, Oviedo (Spain), Vol. 7, pp. 275-286.

JULIVERT, M., FONTBOTE, J.M., RIBEIRO, A. & CONDE, L.E. (1972)
Mapa Tectónico de la Península Ibérica y Baleares a escala 1:1.000.000 Memoria explicativa, IGME (Madrid).

VOLK, P. & LEHMANN, F. (1988)
Development and testing of new techniques for mineral exploration based on remote sensing, image processing methods and multivariate analysis. EEC Contract MA1M-0009-D, Second Progress Report GAF/DLR, pp. 1-9.

7. PUBLICATIONS AND ORAL COMMUNICATIONS OF CONTRACT RESEARCH

AMOR, J.M.; ARTIEDA, J.; CIENFUEGOS, I.; ORTEGA, E. & PALERO, F. (1989)
Image processing and graphic integration: new tools to save time and costs in mineral exploration.
Mineral Exploration Programmes 89. International Mining MIRO, Madrid.

ORTEGA, E. (1990)
Proceso de imágenes, teledetección e integración gráfica, nuevas herramientas para la exploración minera.
Conferencia plenaria en el Congreso de la Sociedad Española de Mineralogía, Oviedo (Spain).

ORTEGA, E. (1990)
La teledetección y el procesamiento de imágenes aplicadas a exploración minera.
Conferencia pronumciada en la Escuela de Ingenieros Técnicos de Minas, Universidad de Castilla-La Mancha.

ORTEGA, E.; ARTIEDA, J.; HAYDN, R. & VOLK, P. (1990)
Remote Sensing in mineral exploration: a critical review.
Remote Sensing: an operational technology for the mining and petroleum industries. London.

DEVELOPMENT AND TESTING OF NEW TECHNIQUES FOR MINERAL EXPLORATION BASED ON REMOTE SENSING IMAGE PROCESSING METHODS AND MULTIVARIATE ANALYSIS

PART 1

Project leader : PETER VOLK
Gesellschaft für Angewandte Fernerkundung mbH (GAF), Munich, Germany

Contract MA1M-0009-D

PREFACE

Research under Contract MA1M-0009-D was carried out as part of a joint project with Minas de Almaden y Arrayanes, Spain (MA1M-0010-E), Technical University of Denmark (MA1M-0015-DK), and Trinity College of Dublin (MA1M-0011-IRL). Contract MA1M-0009-D covered the sub-project "Development of spectral processing concepts for recent and future remote sensing data and their analysis by means of a geographic information system structure for exploration purposes". In Part 1 of this Summary Report, the research results for the entire project are presented, while Part 2 describes especially the research carried out in the sector of optical spectroscopy.

1. OBJECTIVE

A deeper understanding of spectral signatures measured by today's available space and field sensors and their contribution to integrated data analysis for exploration purposes is regarded the overall aim for this project. To more detail, several research aspects had been covered by GAF:

- development of spectral based processing concepts for existing satellite sensors (TM, SPOT);
- construction of an exploration data base for a limited test area of approx. 25 km x 25 km and development of efficient analysis procedures.
- all spectral data processing and integrated analysis should focus on mineral suites which are of special interest in the MAYASA concession, namely Sn-W areas.

It was anticipated to have a close cooperation during every project phase to all other subprojects. This should avoid parallel developments in the research and strengthen the own activities. The general project set-up and the clear guidance through the MAYASA team provided throughout the program an always encouraging environment for such a cooperative spirit.

2. WORKING APPROACH AND PERFORMANCE

2.1 SPECTRAL PROCESSING CONCEPTS

Starting point and motivation for the research topics was the effect of spectral zonings in infrared band combinations around exposed granites and suspected cupolas. The observation of this phenomenon was of utmost importance for any exploration activity on buried granitic cupolas and their associated mineralizations.

Two approaches should provide a deeper understanding of the spectral behaviour and the physical properties of mineralized rocks.

A. Empiric development of a processing strategy based on experience-based parameters.

GAF scientists have been involved since the early beginning of the Landsat era in image processing work. The processing of several hundreds of MSS, TM and other satellite scenes led to an accumulation of an enormous knowledge base for the spectral properties of different rocks, soils and vegetation throughout the world. This knowledge is even the more valuable, the more it is important to work on "real sensor information" from satellites, which generally is of rather modest radiometric and spatial quality compared to field- or airborne instruments. This approach merely is an experience-based way for deriving processing concepts.

B. Development of spectral processing concepts based on data from laboratory and field spectrometric campaigns and their analysis.

A database of spectral signatures available at DLR, and extensive spectral laboratory measurements performed on rock and soil samples should provide the fundamentals for a mineralization - specific analysis concept. Spectroscopic field campaigns with high-resolution instruments and simultaneous satellite- and airborne overflights could give a valuable proof and further refinement to a developed processing concept. In fact, this is an excellent possibility to improve and check the results. This approach corresponds to a spectroscopy-based method, rooting in theoretical spectral assumptions.

This important subtask including all necessary field activities and spectral analysis was performed by the research group of the DLR (see Part 2 of this report). The two independent approaches (A,B) permitted a critical comparison and discussion of the results obtained.

The investigations had been executed by the use of extensive image processing on several TM scenes, SPOT XS and auxiliary data (field geology a.o.). Arithmetical and statistical tools for efficient enhancement procedures had been tested or developed. One of the most prominent results obtained was the definition of a complex processing strategy for TM image data, which effectively supports mapping of contactmetamorphic effects in non-vegetated areas (Fig. 1). The correlation and field check had been performed in close cooperation with MAYASA geologists, to introduce their specific local geological knowledge already at an early stage of the research work.

2.2 INTEGRATED ANALYSIS OF SPECTRAL AND OTHER GEO-DATA FOR SELECTED TEST-SITES

- Overview

During the past decade integration of two-dimensional data sets has evolved as a central topic. In geoscientific disciplines it has settled as a standard tool for multi-data analysis. Geographic Information System (GIS) technology was a pacemaker for this concepts of data management. In exploration geology several scientists in the USA and Europe had developed the basics for exploration case studies throughout the world. Statistical approaches between the different data layers had been applied by TRAUTWEIN et al. (1982) and BOLIVAR et al. (1983), GUINNESS et al. (1983). CONRADSEN & THYRSTEDT (1985), ZHOU (1989) and GOODENOUGH (1989) stressed the importance of dedicated digital image processing tools during the retrieval of thematic information from combined data products. Valuable initial research had been already performed in the previous EEC raw materials program in the Almadén area (CONRADSEN, 1988).

However, some questions still remained unsolved. How is the structure of an exploration data base which is adapted optimally to the requirements of fast access, flexible overlay and last not least provides links to excellent analysis presentations? How can other types of two-dimensional information transferred to such a data base? What are the best suited products for synoptical geological interpretation?

- Internal, Hierarchical Structure:

We used a hierarchical system with 3 levels of information (Fig. 2). The basic or level 1 is characterized by the original sensor information which was partially adapted to 8 bit data volume. The intermediate or level 2 consists of thematically processed data, containing already enhanced information related to geology. A level 2 product could be a combination of 2 or more level 1 products. The highest and most interpretative level 3 is a rather complex combination of several level 1 and 2 products. In its combination it is rather specialized towards a reduction of redundant information and synopsis of independent data sources. The following examples should help to clarify this point:

Input data sets are stored in different layers at the lowest hierarchical level of the database. This level 1 comprises original data at a basic preprocessing level. This includes system and radiometric corrections of satellite data, geometric correction and registration of common map coordinate system of the data, basic data reduction and corrections of the geophysical and geochemical data as well as gridding. The level 2 comprises thematically enhanced data sets of one single information group. Examples are vegetation indices, spectral ratios, contours of geochemical data sets, Fourier processed potential field data. Level 3 data comprise selected combinations and recombinations of level 1 and 2 data sets, where the thematic significant information is filtered and enhanced whereas the redundant information is reduced. The data sets will be represented as image maps or GIS map plots. These thematic products allow an integrated approach by synoptical evaluation of several coregistered data sets at the same time focusing on a certain thematic aspect.

- Data Base Features:

The contents of the exploration data base was selected with 2 main criteria in mind: purpose of the study and availability of data. Geodata sets are in many cases hard to acquire in terms of effort, time and money and maximum use should be made of them. Therefore they should be completely integrated to the data base. Even in cases where no causative or logical model of interrelation between data layers exists all existent data should be used. The data base, GIS and image processing operations might reveal several up to now undetected or unknown relationships and connections. On the other side through the below explained hierarchical structure of the data base it is assured that redundant and irrelevant information is discarded through the refinement and sieving within the data base.

This approach has some interesting features which can be easily adapted to very different exploration scenarii. Additionally, it can be run on every low cost image processing/raster based GIS system and is accessible to conventional image processing tools. This aspect is especially important for future implementations, since many small to medium sized European mining companies cannot afford expensive solutions to support their exploration activities.

The most important features of the data base design are presented in the bar chart (Fig. 3).

3. RESULTS AND CONCLUSIONS

The most important results obtained can be grouped in two main categories.

*1. A very target-specific work emphasized on the problem of detecting buried granitic cupolas with associated W-Sn type mineralizations by means of recently available satellite data. A rather reliable and operational method was developed allowing a preselection of target areas for detailed assessment. Even including some amomalies not relevant to granites, this procedure reduced the number of potential target areas significantly and can be regarded an efficient procedure.

*2. A rasterbased, spatial exploration data bank (EDB) had been designed, implemented and tested, using a 3-level approach to facilitate data management. The existence of a map sheet oriented geological data base, created by the MAYASA team was a vital prerequisite. Thematic relevant data from different sources had been introduced and subsequently enhanced towards the level 3, which consists of "condensed" data sets in respect to mineral targets. Sophisticated display techniques allow to combine up to 6 thematically enhanced data layers. Weak anomalies in the individual sets often cause prominent features in the level 3 products. With the 3-level data base design and the definition of colour coded synthetic stereo images with contour lines a powerful and flexible tool for decision making in exploration could be established.

ref. * 1:

The fact of spectral anomalies in TM data acquired over contactmetamorphic facies could be verified and more, a straight processing concept was developed to enhance even weak signals to a well defined visual anomaly. As the most promising spectral source of information, TM bands 4,5,7 had been identified. Histogram adapted rationing of bands 4 and

5 provided the pattern for an inner contact zone, ratio 4/7 is suitable for the delineation of an outer zone of affected rocks. From several tests in other areas it must be concluded, that for each region and geological regime adjustments of the contrast parameters had to be applied to make full use of the approach. Despite the overall positive results some constraints and limits must be mentioned:

- Due to the sometimes diffuse geometry of contactmetamorphic haloes and an intensive landuse pattern in central Spain, the allocation of contactmetamorphic phenomena cannot be given with the precision of one TM pixel.

- Only TM data provide the necessary infrared bands (from available spaceborne systems).

- The data must be radiometrically excellent. There exist limitations for this processing method. For the Spanish testsites optimum results had been achieved for data taken around sun solstice (summer).

- For one testsite (Guadalupe) the field anomalies showing contactmetamorphic facies are not coinciding directly with the spectral results. The reasons must not necessarily point out, that the method elaborated is working only under certain conditions. Cases had been reported where the mineralized zones are not centred in the metamorphic anomalies.

It is worth to point to the fact that both approaches result in similar considerations about a best-suited processing method. Any investigation on the impact of vegetation on the anomalous spectral signals do not yield reliable hints or proofs for a vegetation - dependent feature outside areas covered with Jara-type vegetation. In the contrary, vegetation indices are different in their spatial pattern from the 4/5 and 4/7 adapted ratio information for non-vegetated areas. Principally the same effects could be verified in the simulated TM bands from DLR spectral analysis.

The investigations on the capabilities of thermal data yielded very different results. On the one hand, contactmetamorphic facies is impossible to detect, probably the relevant radiometric signal is by far too weak to print through the signal variation of other surface categories (humidity, vegetation etc.). Even terrain corrections have not improved this situation. On the other hand, important structures at a regional scale are easy to map in the day- and night time colour coded products.

A TM/SPOT false colour merge proved to be an excellent product to map structural details at scales down to 1:25.000. NOAA satellite data provided interesting large structures on a continental scale.

ref. * 2:

Lithospectral and structural enhanced satellite data play an important role in these products. They:

- improve orientation and correlation with surface features

- indicate tectonical features

- give evidence to lithological anomalies in context with contactmetamorphic facies

Special emphasis was dedicated to existing airborne geophysical data, since their geological mapping potential was regarded excellent. Despite the sometimes low quality, image processing and quantitative analysis provided remarkable information on the location shape, and extent of subsurface bodies.

To highlight the excellent synoptical and synergetic capabilities of data base level 3 products, an example is presented. Fig. 4 is a synthetic stereo image representing lithospectrally colour coded Landsat TM data, geochemistry contour lines, and aeromag data controlling the parallax. On a very first glimpse the image appears somewhat confusing. But if one considers the allocation of the different data layers to the combination levels, and a short period of visual training to this presentation by means of a stereoscope, the benefits for interpretation and decision taking are eye catching. The thematic findings can be summarized:

- The lithospectral data (TM 4/5, 4/7, date: autumn 1988) indicating granite and contactmetamorphic rocks, show an anomaly south of the known granitic outcrop. It is indicated by an association of yellowish to red hues. Green and blue colours represent higher vegetation density and thus camouflage soil and rock signal.

- The contour lines of Tl, As, Be geochemistry clearly mark a common anomaly, located in the centre of the spectral one. A second, more diffuse one is detectable at the western flank of the granite.

