PN-ABD-383

Royaume du Maroc

RABAT, SEPTEMBRE 3, 1988

المملكة المغربية

MINISTERE DE L'ENERGIE
ET DES MINES

وزارة الطاقة والمعادن

5.346

FINAL REPORT OF THE PROJECT

" BLOCK STRUCTURE OF THE LITHOSPHERE AND ITS ROLE IN THE GENESIS AND DISTRIBUTION OF METALLIC ORE DEPOSITS "

ADDRESSED TO
U.S. Agency for International Development
AID/SCI Program in Science and Technology Cooperation (PSTC)
Attention : Dr. M. Rechcigl and Dr. I.M. Asher
Office of the Science Advisor
Washington, D.C. 20523

Grant N° PDC-5542-G-SS-5073-00

Principal Investigators :

Dr. Mohammed BENSAID
Directeur de la Géologie
Ministère de l'Energie et des Mines
RABAT-INSTITUTS, AGDAL
Morocco

Dr. Jan KUTINA
Research Professor
Laboratory of Global Tectonics and Metallogeny
C/O Department of chemistry
The American University
Washington, D/C/ 20016, U.S.A.

Starting date of the project : August 16, 1985

Termination : January 15, 1988 (including five months report period)

The project consists of three components :

a) Moroccan component. Implemented by AID letter N° 936-5542 of September 10, 1985
b) American University component. Implemented by AID letter of August 16, 1985, Grant N° PDC-5542-G-SS-5073-00
c) U.S. Geological Survey component.

Rec'd in SCI OCT. 7 1988

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ABSTRACT

This project, funded by the U.S. Agency for International Development, has introduced a new methodology to mineral exploration in Morocco. Two areas have been defined as new targets for exploration: one for nickel and cobalt, and the other for chromite.

An isostatic anomaly map, adopted from Van den Bosch (1971, 1981) has been used to reveal boundaries which delineate blocks in the deep structure of Morocco. The trough or sedimentary depression from which the High Atlas Mountains originated, shows relation to this deep structure. Clusters of metallic ore deposits occur near intersections of some of the deep-seated structural boundaries. Significant metal concentration has been noted near the borders of the High Atlas Mountains, where the latter intersect with deep-seated structural lineaments extending transversely to this orogenic belt.

Tectolinear interpretation of a Landsat mosaic has revealed the main structural trends in the study area.

The concentration of gabbro-dolerite rocks in the Foum Zguid region, Saharan part of the Anti-Atlas, has been explained as an early Mesozoic magmatic reactivation guided by the intersection of deep-seated structural boundaries which occurred near the northern border of the West African craton. This structural setting and the time of reactivation, as well as the chemical composition of the rocks show similarities with the gabbro-dolerite magmatism which occurred in the Norilsk-Talnakh area near the western border of the Siberian Platform. Concentration of nickel and cobalt has been discovered in one of the differentiates of basic magma in the Foum Zguid region. It is

suggested that larger amounts of these metals may occur beneath the gabbro-dolerite rocks of this area, similarly to the large concentration of copper and nickel ores with significant amounts of platinum-group metals which occur beneath a sheet of dolerites in the Norilsk district in Siberia.

A set of digital colored residual and regional Bouguer anomaly maps and related filtered maps of Morocco have been compiled under a cooperative program between the U.S. Geological Survy and the Service Géologique du Maroc, and are reproduced in Part V of this Report. These maps provide a basis for a more detailed metallogenic study which is proposed as a follow-up research. A preliminary study of these maps has identified gravity anomalies which may be useful in the search for new ore deposits.

PART I

GENERAL OVERVIEW OF THE RESULTS AND THEIR IMPORTANCE FOR MOROCCO

by

Mohammed Bensaid and Jan Kutina

1. Introduction and Project Objectives

This project was initiated in August 1985 for a period of 30 months. It was based on a research proposal of June 11, 1984 submitted through the AID mission in Rabat to the Office of the Science Advisor of U.S.AID in Washington, D.C. The project was supported by a $150,000 U.S. AID grant and by matching funds equal to approximately $200,000 provided by the Moroccan Geological Survey.

The main objective of the project--quoting from the 1984 Proposal--was "Testing of a model of block structure of deeper parts of the lithosphere in which boundaries guide magmatism and predetermine most favorable areas for the concentration of metals." Positive results from preliminary application of the model in Nevada led to a new mineral discovery (Kutina & Bowes, 1982; Bowes et al., 1982). However, the work in Nevada was limited to one particular geotectonic setting and the model testing needed to be verified in different geological environments.