- The 3-D synthetic stereo information clearly shows a rim of high-frequency magnetic anomalies with a prominent feature at the southern tip. A smooth low represents the known granitic outcrop and his southern extension. However, discrete anomalies around could be discussed as a subsurface border line for surface phenomena.

- It is of special interest, that such synoptical interpretative treatments can provide genetic insights in the formation of mineralizations and the geological model due to the different physical parameters sketched in <u>one</u> image at <u>one</u> time.

Summarizing it can be stated that exploration projects on W-Sn ores in context with leucocratic intrusions should incorporate dedicated remote sensing and image processing at an early stage. The research team is convinced that such procedures can cut down the costs of exploration programmes at early stages. The approach elaborated will work in arid to semi-arid/Mediterranean climatic regimes with radiometrically excellent TM data.

It appears as a logical consequence, to widen the scope of research work towards other climate regimes and other important metallogenetic targets. Since it turns out that project experience in thematic image processing is a clue even to the development of very dedicated tasks in geological exploration , it is proposed to collect the knowledge digitally and to build up a framework of decision criteria for the use of remote sensing in exploration. If knowledge in the processing of other spatial data sets (e.g. geochemical, geophysical) is added, a powerful instrument for exploration geologists may be initiated.

4. REFERENCES

Conradsen, K. (1988): The use of structural and spectral enhancement of remote sensing data in ore prospecting. In: Donato M. and Van Wambecke L. (eds.): Summary reports of the subprogramme: metals and mineral substances (1982-85), pp. 531-534. Office for Official Publications of the European Communities, Luxembourg.

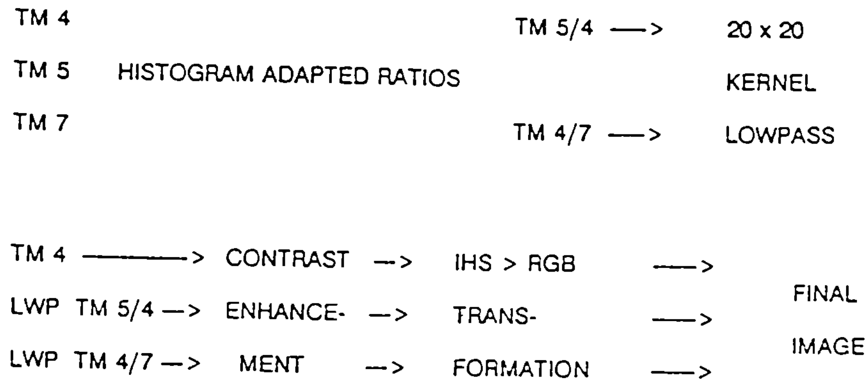


Fig. 1: Scheme of IHS- colourcoded processing (4/5, 4/7 TM adapted Ratio data).

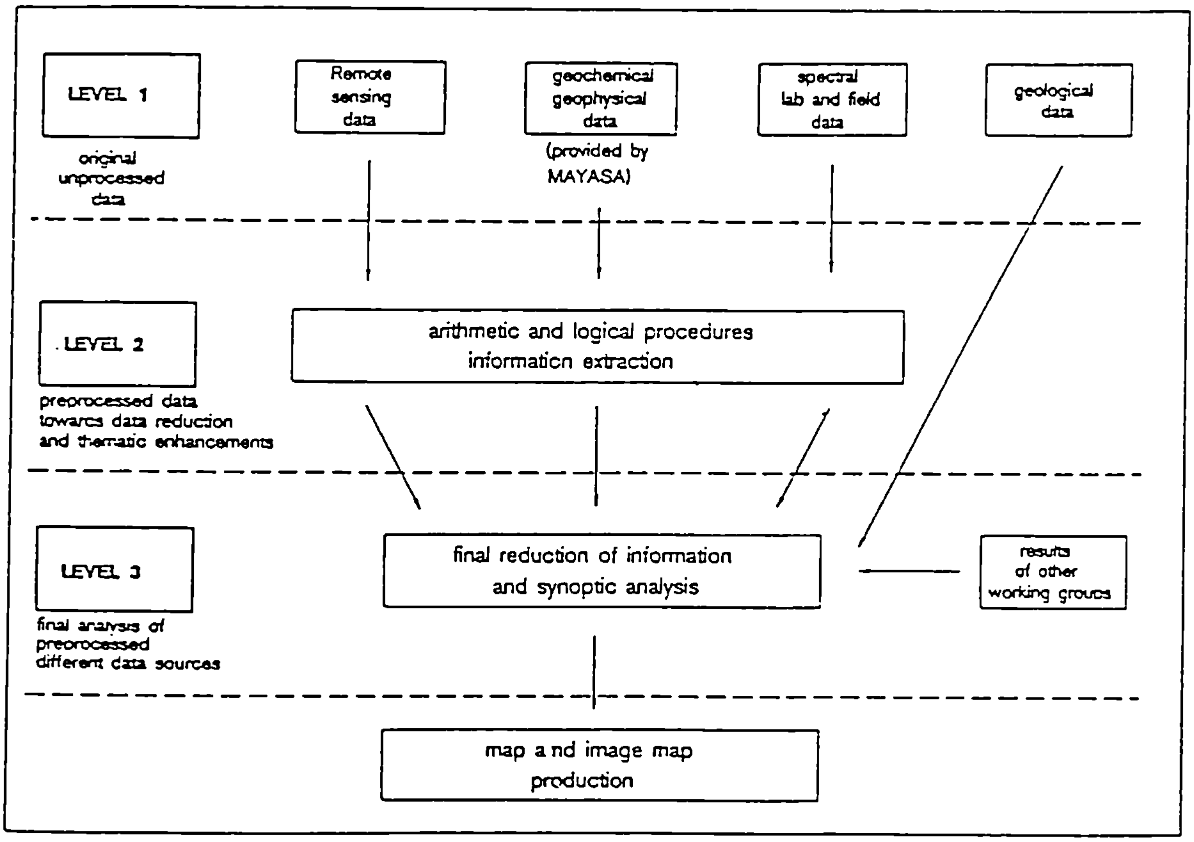


Fig. 2: Hierarchical Structure of Exploration Data Base

	db level 1	db level 2	db level 3
complexity	low	medium	high
redundancy of information	high	medium	low
thematic enhancement	low	medium	high
# of data layers	high	medium	low
relation to original information	high	medium	medium
analysis potential	low	medium	high

Fig. 3: Important features of the data base structure applied

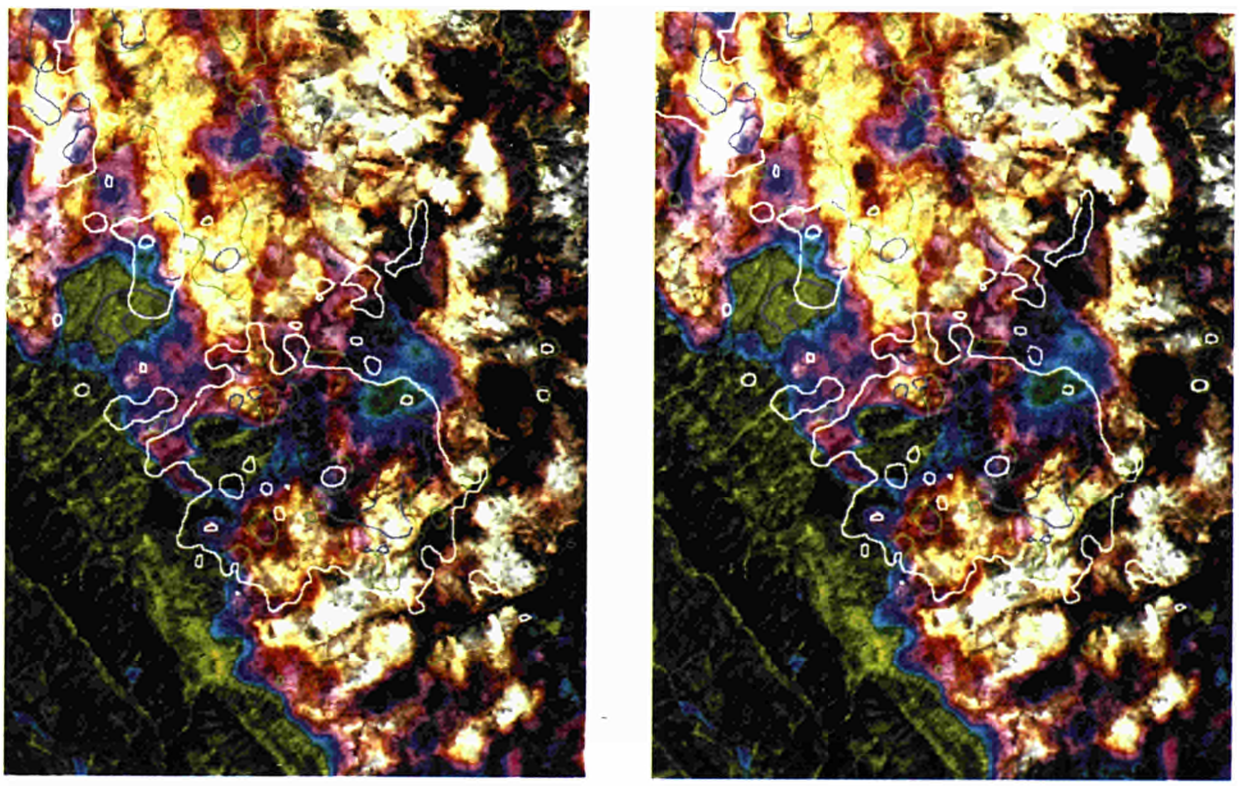


Fig.4: Level 3 product merging spectral anomalies derived from Landsat TM autumn 1988 data, geochemical anomalies Ti, As, Be and geomagnetic data.

DEVELOPMENT AND TESTING OF NEW TECHNIQUES FOR MINERAL EXPLORATION BASED ON REMOTE SENSING, IMAGE PROCESSING METHODS AND MULTIVARIATE ANALYSIS

PART 2

BY: K. Werner and F. Lehmann
DLR, German Aerospace Research Establishment, Oberpfaffenhofen, Germany

Contract MA1M-0009-D

PREFACE

Research under Contract MA1M-0009-D was carried out as part of a joint project with Minas de Almaden y Arrayanes, Spain (MA1M-0010-E), Technical University of Denmark (MA1M-0015-DK), and Trinity College of Dublin (MA1M-0011-IRL). Contract MA1M-0009-D covered the sub-project "Development of spectral processing concepts for recent and future remote sensing data and their analysis by means of a geographic information system structure for exploration purposes". In Part 1 of this Summary Report, the research results for the entire project are presented, while Part 2 describes especially the research carried out in the sector of optical spectroscopy.

1. OBJECTIVES

During the last decade optical field spectrometers covering the wavelength interval from 0.4 μm to 2.5 μm were developed from a stage of low spectral resolution and heavy instrumentation to a stage of very high spectral resolution and real handheld instruments. Laboratory and field spectroscopy investigations of American, Australian and European scientists (Ref. 1-4) proved clearly that optical spectroscopy has a high potential for geologic mapping and mineral chemical analysis. Especially the wavelength intervals from 0.4 μm to 2.5 μm (oxides and hydroxides of transition elements, e.g. ironoxide; layered silicates e.g. clay minerals, alteration minerals, mica) and the wavelength interval from 8.0 μm to 13.0 μm display diagnostic spectral features of the mineralogical composition of soils and rocks (Ref. 5-7).

Based on the results of this world wide research it was obvious that real handheld optical spectrometers and very high spectral resolution airborne imaging spectrometers could be a fast, effective and low cost tool for exploration, helping to reduce the exploration costs for geochemistry, XRD and other geophysical analyses.

In the frame of the present contract and in cooperation with MINAS DE ALMADEN, DLR carried out two intensive field spectroscopy campaigns and one airborne imaging spectroscopy campaign (in the framework of the EISAC 1989 campaign, European Imaging Spectroscopy Airborne Campaign, organised by JRC, Ispra, ESA and DLR; Ref. 8-9) with the following objectives:

- mapping of the mineralised granite and the contactmetamorphic zone in the Reventon area, Spain, by use of laboratory and field spectroscopy methods.

- Detection of suboutcropping granite cupolas and veins in the southern Reventon area by use of optical spectroscopy methods (laboratory and field spectroscopy, airborne spectroscopy, development of satellite data processing concepts in cooperation with GAF) for exploration purposes.

- The definition of interesting areas for exploration in cooperation with other project teams (combination of data for the recommendation of drilling points).

- The comparison of XRD analysis and optical spectroscopy and a correlation analysis of both datasets with the aim to reduce the amount of the expensive analysis in future mapping and exploration projects.

- Correlation analysis of satellite (LANDSAT TM) and field or laboratory spectroscopy data with the objectives to analyse misinterpretations in satellite data of partly vegetated areas due to the mixed signature problem (most areas in Europe are partly vegetated).

- Investigating the potential of high spectral resolution thermal infrared CO_2-Laser spectroscopy for mineral chemical composition analysis (DLR - Battelle Institute (Ref. 10), DLR - CSIRO Australia (Ref. 11)).

- Estimating the future potential of real handheld field spectroscopy as a geophysical tool in exploration.

2. MATERIALS AND METHODS

Basis for laboratory spectroscopy in the project's research were 100 soil samples collected by geologists of Minas de Alamaden along several profiles in the Valdelacasa concession area (grid 1, see table 1). Although investigations related to the project were carried out in different research areas (Alia, Logrosan, La Parrilla, Zorita), the main activities of DLR's laboratory and field spectroscopy were concentrated in the Reventon/Valdelacasa area. The spectroscopy analyses carried out in the project's framework are demonstrated in table 1.

The spectral measurements comprised laboratory spectroscopy on soil samples using different types of high spectral resolution spectroradiometers (IRIS mark IV, GER Company; Lambda 9, Perkin Elmer; CO_2-Laser, CSIRO); spectral field measurements (IRIS mark IV; HHRR MK I, Barringer Research) have been carried out during two field campaigns. They were organised by DLR and supported by Minas de Almaden and scientists from German and British research institutes experienced in reflectance spectroscopy measurements.

The objective of field spectroscopy was to obtain spectral data of natural surfaces:

- bare soil in its natural state
- targets with different percentages of vegetation coverage/mixed signatures
- spectral data of targets comparable to remote sensing (airborne, satellite) data
- external calibration targets

Apart from regional geochemical data (stream samples, ICP) and geophysical analysis (gravimetry, areomagnetics etc.) additional analytical methods have been applied on spectrally analysed soil samples from the Reventon testsite: the mineralogical components of selected soil samples spreading over the different geological sites of the research area (outcropping granites, contactmetamorphic influenced and non influenced sedimentary formations) have been determined by XRD analysis; soil geochemical analysis (26 elements) has been carried out in the spectrally anomalous area south of the old Reventon mine.

3. ANALYSIS OF RESULTS

The acquired spectral datasets have been processed by use of the DLR software LARIS, a package for the analysis of high spectral resolution data. After calibration and several preprocessing steps the data was processed by evaluation of significant spectral features, including a reduction of the enormous amount of spectral values within the analysed wavelength range. The following processing techniques proved to be most promising for project's research aims:

- TM band calculation: employing the TM band filter characteristics, the spectral values of TM bands 1-5,7 corresponding wavelength ranges were determined. The results allow a qualitative comparison with Landsat TM data.
- hull quotient calculation: extraction and enhancement of absorption features caused by soil mineralogy, especially indicating variations of the clay mineral content (see figure 1). Overall reflectance (albedo) values are supressed by this technique.

- ratio calculation: ratioing spectral values at selected wavelengths or wavelength intervals. This method proved to be useful on both original spectra, hull quotient spectra and TM band corresponding spectral values.

An example for statistical analyses of the spectral features of Reventon soil samples (grid 1) is given in figure 2. Double ratio calculations applied on original spectra at selected wavelengths allowed a seperation of spectral groups in the diagram; those "clusters" have been colour coded and assigned to the grid pattern.

4. SPECTRAL AUREOLES

Around the granitic contact zones, the Reventon mine area and other anomalous locations, the spectral behaviour of soils displays zoning effects which are defined as 'spectral aureoles', surrounding those areas. Comparing the geographical distance of samples to a neighbouring anomaly (see figure 3a) with the distance of the corresponding double ratio values of those samples in a double ratio field (see figure 3b), an anomalous behaviour can be observed: close to the anomaly the distance in the double ratio diagram is decreasing in a more or less linear way (which is expected due to the decrease in strongly absorbing minerals like montmorillonite or kaolinite). Then the absorption feature depth is increasing again (see B2 in figure 3b) and finally decreasing with increasing distance to the anomaly (B3).

A possible interpretation of those spectral aureoles could be given by contactmetamorphic influence and temperature dependent zonings around those anomalies caused by recrystallisation.

For a correlation of the analysed spectral features and soil mineralogy 25 samples of the Reventon grid 1 have been selected for XRD analysis. Although the mineralogical composition in this geological environment is characterised by generally low variations, a qualitative interpretation of XRD analyses of soil samples allowed a division into three main areas:

- AREA 1: On or near the granite
  Generally higher quartz and feldspar with lower clays. The clays are dominated by muscovite/illite with some montmorillonite. On moving away from the granite there is an increase in the relative proportions of chlorite. Kaolinite has low values in this region.

- AREA 2: Main altered area
  Higher clay values than the granite, with higher chlorite and still quite low kaolinite values. Declining illite and muscovite values.

- AREA 3: Outside main altered area
  Still moderately high chlorite values, much higher kaolinite values and much lower muscovite/illite values.

The correlation between the 2.2 µm absorption feature and the relative proportions of the analysed clay minerals is demonstrated in Fig. 2: the spatial position of 25 XRD analysed soil samples in this diagram can roughly be assigned to the correlation straight-line.

In cooperation with GAF (Gesellschaft für Angewandte Fernerkundung mbH), responsible for the evaluation of image processing concepts of satellite data (TM SPOT) in the project's framework, the results of laboratory and field spectroscopy data within the TM band wavelengths intervals have been analysed in comparison to Landsat TM data. Ratio calculations of the near infrared and shortwave infrared channels (TM 4,5,7) proved to be the most useful band combinations for the delineation of granitic and contactmetamorphic influenced areas.

The influence of vegetation cover on the spectral response of satellite data, however, is obvious by comparing Landsat TM data and soil spectroscopy data. Spectral field measurements carried out in the Reventon testsite proved the influence of even moderately vegetated targets on the spectral response. VNIR/SWIR reflectance spectra acquired on one heterogeneously vegetated field are displayed in Fig. 4: spectrum 1 represents the bare soil target; spectrum 2 (ca. 20 % grassland covered soil) shows the typical reflectance increase at 0.7 µm due to vegetation, but still displays the 2.2 µm absorption feature, whereas the soil spectral characteristics of the ca. 80 % grassland covered target (spectrum 3) are completely masked.

The occurence of vegetation cover in the investigation areas has to be regarded as a restricting factor in the analysis of spectral remote sensing data for soil mineralogy / exploration purposes. The distribution of different vegetation types, however, is strongly related to morphological variations (cultivated / uncultivated areas); they are obviously dependent on lithological changes, with more pronounced morphology in areas of outcropping granitic cupolas, but especially in areas of evident contactmetamorphic influence on the Precambrian shale / graywacke (hardening of rocks). Since those areas are less cultivated and more densely covered by natural mediterranean vegetation (garigues, maquis), the vegetation distribution can be considered as an additional indication for lithological variations.

First results of high spectral resolution airborne imaging spectrometer data, obtained during the EISAC campaign 1989 in the Reventon testsite using the GER airborne scanner are very promising; especially the spectral information in the shortwave infrared wavelength region between 2.0 µm and 2.4 µm (28 spectral bands) provides a valuable potential for exploration applications, especially for the reduction of expensive field exploration activities.

Figure 6 shows two subscenes of calibrated and corrected GER airborne data (correction for atmospheric influence, illumination, adjacency effects by DLR computer model SENSAT-3, and additional external calibration site correction; Werner & Lehmann, 1990).

In the natural colour composite all ploughed fields are displayed by high intensities, while in the shortwave infrared colour composite only areas which are characterised by high reflectance in the SWIR and strong 2.2 µm absorption features are pronounced by high intensities. Outcropping granitic cupolas (upper part of the image) and contactmetamorphic influenced areas are delineated by this band combination.

5. CONCLUSIONS

- Laboratory and field optical spectroscopy is a fast and low cost method for geologic mapping, the detection of tracing minerals (e.g. alteration minerals), the analysis of changes in mineral composition (e.g. contact zones) and the reduction of expensive laboratory analysis.

- Real handheld field spectrometers could be used very soon as a standard geophysical tool for mapping and exploration by geologists working in the field, especially when the existing data analysis software packages are improved and extended by the results of different case studies and application scenarios (mineralisation type, ore genesis, environmental conditions, climate and alteration effects).

- CO_2-Laser laboratory spectroscopy increases the analysis potential of visible and near infrared spectroscopy data due to the diagnostic spectral features of minerals in the thermal infrared and the often observed redundancy of spectroscopic effects of minerals in the shortwave (OH-overtones) and thermal infrared (molecular vibrations).

- Laboratory and field spectroscopy provide the basis to develop interpretation strategies for satellite and airborne data and to avoid misinterpretations of those data (e.g. due to the mixed signature problem).

- Optical field spectroscopy is an excellent tool for mapping and exploration in a partly vegetation covered environment (mixed signatures).

- First results of high spectral resolution airborne data, obtained during the EISAC campaign 1989 in the Reventon testsite using the GER airborne scanner are very promising; especially the spectral information in the shortwave infrared wavelength region between 2.0 µm and 2.4 µm (28 spectral bands) provides a valuable potential for exploration applications.

6. REFERENCES

(1) Hunt, G.R., Salibury, J.W. (1970-1976). Visible and Infrared Spectra of Minerals and Rocks I - XII. Mod. Geology, Vol. 1-5.

(2) Gaffey, S.J. (1984). Reflectance Spectroscopy of Carbonate Minerals and Rocks in the Visible and Near Infrared (0.35-2.5 µm): Potential as a tool for Geological mapping and Exploration. Int. Symp. on Remote Sensing Environment, Third Thematic Conference, Colorado Springs, Colorado.

(3) Huntington, J.F., Green, A.A. (1988). Recent Advance and Practical Considerations in Remote Sensing Applied to Gold Exploration. Proc. Bicentennial Gold '88, Melbourne, pp. 246-262.

(4) Milton, E.J. (1987). Principles of Field Spectroscopy. International Journal of Remote Sensing, Vol. 8, No. 12, pp. 1807-1827

(5) Hunt, G.R., Salisbury, J.W. (1975). Mid-Infrared Spectral Behavior of Sedimenatry Rocks. Environ. Res. Paper 510-AFCRL-TR-75-0356, AD/A016 427 Washington DC: NTIS.

(6) Lehmann, F., Richter, R. (1988). Thermal Infrared Laser Spectroscopy - The Potential of Dual Active/Passive Thermal Infrared Sensors for Earth Observation. Proc. of 4th Int. Coll. of Spectral Signatures of Objects, Aussois, France, (ESA SP-287).

(7) Wiesemann, W., Lehmann, F. (1985). Reliability of Airborne CO 2 DIAL measurements. Appl. Opt., Vol. 24, 3481.

(8) Lehmann, F., Mackin, S., Richter, R., Rothfuss, H., Walbrodt, A. (1989). The European Imaging Spectrometry Campaign 1989 (EISAC) - Preproessing, Processing and Data Evaluation of the GER Airborne Imaging Spectrometer Data. Progress Report to the European Community, JRC, Ispra. DLR, Oberpfaffenhofen, F.R.G.

(9) Werner, K., Lehmann, F. (1990). EISAC 1989 - Field Spectroscopy Campaign in the Almaden Testsite 09.-11.06.1989. Report to the European Community, JRC, Ispra. DLR, Oberpfaffenhofen, F.R.G.

(10) Lehmann, F., Wiesemann, W., Werner, C. (1984). Results and Future Aspects of CO_2 - Laser Systems in Remote Sensing. 18th Int. Symp. on Remote Sensing Environment, Paris, France.

(11) Whitbourn, L., Hausknecht, P. (1990). Rapidly Tuned 9 to 11μm CO_2 Laser System for Airborne Remote Sensing. 23rd Int. Symp. on Remote Sensing Environment, Bangkok, Thailand.

Spectral Range	400 - 2500 nm				9000-11000 nm
	laboratory		field		laboratory
Instrument / Testsite	Iris Mark IV	Perkin Elmer	Iris Mark IV	Barringer	CO_2- Laser
Reventon					
Grid 1 (•)	96	98			25
Grid 2	69	69	63	35	
Grid 3 (+)	44	37			
Grid 4	22		20		
Logrosan	78	78			
Alla	31	31			
La Parilla	7	7			
Zorita	19	19		85	

(•) = XRD-Analysis (25 sampels)

(+) = Geochemical Analysis / 26 elements

Table 1. Reflectance spectroscopy analyses in the framework of the project
The numbers indicate the amount of samples of laboratory spectroscopy analyses and the numbers of field targets

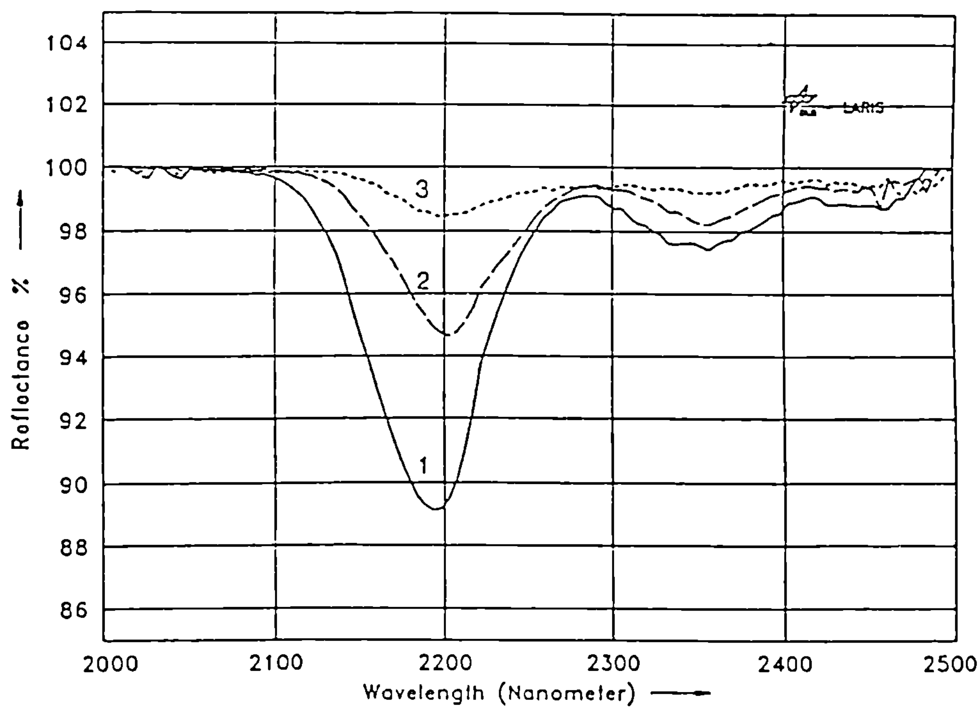


Figure 1. Hull quotient spectra
1 – granitic soil
2 – soil with contactmetamorphic influence
3 – unaltered soil