Morocco provided a special opportunity for testing the above model and the new methodology of exploration, because:

1. It is located adjacent to a former junction of three lithospheric plates (North America, Africa and Eurasia), the motion of which has caused movements along intraplate boundaries, especially in the marginal parts of the plates.

2. An extensive data base is available in Morocco including, in particular, new structural and geological maps (Saadi, 1982; Saadi et al., 1985), a detailed gravimetric study (Van den Bosch, 1971, 1981), a magnetic study (Demnati, 1979), a new "Carte des Gîtes Minéraux du Maroc" on the scale of 1:500,000 (Ministère de l'Energie et des Mines, Rabat, unpubl. edition 1980) which was made available for the project, as well as other geological and geophysical data.

Our objectives included, in particular:

1. Select a "pilot area" in Morocco for application of the new methodology. The extent of the area is shown in Figures 1 and 2 in the paper by Bensaid et al., 1985, reproduced in Part II of this Report.

2. Review the geology and metallogeny of the pilot area, and assemble available geophysical data.

3. Prepare a satellite (Landsat) mosaic of the pilot area and carry out its tectolinear interpretation. (Preceded by training of the Moroccan participants in remote sensing methods in the United States, under W.D. Carter, President of Globex, Inc. in Reston, Virginia, and by attending an advanced course in remote sensing methods by L. Rowan and A. Goetz in San Francisco.)

4. Study block structure of the pilot area, using available geophysical information, especially the gravimetric data by Van den Bosch (1971, 1981). As shown in Part IV of this Report, the isostatic anomaly map proved to be extremely useful in the analysis of deep-seated structural boundaries.

We have also included the compilation of the digital colored residual and regional Bouguer gravity anomaly maps with different wavelength filtering, as developed in the Branch of Geophysics, U.S. Geological Survey in Denver (Hildenbrand et al., 1982). This filtering of gravity data removes

the masking effect of the longwavelength (regional) anomalies and enhances the appearance of the shortwavelength (residual) anomalies. This helps to reveal the mass distribution in the crust and mantle and provides essential knowledge in the study of deep structure of the lithosphere. The importance of these maps for the analysis of deep controls of mineralization has been demonstrated in the western United States by Kutina and Hildenbrand (1987). Preliminary results from that study were available to us when planning the project.

5. Study relationships between the distribution of major concentrations of metals and the block structure of the study area, and use the pattern of regularities in defining target areas favorable for the concentration of strategic metals (in particular cobalt).

6. Carry out a detailed study of a selected target area, using geological, mineralogical and geochemical methods. Evaluate the mineral potential of that area.

In summary, the joint study of the Moroccan and U.S. participants provided the opportunity

- to test, in Morocco, the role of a block structure of the lithosphere in the concentration of metals;
- to transfer new methodologies and techniques in mineral exploration in Morocco, including (a) training of Moroccan participants in the remote sensing methods in the United States, and (b) traveling to the U.S. Geological Survey in Denver to participate in the computer processing of gravity data and to compile the new color gravity maps of Morocco;
- to obtain a Bausch & Lomb instrument for an advanced study of satellite images which can be used in the follow-up studies;
- to define, through the project, a new target area for mineral exploration in Morocco.

2. Main Results of the Project

1. The structural evolution of Morocco, with new ideas on basement controls of mineralization has been reviewed in a paper by Bensaid, Kutina, Mahmood, and Saadi (1985), published during the first year of the project. The paper is reproduced in Part II of this Report. Figures 1 and 2 show the area selected for our study, and Figure 3 shows the model of block structure of the lithosphere to be tested in our project.

2. A new geological map of the study area at a scale of 1:500,000 has been prepared and partly used in the paper by Bensaid and Mahmood (1986) reproduced in Part III of this Report.

3. A mineral deposit map of the same area, at the same scale, has been compiled and also used in the above paper by Bensaid and Mahmood (1986).

4. Tectolinear interpretation of a Landsat mosaic of the study area, partly supervised by W.D. Carter, has been made and used in the paper by Bensaid and Mahmood (1986) presented at a COSPAR conference in Toulouse, France (Part III of this Report).

5. A pattern of deep-seated structural boundaries of the study area has been recognized and the main features of the block structure of Morocco defined. This work has been done by J. Kutina, using an isostatic gravity anomaly map adopted from Van den Bosch (1971, 1981). It was found that the trough or sedimentary depression from which the High Atlas Mountains later formed, was related to the block structure of the territory (see fig. 4 in the paper by Kutina et al., 1988, presented at the 7th International Conference on Basement Tectonics in Kingston, Ontario in August 1987 and reproduced in Part IV of this Report). Also, important ore deposits and clusters of deposits show the relationship to the block structure of Morocco, some concentrating near the intersections of the South Atlas Fault with block

ɔundaries extending north-south, transversely to the course of the High Atlas Mountains (fig. 5 in Part IV of this Report).