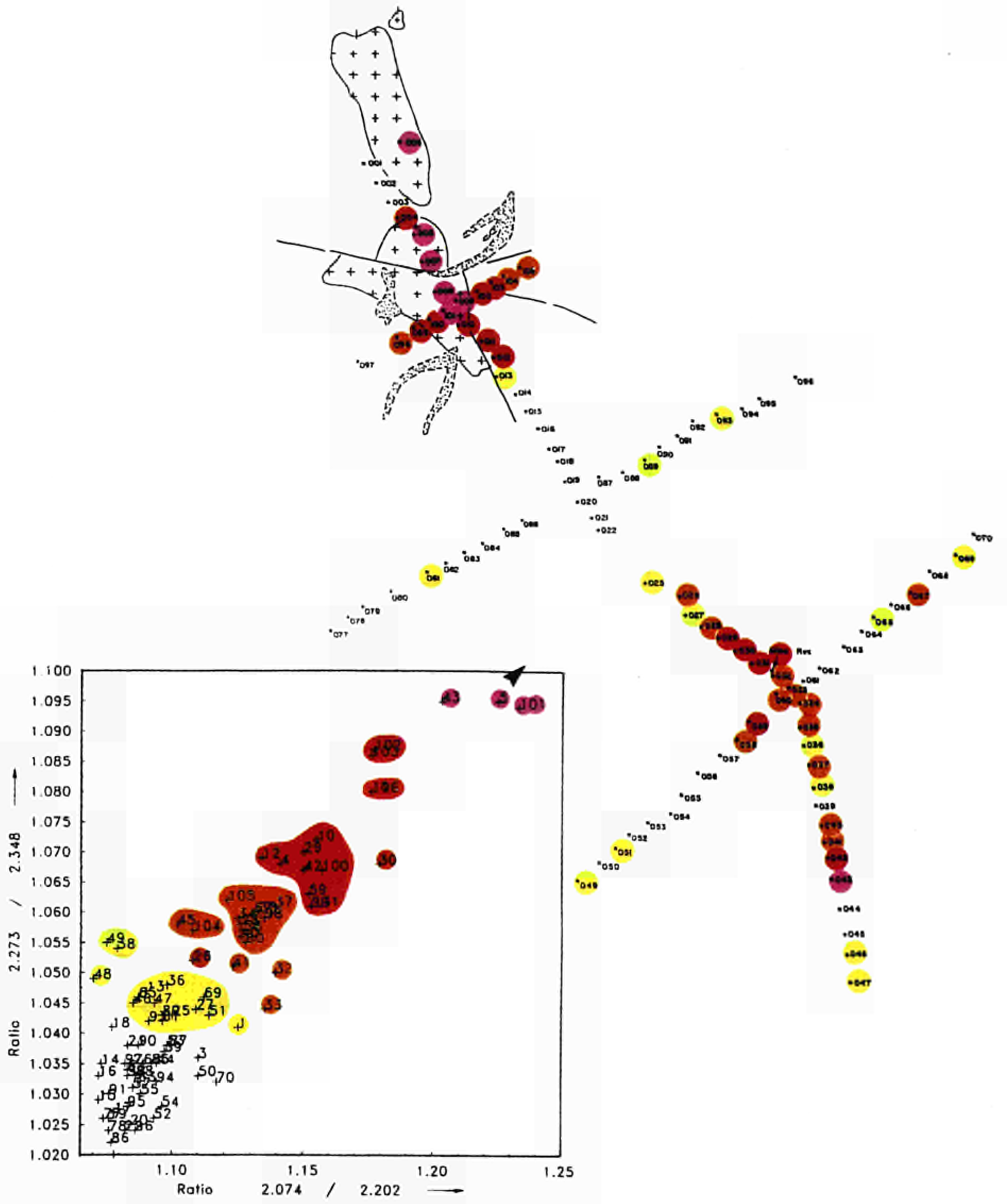


Figure 2. Double ratio calculation applied on original spectra (grid 1) obtained with the IRIS Mark IV
x-axis = 2.07 / 2.2 μm; y-axis = 2.27 / 2.34 μm;
the colour assignment indicates the spectral distribution in the diagram according to the geographic position (grid 1)

Evaluation: The position of the samples in this double ratio field is controlled by the absorption depth at 2.2 μm (kaolinite, montmorillonite) and 2.35 μm (montmorillonite, illite) from lower left to upper right. Granite samples 6,7,8,9 are located outside the diagram (arrow) due to strong absorptions of montmorillonite, muscovite, illite (max: sample 7: ratio 2.07 / 2.2 μm = 1.26, ratio 2.27 / 2.35 μm = 1.6; XRD: 15 % montmorillonite).

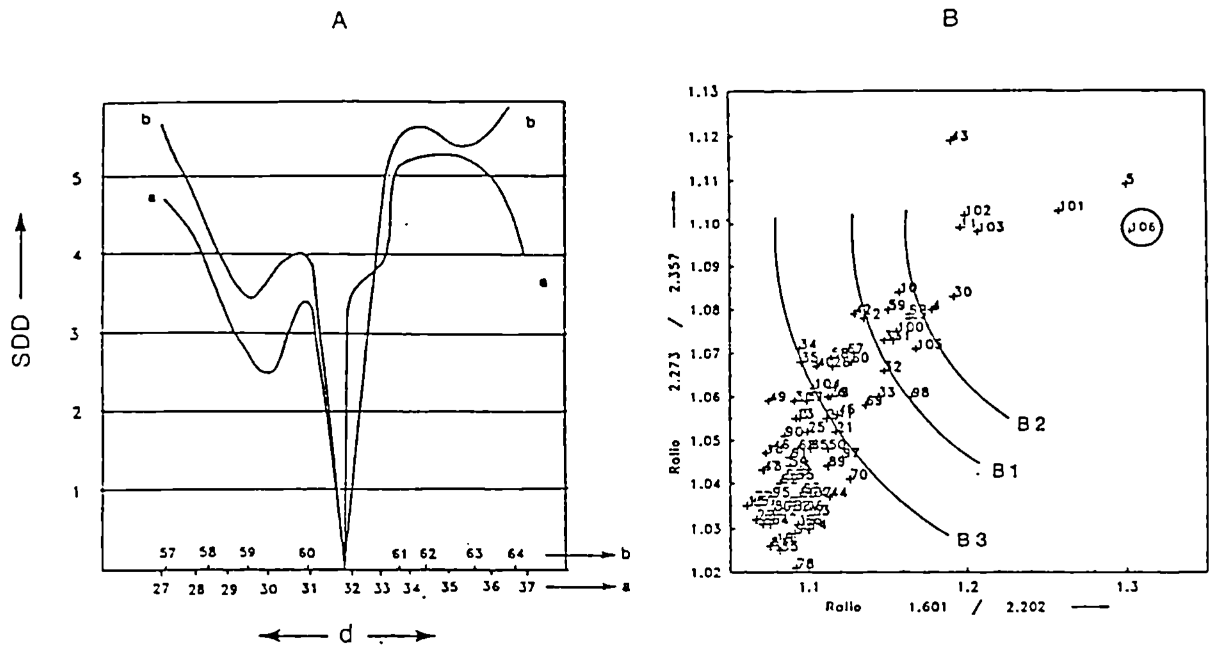


Figure 3. Spectral aureoles of the Reventon mine area

A) Spectral aureoles based on the spectral behaviour of samples taken along two profiles (a,b), crossing near the anomaly of the Reventon mine.
(d: distance of sampling locations, 1 cm = 200 m;
SDD: Spectral Double Ratio Field Distance = distance from the anomalous sample to the position of the neighbouring samples in the double ratio field, controlled by the absorption features at 2.2 μm and 2.35 μm, see graph B).

B) Position of spectral values of samples in the double ratio field versus anomaly 106 (Reventon mine):
B 1 : samples neighbouring the anomalous area
B 2 : samples near the anomalous area
B 3 : samples far from the anomalous area

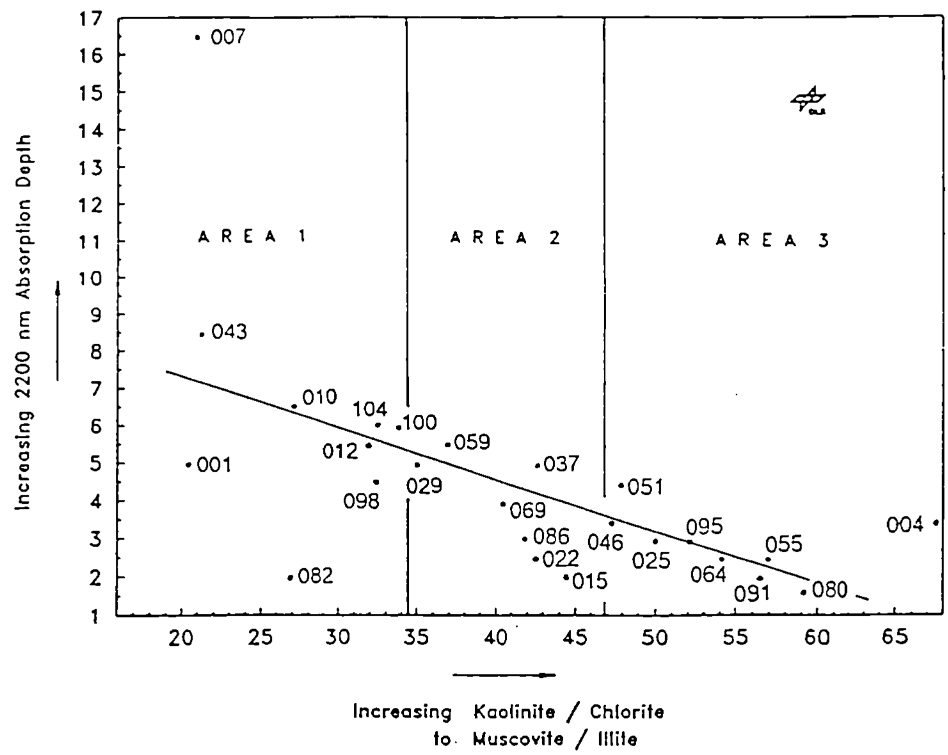


Figure 4. Correlation between XRD and spectral analysis (grid 1 samples)
x-axis: kaolinite-chlorite to muscovite-illite peak
y-axis: 2.2 μm absorption depth

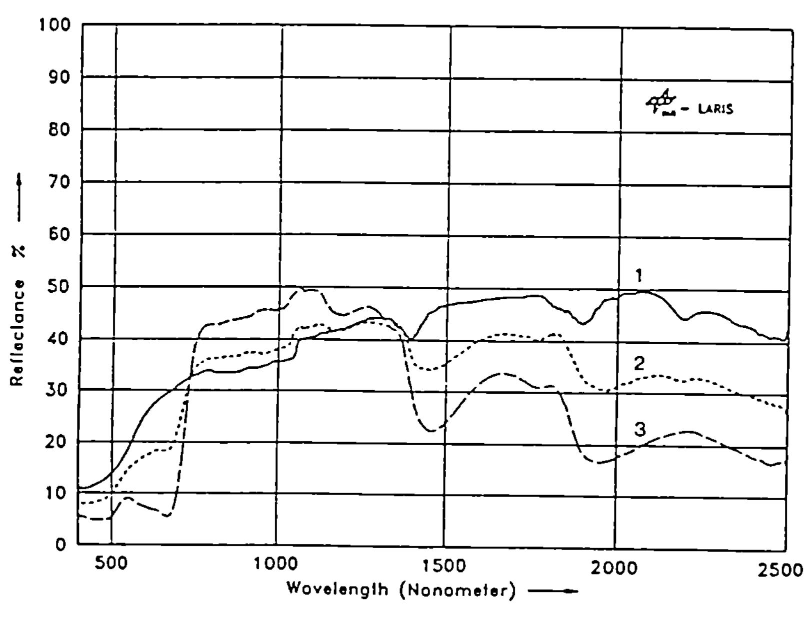


Figure 5. In situ relative reflectance spectra of targets with different percentages of vegetation cover

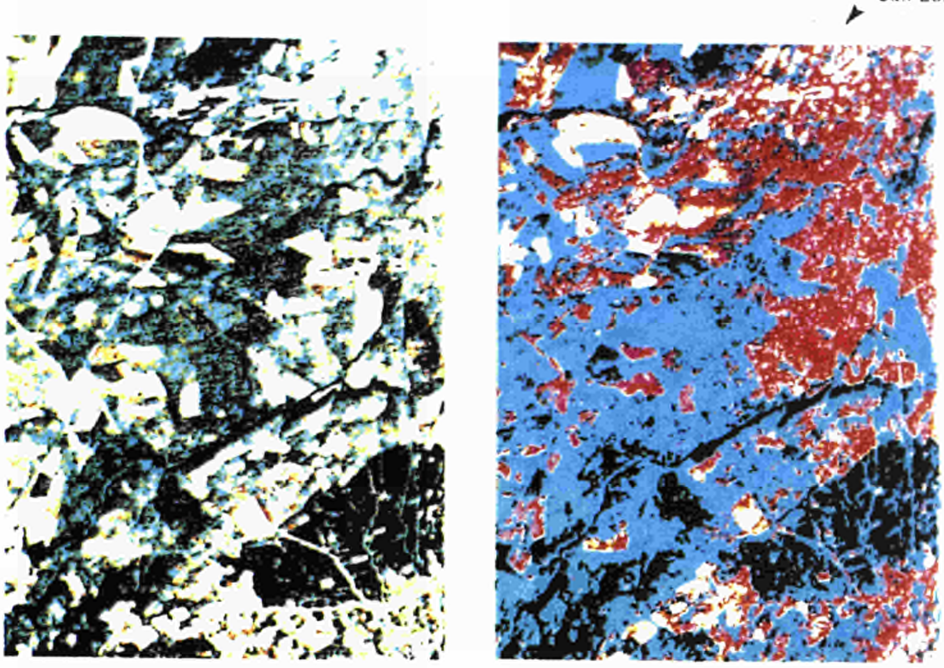


Figure 6. **RGB colour composites of GER imaging spectrometer data** (Scale 1 : 85 000)

Left: natural colour composite derived from bands at 675 nm, 551 nm, 489 nm (RGB)
Right: shortwave infrared colour composite from bands at 2070 nm, 2135 nm, 2200 nm (RGB)

In the natural colour composite all ploughed fields are displayed by high intensities, while in the shortwave infrared colour composite only areas, which are characterised by high reflectance in the SWIR and strong 2.2 μm absorption features are pronounced by high intensities. Outcropping granitic cupolas (upper part of the image) and contactmetamorphic influenced areas are delineated by this band combination.

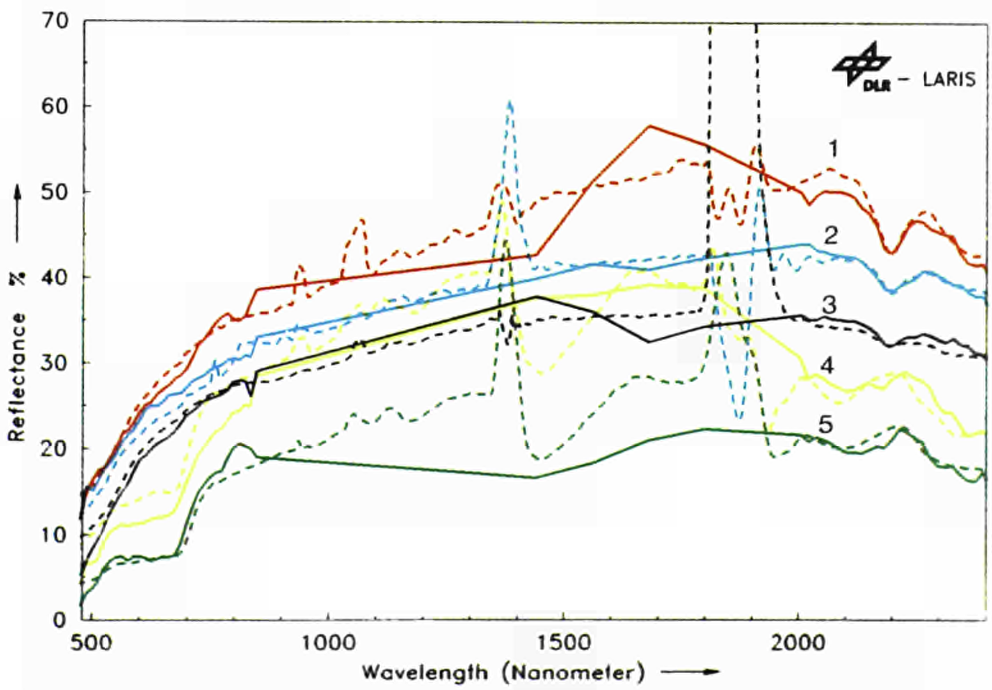


Figure 7. **Comparison of GER airborne data and IRIS Mark IV field spectra**
Reventon relative reflectance spectra from GER airborne scanner data (solid lines) and the corresponding field spectra measured with the IRIS Mark IV spectroradiometer (dotted lines). Red, blue and black colours (1,2,3) represent spectra of recently or freshly ploughed arable land with typical differences in spectral signatures. Yellow and green curves (4,5) are grassland spectra representing targets with different percentages of vegetation cover and plant height

DEVELOPMENT AND TESTING OF NEW TECHNIQUES FOR MINERAL EXPLORATION BASED ON REMOTE SENSING, IMAGE PROCESSING METHODS AND MULTIVARIATE ANALYSES-MAIN TARGET AREAS ALMADEN SPAIN AND C. IRELAND.

Project Leaders : A. PHILLIPS, J. HASLETT and P. CRAIG
Trinity College Dublin, Ireland

Contract MA1M-0011-IRL

PREFACE

Research contract MA1M-0011-IRL was part of a joint investigation carried out by Trinity College of Dublin, Technical University of Denmark (MA1M-0015-DK) and Gesellschaft für Angewandte Fernerkundung - G.A.F. (MA1M-0009-D) under coordination of Minas de Almaden (MA1M-0010-E).

1. OBJECTIVES AND INTRODUCTION

In a previous EC-funded study, it was demonstrated that the large tonnage, high grade Irish Zn - Pb stratiform deposits are sited in Lower Carboniferous carbonate deposits where Caledonian granites or Ordovician basic volcanic centres in the basement have caused dilation at major bends or terminations of shear zones in the cover (Phillips; 1988). The study also showed that high grade, low tonnage Pb-Zn-Ag, vein deposits of the Almaden area in Spain are sited at dilation zones developed where the strike of shear zones is changed by northerly striking more massive greywacke units within the polyphase deformed Precambrian basement. There is some evidence that granites of Hercynian age may have driven this hydrothermal mineralization. Figure 1 summarises these two genetic models. Thus there are strong theoretical arguments to suggest that the locations of the mineral deposits are related to geological structure. This geological structure is also displayed in part as lineaments in remotely sensed and geophysical data.

The main objective of this study has thus been to investigate statistically the structure of mineralization locations (as reflected either by sampling or by old workings), and its relationship to geological structure (as reflected in lineaments manually interpreted from satellite imagery, and in gravity data) for two areas - central Ireland and south central Spain.

Furthermore, in the previous EC-funded study statistical pattern analyses were carried out of lineaments detected from enhanced satellite imagery. This led to the identification of zones of apparent clockwise or anticlockwise shear of lineament systems. These possible shear zones were then checked against independent data derived from ground structural mapping and analysis of gravity and magnetic data. This resulted in the prediction of a widespread system of shear zones or faults in north central Ireland. In continuation of that work an additional objective of the present research has been to check the validity of these predictions by carrying out detailed structural and stratigraphic mapping of an area of particular interest between the Zn-Pb mine of Navan, Co. Meath and the east coast of Ireland.

2. METHODS

The methods have involved :

- Using inexpensive microcomputer systems to produce a range of new software for statistical analysis of lineament data from remote sensing and gravity data, which would be suitable for practical mineral exploration programmes.

- Developing new statistical methods of analysing relationships between points (mineral deposits) and lines (lineaments) to aid the prediction of dilation zones.

2.1 NEW SOFTWARE

The most suitable computing environment was identified as that offered by the Macintosh IIcx with a high resolution colour screen. In view of the strategy of the project to develop practical exploration tools for the mineral industry, one of the most important results of the project has been the development of innovative software for the Macintosh II microcomputer for the following purposes :

- For interactive graphical analysis of spatially referenced data using a multi-windows environment.

- For the range of new formal statistical analyses which were developed during the project.

For interactive graphical analyses with images and maps, a program called ZOOM was developed in which some of the features are as follows :

- Display of points & lines.

- Simple control of colour/size of plotting symbols and lines.

- Display of 8-bit images.

- Overlay, pan, zoom.

- Simple transfer to printed documents.

- All changes interactive and mouse controlled.

The project was also able to take advantage of SPIDER (SPatial Interactive Data Explorer) a radical new package being developed at TCD on the Macintosh to assist in the exploratory analysis of spatially referenced data. This offers:

- Multiple Simultaneous Views of Data in separate windows.

- Map View (with overlays).

- Statistical Views (eg. histogram).

- Dynamic Interactive Linking.

- Select & Hilight in one view, with corresponding cases immediately hilighted in other views.

The analysis of data during the project was carried out in two complementary ways using this suite of software. Firstly the data was explored using interactive graphical techniques. This was then used to define what would be the most appropriate formal statistical technique to use. Secondly these formal techniques were applied. In addition the results predicted by the formal methods were checked by graphical inspection.

The second objective of the research was to check the validity of shear zones predicted from previous multidata correlation studies. This involved a detailed structural, stratigraphic and lithogeochemical study of the 35 x 15 km area east of Navan in central Ireland.

3. ANALYSIS OF RESULTS

3.1 THE NEW METHODS

3.1.1 Distance-based methods for structure in deposit locations

In searching for an internal order in the distribution of mineral deposits, a well known method was used. This involves comparison of the distribution of the distance of deposit points to their nearest neighbours with that corresponding to a completely spatially random point distribution. The method showed that the Spanish deposits could be viewed as being arranged in statistically random points within disks of about 800 m diameter. The disk centres are randomly spaced at separations which can be greater than 800 m, but the disks may also overlap. An explanation for this pattern may be that it reflects the effective widths of zones where units of coarser greywacke formations, striking N-S, are traversed by shear zones. The Irish data shows a different and less structured pattern.

3.1.2 Fourier analysis for structure in deposit locations

The Spanish model for the spatial control of mineralization predicts that there will be a tendency for the direction between pairs of deposits to be biased towards the strike directions of shear zones. A form of Fourier analysis using kernel density estimation was developed. This involves comparing the results of fast Fourier transform analysis of the position of observed deposits with the results of such analysis for points distributed according to a null model of Spatial Randomness (no perfect direction) at different scales. The two dimensional periodogram produced by this method allowed patterns of distribution of different scales to be recognised. The Spanish deposits show an alignment along an 045° trend, confirming the conclusion reached from the previous ground structural studies. The Irish deposits show no preferred alignment; this is again consistent with the very different structural control which was established for them.

3.1.3 Relationship between remotely sensed lineaments and mineral deposit locations

New statistical methods were developed for analysing relationships between lines and points. Firstly, an index based on distances to all lines was computed for each point. This was compared with the index obtained from a random pattern of points. Lines (remotely sensed lineaments) were transformed into lineament density functions using a Gaussian "blurring" technique. The Spanish data showed that approximately 60 % of deposits have a lineament closer than 400 m whereas only 50 % of randomly chosen points have a lineament so close. By restricting the analysis to specific trends of lineaments it was shown that there is some evidence of a relationship between the Spanish deposits and lineaments whose strike lies between 045° and 090°. This is consistent with the ground structural data. Also in conformity with the ground structural evidence, the Irish deposits show no relationship with remotely sensed lineaments.

3.1.4 Prediction of mineralisation probability

The index, or function of proximity to lineaments for each deposit, suitably rescaled to allow for the effects of varying point density, was used to predict the probability of mineralization. The lineaments striking 045°-090° and 135°-180° in the Spanish area were found to be the optimal predictors. They succeeded in predicting an area of mineralization which coincides with a distinct cluster of known deposits. In addition a further area of mineralization was predicted in a new area to the northwest. This needs further geological evaluation.

3.1.5 Prediction of mineralization probability from gravity data

Unfortunately there is no adequate gravity data available for the Spanish area. However analysis of the good cover of gravity data in Ireland proved to be of considerable interest. The Bouger anomaly data was interpolated onto a 500 m grid. In order to recognise linear features which might reflect faults or shear zones, the data was processed in three different ways :

- The steepest gradient was computed for each point.
- Local variation was measured by applying a high pass filter.
- Local variability was measured using context stretching.

An optimal predictor of mineralization was found to be a linear combination of rescaled gradient and context stretched coefficients. The predictor succeeded in assigning high values for likelihood of mineralization to the known mineralized sites. In addition it predicts some new sites which merit further geological consideration. The predictor demonstrated that there is a positive correlation between positive gravity anomalies (mostly Ordovician volcanic centres) and mineralization in the area studied. This is compatible with the known association of the Navan deposit with Ordovician volcanic rocks. The association of deposits with basement granites found previously in the West Midlands was not found in the more easterly area studied.

The results of the mapping programme in eastern Ireland are summarised in Figure 2. Figure 3 summarises the correlations between shear zones predicted from the previous multidata correlation methods and those identified by the mapping programme.

4. CONCLUSIONS

The new interactive graphics software for Macintosh microcomputers is a valuable aid to mineral exploration.

The results of the statistical analyses, already summarised, indicate that the small tonnage Spanish deposits are distributed at many minor bends along a series of dominantly

ENE trending dextral shear zones. In contrast, the large tonnage Irish deposits are not distributed along shear zones but are concentrated at major bends or terminations of shear zones. These mineralized sites appear to have been generated primarily by the mechanical effect of Ordovician volcanic centres in east central Ireland.

The new sites of high probability of mineralization in Spain and in Ireland merit further geological evaluation.

The results of the statistical analyses should be accepted with caution. However they gain credibility from the fact that they are compatible with the two very different models for the structural control of mineralization in Spain an Ireland respectively.

The results of the field mapping programme showed that the previous multidata correlation methods were successful in identifying the main fault and shear zone pattern in a poorly exposed and structurally complex inlier of Lower Palaeozoic rocks. As a result of the multidata correlation methods being based upon analysis of 2 x 2 km cells, a finer resolution than this for the position of individual shear zones was not possible. It was encouraging that the sense of apparent horizontal shear predicted from the multidata studies, agreed with the later phases of movements which were found on these structures in the field.

5. PUBLICATIONS AND ORAL COMMUNICATIONS

5.1 PUBLICATIONS

Phillips, W.E.A. (1988): The correlation of geological; geochemical and geophysical data with satellite imagery in North Central Ireland. EUR 11521 - Summary reports of the subprogramme: metals and mineral substances (1982-85) - Volume 1, pp 523-530. Luxembourg, Office for Official Publications of the European Communities.

Vaughan A. and Johnston J.D. (in press) Structural constraints on the geometry of the Iapetus Suture. Journal of the Geological Society of London.

5.2 ORAL COMMUNICATIONS (OTHER THAN EC ORGANISES)

Paper to International Meeting on Statistics in Earth and Space Sciences. August 1989. Catholic University of Leuven, Belgium.

Seminar to the Department of Statistics, University of Edinburgh. March 1990.

FIGURE CAPTIONS

Figure 1 :

a. Illustration of the structural controls of mineralization associated with faults and shear zones.

b. Structural model for the control of base metal mineralization in the Alcudia Valley Spain. The mineralization is controlled by dilational bends on D2 shear zones which follow pre-existing D 1 Hercynian cleavage. The dilation zones occur where the cleavage is "refracted" within coarse grained greywacke units. D = dilational bend with mineralization, C = compressional bend without mineralization.

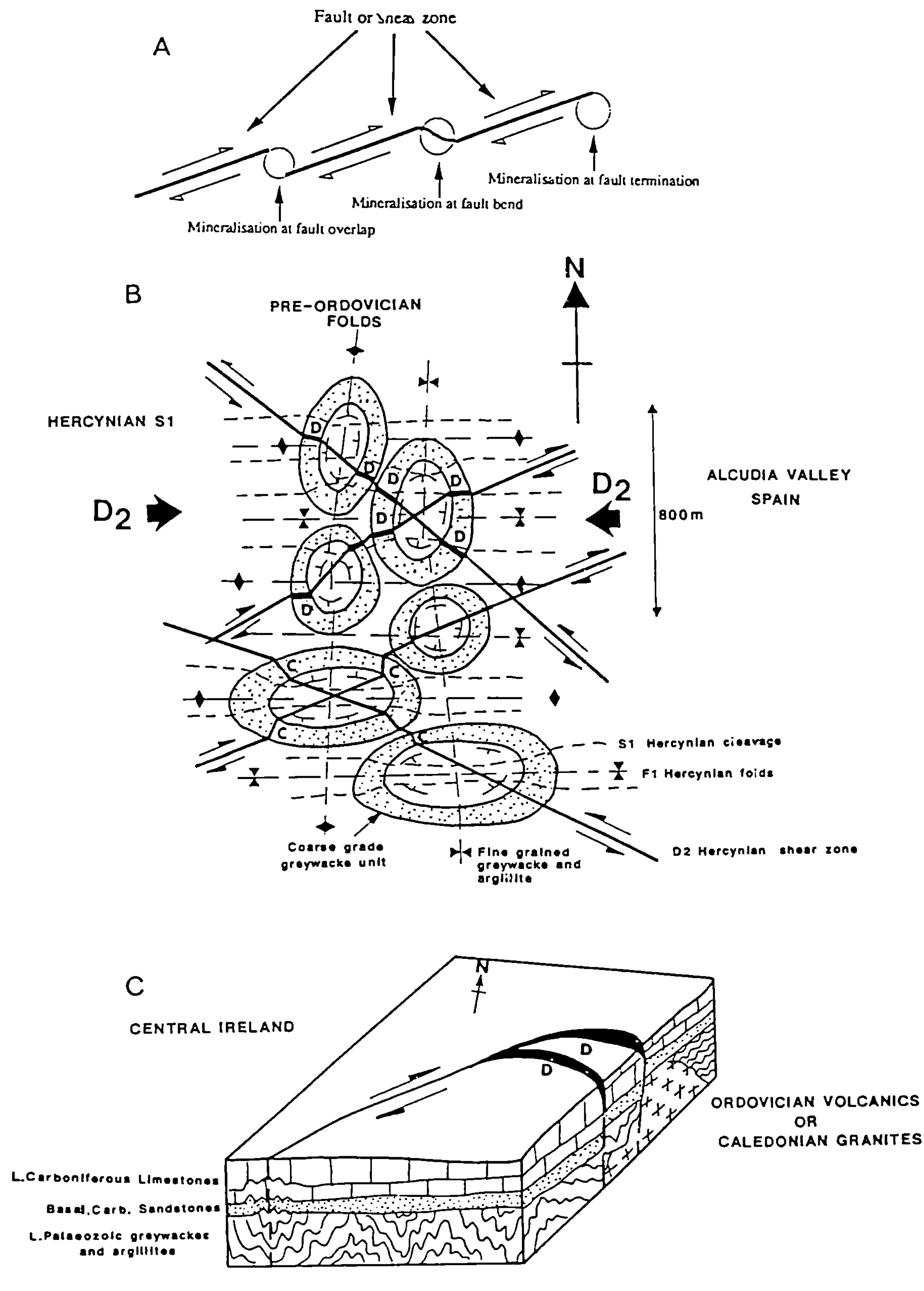
c. Structural model for the control of base metal mineralization in Lower Carboniferous carbonate sediments in central Ireland. D = mineralised dilation zone.

Figure 2 :

Geological map and structural cross sections of Lannvirn-Wenlock rocks of the test area mapped in east-central Ireland. CH = Clogher Head. IS = Iapetus Suture. S = Salterstown. TF = Tinure Fault (local sector of Iapetus Suture).

Figure 3 :

Map of the test area in east-central Ireland showing correlation between faults and shear zones mapped on the ground and those inferred from multi-data correlations.



A
Fault or shear zone
Mineralisation at fault overlap
Mineralisation at fault bend
Mineralisation at fault termination
B
PRE-ORDOVICIAN FOLDS
N
HERCYNIAN S1
D2
D2
800m
ALCUDIA VALLEY SPAIN
D
C
S1 Hercynian cleavage
F1 Hercynian folds
Coarse grade greywacke unit
Fine grained greywacke and argillite
D2 Hercynian shear zone
C
CENTRAL IRELAND
N
D
ORDOVICIAN VOLCANICS OR CALEDONIAN GRANITES
L.Carboniferous Limestones
Basal.Carb. Sandstones
L.Palaeozoic greywackes and argillites

Fig. 1

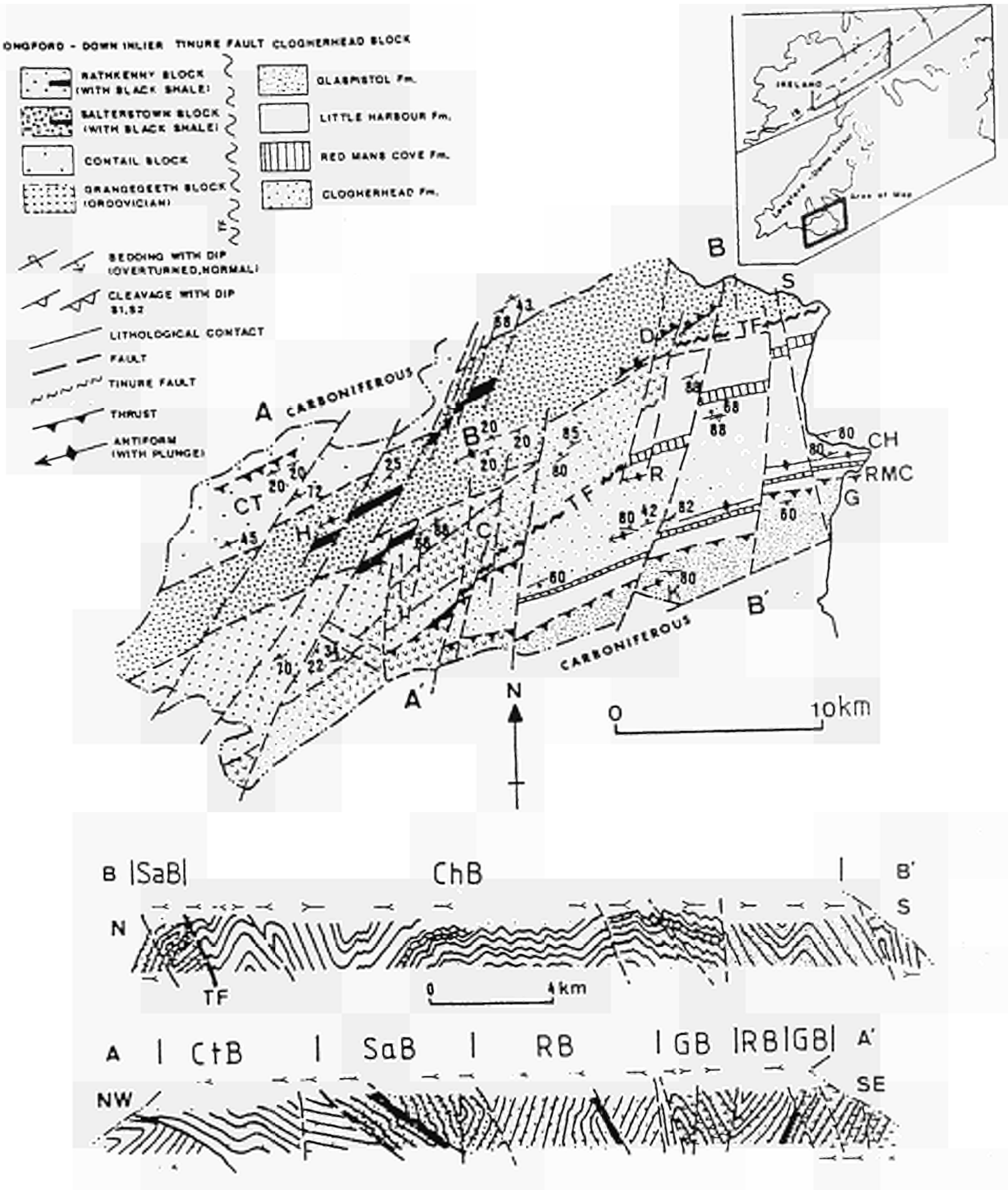
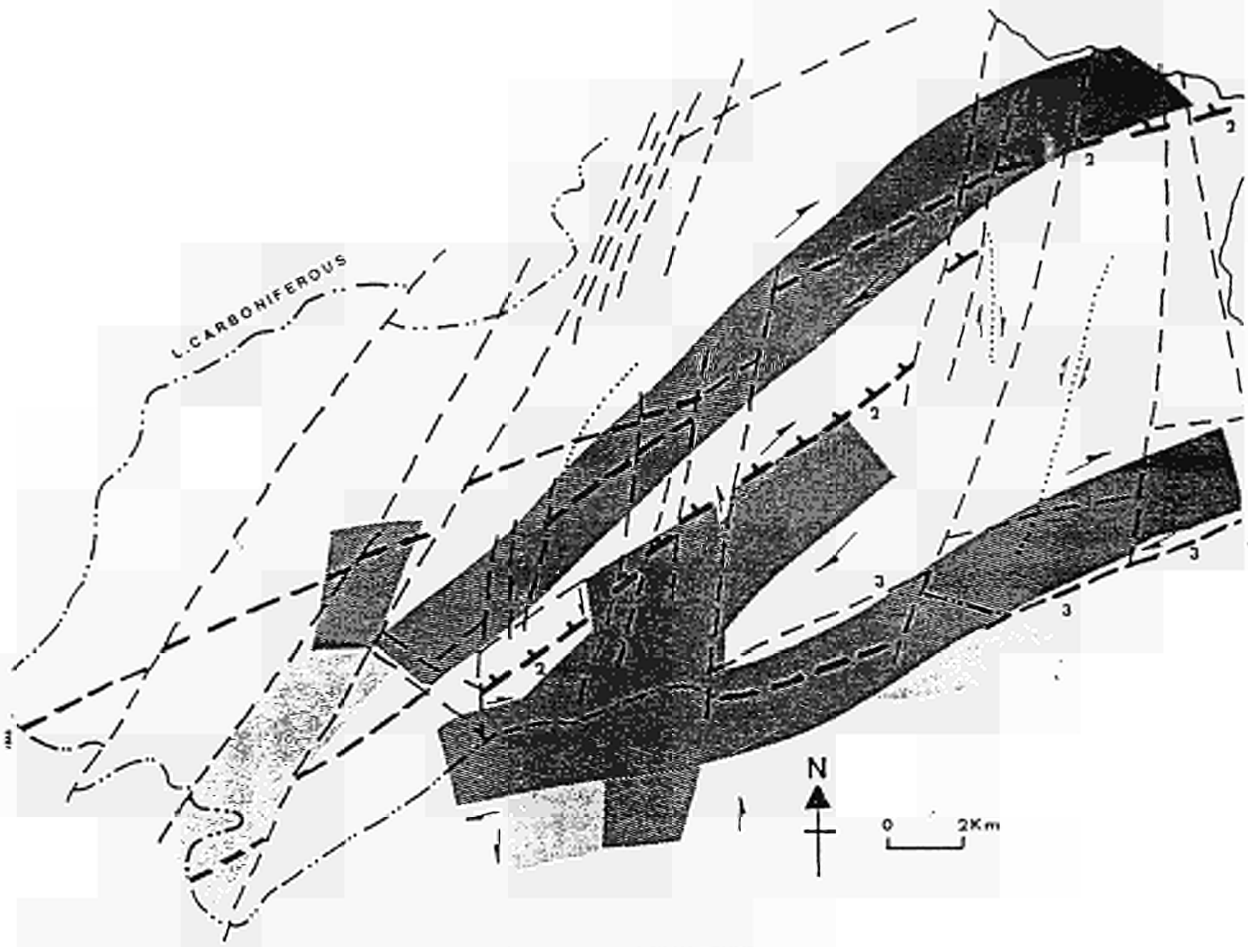

ONGFORD - DOWN INLIER TINURE FAULT CLOGHERHEAD BLOCK
RATHKENNY BLOCK (WITH BLACK SHALE)
SALTERSTOWN BLOCK (WITH BLACK SHALE)
CONTAIL BLOCK
GLASPISTOL Fm.
LITTLE HARBOUR Fm.
RED MANS COVE Fm.
CLOGHERHEAD Fm.
BEDDING WITH DIP (OVERTURNED,NORMAL)
CLEAVAGE WITH DIP S1,S2
LITHOLOGICAL CONTACT
FAULT
TINURE FAULT
THRUST
ANTIFORM (WITH PLUNGE)
IRELAND
CARBONIFEROUS
CARBONIFEROUS
0 10km
B |SaB| ChB | B'
N S
TF
0 4km
A | CtB | SaB | RB | GB |RB|GB| A'
NW SE

Fig. 2



SHEAR ZONES DEFINED ONLY FROM LINEAMENT ROTATION ZONES.

SENSE OF SHEAR FROM REMOTE SENSING LINEAMENT ANALYSIS

SHEAR ZONES DEFINED FROM REMOTE SENSING AND EITHER GEOPHYSICAL OR GROUND STRUCTURAL DATA

SHEAR ZONES DEFINED FROM REMOTE SENSING GROUND STRUCTURAL AND GEOPHYSICAL DATA

UNCONFORMABLE BASE OF UPPER PALAEOZOIC ROCKS

MINOR FAULTS

OTHER MAJOR STRIKE FAULTS

CALEDONIAN COLLISION SUTURE (TINURE FAULT)

Fig. 3

DEVELOPMENT AND TESTING OF NEW TECHNIQUES FOR MINERAL EXPLORATION BASED ON REMOTE SENSING, IMAGE PROCESSING METHODS, AND MULTIVARIATE ANALYSIS

Project Leader: K. CONRADSEN
IMSOR, Technical University of Denmark, Lyngby, Denmark

Contract MA1M-0015-DK

PREFACE

The research carried out under this contract was part of a joint project between Minas de Almadén y Arrayanes, S.A., Almadén, Spain (Contract MA1M-0010-E), Gesellschaft für Angewandte Fernerkundung (GAF) and DLR - German Aerospace Research Establishment, München and Oberpfaffenhofen, Germany (Contract MA1M-0009-D), Trinity College, Dublin, Ireland (MA1M-0011-IRE), and IMSOR, Lyngby, Denmark.

1. OBJECTIVES

The general aim of the project was - as outlined in the title - to develop and test new techniques for mineral exploration based on remote sensing, image processing methods and multivariate analysis. The target area for the investigations undertaken by IMSOR was Almadén, Spain. More specifically new software should be developed for the statistical image processing, the treatment of structural data, and the data integration. Furthermore it was considered important to adapt the software developed for use on microcomputers.

From the above more general objectives, the responsibilities of IMSOR were :

i) integration of datasets,
ii) automatic detection of lineaments,
iii) classification and multivariate analysis of the datasets
iv) development of 3D models,
v) software development.

In the sequel are described the main results obtained from a data analytic point of view. The geological conclusions are given in the reports by the other team members.

2. MATERIALS AND METHODS

The main test areas were the Alcudia and the Guadalupe/Valdelacasa regions. The main satellite information available were Landsat 5 imagery from summer and from winter, and a SPOT stereo pair. The geochemical information included data from 7,649 sites in Alcudia, 16,504 sites in Guadalupe, and 17,488 sites in Valdelacasa. All samples were analysed for the contents of 27 geochemical elements. The geophysical information was mainly aeromagnetic observations, but also gravity measurements in some places.

One aspect of the integration of the datasets was the combination of the geophysical, geochemical, and multispectral data in a common database by interpolating and resampling the data to a common UTM grid. Another aspect is the joint analyses and correlation by means of e.g. CART, a technique that will be described in the sequel.

When inspecting sample site images of the individual elements a conspicuous map sheet effect is noted for some elements. This is due to variations in the chemical analyses in the laboratory. Since the data were analyzed in batches corresponding to samples from one map sheet the irregularity could be seen as a chessboard pattern in the regional maps showing concentrations of the elements from the geochemical analyses. It was found to be impossible to remove this effect by linear methods. Therefore the calibration was done by a successive histogram equalization routine. The basic idea is to compute histograms for observations lying in a narrow band on each side of a map sheet border and then determine transformations so that the histograms coincide at every fifth percentile. The process is started in a corner map sheet, e.g. to the north west and the east and the south neighbours are readily transformed. Now the map sheet south east of the initial map sheet has to conform to the two former map sheets. This is done by weighting the two transformations that are obtained as described above. The weights applied are inverse distances. Continuing in this fashion the procedure propagates in the SE direction until all map sheets are transformed.

The interpolation of the irregularly distributed geochemical sample values was done by means of kriging techniques. After investigations of the feasibility of more elaborate methods (e.g. co-kriging) it was decided to develop routines that, to a higher extent, take the spatial lay-out into account. We refer to this type of kriging as quadrant kriging. The semi-variograms were estimated without using values from pairs of sampling sites in different map sheets. Subsequently spherical models with nugget effects were estimated by means of a weighted, iterative, non-linear least squares estimation procedure. In Alcudia block-kriging was done to a 200 m x 200 m grid and in Guadalupe/Valdelacasa point kriging to a 500 m x 500 m grid. In areas where a better resolution was needed further interpolation was done by bicubic spline interpolation.

At a number of sampling sites geochemical variables as well as heavy mineral counts were available. By means of a concept for constructing tree-based classification algorithms (CART.: Classification And Regression Trees) models were made for predicting presence or absence of heavy minerals in areas where no counts were made. This enabled the construction of 'probability maps' for the most important heavy minerals, gold, scheelite, cassiterite, wolframite, etc.. Maps constructed in a similar way just using Mahalanobis distances instead of CART have been constructed in the Reventon area, the only difference being that the 'training' is based on an outcropping granite instead of heavy mineral counts.

A new concept for assessing micro- and macro-structural features has been developed. Empirically it was found that the red wavelength band (TM3) depicted the geological features to the same extent as, or better than, other bands, band ratios or band combinations. Furthermore it was realized that scale heavily influenced the results. It was therefore decided to operate with two levels of pixel size, namely 30 and 200 ms. The linear features are now determined by directional filterings and line enhancement operations. The directional filtering is done in 4 different directions by means of standard directional filters of the GOP 302 image processing system. Based on the resulting 4 images a line enhancement operation yields line elements. This is done at each resolution and in this way a micro- and macro-structure image is obtained. These are used directly in the visual presentation of combined data. By means of morphological operations and a 'vector from raster image' estimation procedure usual lineament maps are produced.

The multidimensional datasets were analysed by different multivariate techniques. The consistency between element concentrations and the lithological units was confirmed through discriminant analyses. Factor analyses were used in analysis of the correlation structure between elements, and the relation between the spatial correlation and the element correlations was assessed by means of Minimum/Maximum Autocorrelation Factors (MAFs).

Since the dimensionality of the datasets available in studies like the present one is increasing rapidly due to the development within scanner and measurement technology some new data analytic tools for handling such data were evaluated. Projection pursuit may be thought of as a generalization of methods like principal components, MAFs, canonical discriminant functions. The grand tour is a systematic way of evaluating projections (linear combinations) of high dimensional data.

A parallel problem is the question of selection of features in e.g. classification studies. The existing methods are primarily based on linear techniques. Therefore they are not optimal, and a non linear technique based on Jeffreys-Matusitas distance measure was developed.

The development of a procedure for estimating 3D models based on stereo pairs was based on the availability of hardware that was very fast in convolving images. Therefore a very direct approach in estimating the disparity between points in the stereo pair could be implemented. Basically it is a cross-correlation method that operates in an iterative way. In each iteration a rotation and a warping is estimated. The images are transformed in order to obtain a maximum similarity, and this enables a more precise estimation of the disparity in the next step. The estimated model has been geometrically corrected in order to fit a map sheet (1:50,000) of one of the prime target areas. The isolines in the height model are 20 m curves. Based on the model different corrections and calibrations of other image data (e.g. Landsat) were performed.

In the analysis of multisource image data the presentation of results is crucial. A common theme is to use methods that traditionally are applied in depiction of 3D information like synthetic stereo, height information through shading or colouring etc.

The software developed comprises portable software for the ERDAS image processing system, and software requiring more specialized hardware like e.g. the GOP image processor.

3. ANALYSIS OF RESULTS

In short, the main purpose of the IMSOR part of this research programme was to develop methods for the analysis of the data that are available in a major exploration program over a considerable area. This was to take place in a realistic environment where all the problems that may occur in practice are taken into consideration. The discussion of the results obtained will show that it is found that this goal has been met.

In the analysis of large amounts of geochemical samples it is very likely that calibration problems will occur, and consequently one often - like earlier mentioned - observes e.g. chessboard patterns in maps showing the analyses of the different elements. The method developed for correcting these patterns seems to yield very good results. It has been possible to detect known geological units based on the corrected maps, which indicates that the constructed structure depicts real phenomena and not artifacts. In this phase the multivariate analyses (factor analysis, MAFs, discriminant analysis) served a twofold purpose. One was acting as a quality control measure, the other to give further insight in the distribution of element concentrations.

The prediction of heavy mineral counts by means of a tree based classification procedure (CART) was likewise found to be very useful. For different heavy minerals, areas with a higher potential have been delineated, and some of these predictions have been confirmed by other types of investigation. It is believed that this type of analysis may become a very useful tool in exploration geology. It gives a problem oriented summary of the information available, and it may, in initial phases of an exploration programme, be used to depict target areas where more extensive measurements can be taken.

Variable	Rel. Imp.	Variable	Rel.Imp.	Variable	Rel. Imp.
Mg	100	Ca	58	As	24
Cr	100	Al	55	Sb	23
Ba	80	V	55	Cd	9
Fe	79	Y	51	Hg	8
Mn	72	Pb	50	Sn	8
Cu	70	Zn	48	W	5
P	61	Nb	45	Be	5
Ni	61	Ti	37		

Table 1. CART variable importance ranking for predicting gold.

To be more specific we show some short examples of the results that are obtainable by these techniques. Table 1 shows the relative importance of different elements in predicting gold, based on the covariation between the heavy mineral samples of gold and the geochemical measurements. It is obvious that an interpretation requires knowledge of the geology of the area, but given that knowledge it is also clear that the list may be very informative. Similar remarks hold for the interpretation of Figure 1 where we show the predicted likelihood of presence of another heavy mineral.

The introduction of methods like 'the grand tour' and projection pursuit are likewise expected to be very useful. Their major potential lies however within datasets with many channels (imaging radiometers a.l.), and suitable data were not available in time for inclusion in the present work. The analysis of the lower dimensional Landsat scenes showed many interesting transformations, confirming the above mentioned expectations.

The feature selection algorithm based on Jeffreys-Matusitas distance has already shown a superior behaviour in many applications. It has of course a potential also outside remote sensing and statistical image processing, but since many classifications of image data are based on features expressing spatial properties besides the original variables, the need for a selection algorithm seems to be bigger in this case.

One of the major tasks in structural analysis of geological image data is the mapping of lineaments and the subsequent computation of lineament statistics. Based on micro-relief properties a prototype procedure for estimating the distribution of the direction of lineaments was developed in an earlier project. These procedures have been refined, and a strongly expressed demand for a completion with an actual lineament drawing procedure are satisfied with the programme developed. The programme is controlled by means of several parameters, and it seems to work well in the test area. Therefore it is expected to be a useful tool that may produce fully repeatable lineament data in an automatic fashion. Obviously the geologist will have to check the outcome 'manually' in order to exclude features like e.g. highways, since no attempts have been made to distinguish between linear features of different origin.

The estimation of three dimensional elevation models based on stereo pairs of images by means of a direct matching (as opposed to feature matching) was evaluated by a visual comparison between the estimated height values and the topographic maps of the area. The result of this comparison was very encouraging. The availability of reliable terrain information in the analysis of data sets like the present opens up for a whole new range of interesting analyses. Catchment areas may be determined, satellite imagery may be calibrated according to direction and size of slope etc.

The usefulness of the different presentation concepts has been confirmed by the partners in the project. A further evaluation must await the experience collected by actual use of the said products.

As a summarizing conclusion it can be stated that the application of computer intensive statistical tools in the analysis of combined geodata on a regional scale yields a useful contribution to the exploration for mineral deposits. The better the geological exploration model is, the bigger is the value of a proper statistical analysis.

4. PUBLICATIONS

Conradsen, K, A.A. Nielsen & K. Windfeld: Analysis of Geochemical Data Sampled on a Regional Scale. To appear in A.T. Walden & Peter Guttorp (eds.): Statistics in the Environmental and Earth Sciences. Griffin Books. 23 pp.

Conradsen, K., & B.K. Ersbøll: Variable Selection in Non-Linear Discriminant Analysis. Submitted for publication. 25 pp.

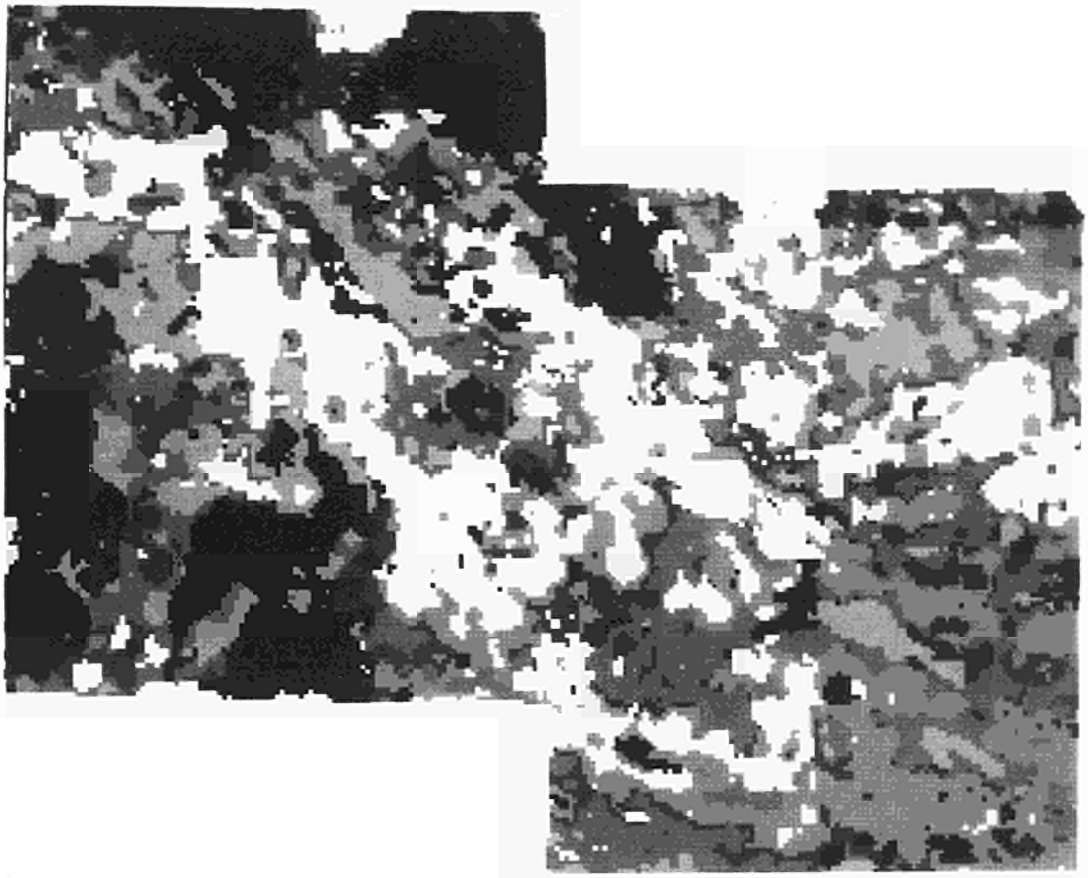


Figure 1: Probability plot for the occurrence of a heavy mineral (sillimanite) based on CART predictions from geochemical maps. The black values correspond to a high probability. The area is the Guadalupe/Valdelacasa district.

European Communities — Commission

EUR 13647 — Summary reports of the R&D programme : Primary raw materials (1986-89) Volume I

Edited by M. Donato

Luxembourg: Office for Official Publications of the European Communities

1992 — LIV, 282 pp., 5 tab., 7 fig. — 21.0 × 29.7 cm

Resources series

ISBN 92-826-3794-8

Price (excluding VAT) in Luxembourg: ECU 33

This document contains the summary reports of cost-sharing R&D contracts funded under the Primary raw materials subprogramme of the Commission of the European Communities. This was part of the R&D programme on raw materials and advanced materials (1986-89).

The main objectives of the Primary raw materials subprogramme were to enhance the competitiveness of the European Community mining and metallurgical industries and to reduce European Community vulnerability for minerals, particularly those of critical or strategic interest.

This programme was funded with ECU 20 million for the period 1986 to 1989 of which ECU 17 million was allocated to research contracts. The balance was allocated to the management of the programme (staff, organization of contact group meetings, expert meetings, international cooperation and other costs).

The subprogramme comprised three research areas :

1. Research and development exploration

Economic geology, methods of geochemical and geophysical prospecting, remote sensing.

2. Mining technology

Rock fracturing, rock mechanics, support systems, problems associated with depth, robotics, methods of modelling and simulation, problems of small-size mines.

3. Mineral processing

Hydrometallurgy of complex sulphide ores, oxidized ores, refractory ores, mine tailings and metallurgical residues; modelling and control in mineral processing; industrial minerals.

Iron, fossil fuels and building materials were excluded from the programme.

Venta y suscripciones • Salg og abonnement • Verkauf und Abonnement • Πωλήσεις και συνδρομές
Sales and subscriptions • Vente et abonnements • Vendita e abbonamenti
Verkoop en abonnementen • Venda e assinaturas

BELGIQUE BELGIË

Moniteur belge / Belgisch Staatsblad
Rue de Louvain 42 Leuvenseweg 42
1000 Bruxelles 1000 Brussel
Tél (02) 512 00 26
Fax 511 01 84
CCP Postrekening 000-2005502-27

Autres distributeurs
Overige verkooppunten

Librairie européenne/ Europese Boekhandel
Avenue Albert Jonnart 50
Albert Jonnartlaan 50
1200 Bruxelles 1200 Brussel
Tél (02) 734 02 81
Fax 735 08 60

Jean De Lannoy
Avenue du Roi 202 Koningslaan 202
1060 Bruxelles 1060 Brussel
Tél (02) 538 51 69
Télex 63220 UNBOOK B
Fax (02) 538 08 41

CREDOC
Rue de la Montagne 34 / Bergstraat 34
Bte 11 Bus 11
1000 Bruxelles 1000 Brussel

DANMARK

J. H. Schultz Information A/S
EF-Publikationer
Ottiliavej 18
2500 Valby
Tlf. 36 44 22 66
Fax 36 44 01 41
Girokonto 6 00 08 86

BR DEUTSCHLAND

Bundesanzeiger Verlag
Breite Straße
Postfach 10 80 06
5000 Koln 1
Tel. (02 21) 20 29-0
Telex ANZEIGER BONN 8 882 595
Fax 20 29 278

GREECE/ΕΛΛΑΔΑ

G.C. Eleftheroudakis SA
International Bookstore
Nikis Street 4
10563 Athens
Tel (01) 322 63 23
Telex 219410 ELEF
Fax 323 98 21

ESPANA

Boletín Oficial del Estado
Trafalgar, 27
28010 Madrid
Tel (91) 44 82 135

Mundi-Prensa Libros, S.A.
Castello, 37
28001 Madrid
Tel (91) 431 33 99 (Libros)
431 32 22 Suscripciones)
435 36 37 Dirección)
Télex 49370 MPLI-E
Fax (91) 575 39 98

Sucursal

Librería Internacional AEDOS
Consejo de Ciento, 391
08009 Barcelona
Tel (93) 301 86 15
Fax (93) 317 01 41

Llibreria de la Generalitat de Catalunya
Rambla de s Estud s, 118 (Pa au Moja)
08002 Barcelona
Tel (93) 302 68 35
302 64 62
Fax (93) 302 12 99

FRANCE

Journal officiel
Service des publications des Communautés européennes
26, rue Desaix
75727 Paris Cedex 15
Tel. (1) 40 58 75 00
Fax (1) 40 58 75 74

IRELAND

Government Supplies Agency
4-5 Harcourt Road
Dublin 2
Tel. (1) 61 31 11
Fax (1) 78 06 45

ITALIA

Licosa Spa
Via Duca di Calabria, 1 1
Casella postale 552
50125 Firenze
Tel. (055) 64 54 15
Fax 64 12 57
Telex 570466 LICOSA I
CCP 343 509

GRAND-DUCHÉ DE LUXEMBOURG

Messageries Paul Kraus
11, rue Christophe Plantin
2339 Luxembourg
Tél. 499 88 88
Télex 2515
Fax 499 88 84 44
CCP 49242-63

NEDERLAND

SDU Overheidsinformatie
Externe Fondsen
Postbus 20014
2500 EA 's-Gravenhage
Tel. (070) 37 89 911
Fax (070) 34 75 778

PORTUGAL

Imprensa Nacional
Casa da Moeda, EP
Rua D. Francisco Manuel de Melo, 5
1092 Lisboa Codex
Tel (01) 69 34 14

Distribuidora de Livros Bertrand, Ld.ª
Grupo Bertrand, SA
Rua das Terras dos Vales, 4-A
Apartado 37
2700 Amadora Codex
Tel (01) 49 59 050
Telex 15798 BERDIS
Fax 49 60 255

UNITED KINGDOM

HMSO Books (PC 16)
HMSO Publications Centre
51 Nine E ms Lane
London SW8 5DR
Tel (071) 873 2000
Fax GP3 873 8463
Te ex 29 71 138

ÖSTERREICH

Manz'sche Verlags- und Universitätsbuchhandlung
Kohlmarkt 16
1014 Wien
Tel. (0222) 531 61-0
Telex 11 25 00 BOX A
Fax (0222) 531 61-39

SUOMI

Akateeminen Kirjakauppa
Keskuskatu 1
PO Box 128
00101 Helsinki
Tel. (0) 121 41
Fax (0) 121 44 41

NORGE

Narvesen information center
Bertrand Narvesens vei 2
PO Box 6125 Etterstad
0602 Oslo 6
Tel. (2) 57 33 00
Telex 79668 NIC N
Fax (2) 68 19 01

SVERIGE

BTJ
Box 200
22100 Lund
Tel. (046) 18 00 00
Fax (046) 18 01 25

SCHWEIZ / SUISSE / SVIZZERA

OSEC
Stampfenbachstraße 85
8035 Zurich
Tel. (01) 365 54 49
Fax (01) 365 54 11

CESKOSLOVENSKO

NIS
Havelkova 22
13000 Praha 3
Tel. (02) 235 84 46
Fax 42-2-264775

MAGYARORSZÁG

Euro-Info-Service
Budapest I. Kir.
Attila út 93
1012 Budapest
Tel. (1) 56 82 11
Telex (22) 4717 AGINF H-61
Fax (1) 17 59 031

POLSKA

Business Foundation
ul Krucza 38/42
00-512 Warszawa
Tel. (22) 21 99 93, 628-28-82
International Fax&Phone
(0-39) 12-00-77

JUGOSLAVIJA

Privredni Vjesnik
Bulevar Lenjina 171/XIV
11070 Beograd
Tel (11) 123 23 40

CYPRUS

Cyprus Chamber of Commerce and Industry
Chamber Building
38 Grivas Dh genis Ave
3 Deligiorg s Street
PO Box 1455
Nicosia
Tel (2) 449500 462312
Fax (2) 458630

TURKIYE

Pres Gazete Kitap Dergi Pazarlama Dağitim Ticaret ve sanayi AŞ
Narlıbahçe Sokak N. 15
Istanbul-Cağaloğlu
Tel (1) 520 92 96 - 528 55 66
Fax 520 64 57
Telex 23822 DSVO-TR

CANADA

Renouf Publishing Co. Ltd
Mail orders — Head Office:
1294 Algoma Road
Ottawa, Ontario K1B 3W8
Tel. (613) 741 43 33
Fax (613) 741 54 39
Telex 0534783

Ottawa Store:
61 Sparks Street
Tel. (613) 238 89 85

Toronto Store:
211 Yonge Street
Tel. (416) 363 31 71

UNITED STATES OF AMERICA

UNIPUB
4611-F Assembly Drive
Lanham, MD 20706-4391
Tel Toll Free (800) 274 4888
Fax (301) 459 0056

AUSTRALIA

Hunter Publications
58A Gipps Street
Collingwood
Victoria 3066

JAPAN

Kinokuniya Company Ltd
17-7 Shinjuku 3-Chome
Shinjuku-ku
Tokyo 160-91
Tel. (03) 3439-0121

Journal Department
PO Box 55 Chitose
Tokyo 156
Tel (03) 3439-0124

AUTRES PAYS
OTHER COUNTRIES
ANDERE LANDER

Office des publications officielles des Communautés européennes
2 rue Merc er
2985 Luxembourg
Te 49 92 81
Te ex PUBOF LU 1324 b
Fax 48 85 73 48 68 17
-109 6003/700

26 09 410066 426709 4 00 4

12/91

15

CD-NA-13647-EN-C

NOTICE TO THE READER

All scientific and technical reports published by the Commission of the European Communities are announced in the monthly periodical **'euro abstracts'**. For subscription (1 year: ECU 110) please write to the address below.

Price (excluding VAT) in Luxembourg: (Volume 1) ECU 33
(Volumes 1-3) ECU 90

ISBN 92-826-3794-8

9 789282 637944

OFFICE FOR OFFICIAL PUBLICATIONS
OF THE EUROPEAN COMMUNITIES

L-2985 Luxembourg