6. The major concentration of dolerites and gabbros, occuring in the Foum Zguid area in the Saharan part of the Anti-Atlas, has been explained as the product of an early Mesozoic magmatic reactivation related to the block structure of Morocco and taking place near the northern border of the West African craton. This structural setting and the time of reactivation correlate with the gabbro-dolerite magmatism in the Norilsk-Talnakh region near the western border of the Siberian Platform. The similarity is of particular interest for the Foum Zguid area because of the presence of a large concentration of Cu-Ni ores with platinum group metals in the Norilsk-Talnakh district, associated with gabbroic rocks. (For more details, see the paper by Kutina, Bennani and co-workers, reproduced in Part IV of this Report.)

7. J. Kutina and A. Bennani performed a systematic investigation of the Foum Zguid area, searching for signs of magmatic differentiation within the suites of gabbro-dolerite rocks. The quantitative chemical analyses of samples from the Foum Zguid region, made by a team of analytical chemists in the Branch of Geochemistry, U.S. Geological Survey, has revealed a trend in the differentiation of the basic magma, showing similarities with the gabbro-dolerites of the Norilsk-Talnakh district in Siberia. (The analyses are reproduced in Part IV of this Report.)

8. J. Kutina and A. Bennani have discovered a local concentration of nickel and cobalt in and around one of the magmatic differentiates in the Foum Zguid region (locality No. 8 in fig. 6 in Part IV of this Report). Microscopic study by Kutina, and the electron microprobe analyses by K. Fredriksson and J. Nelen, Smithsonian Institution, have identified pyrrhotite and pentlandite (the latter with 2-3% Co) occurring in "schlieren" in the

respective magmatic rock, and a dissemination of minute grains of a Ni-Fe-Co sulfide (with high contents of nickel and cobalt) in the surrounding rocks (see the analyses in Table 5 in Part IV of this Report). The area has been recommended as a target for mineral exploration.

9. Low-level, but anomalous gold contents have been found in a low temperature hydrothermal quartz within a suite of Ordovician quartzite, in an area where the axis of the Hamsailikh anticline (SSW of Foum Zguid) changes its strike (localities Nos. 3-5 in fig. 6, Part IV of this Report).

10. A new locality of a serpentinized ultrabasic rock has been discovered during the last expedition by Kutina and Bennani, in an area NE of Foum Zguid (between Es Smeyra and Oçar-en-Nkkeyla. The samples are rounded, now occurring in a secondary place. A follow-up field work is planned to locate the primary source of the serpentinite and examine it for possible potential for chromite.

11. Moroccan geophysicists M.F. Hamouda and A. Bellot have assembled the existing gravity data from Morocco and complemented them by new gravimetric measurements performed in the Saharan parts of the Anti-Atlas (Bellot, Alji, & Hamouda, 1988) to be used in the preparation of new, filtered gravity anomaly maps (see the next paragraph).

12. The gravity data of Morocco, as collected and updated by Bellot and Hamouda in the Geological Survey of Morocco, have been processed in the Branch of Geophysics, U.S. Geological Survey in Denver. A set of digital colored residual and regional Bouguer gravity anomaly maps of Morocco with different wavelength filtering, and related filtered anomaly maps, have been produced as a cooperative study between the U.S. and the Moroccan geological surveys. One set of these maps, on the scale of 1:2,000,000 has been prepared for publication (Hildenbrand, Kucks, Hamouda, & Bellot, 1988,

reproduced in Part V of this Report at a reduced scale), and another set, o the scale of 1:1,000,000 has been prepared for the Moroccan Geological Survey.

13. The above gravity anomaly maps will be compared with major structural features and used in the study of deep controls of mineralization to performed in a follow-up study. Preliminary examination, reported by Kutin gives very encouraging results.

14. The project has fulfilled its goals, introducing new methodology to mineral exploration in Morocco, defining two new targets for mineral exploration--one for nickel and cobalt and the other to be tested for a possible potential in chromite. The exploration potential of the southern and eastern Anti-Atlas has been enhanced and the Moroccan exploration stimulate The expenditures of the project have been slightly modified and matching funds provided in order to use them efficiently and to ensure a follow-up of the project.

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Global Tectonics and Metallogeny, Vol. 3, No. 1, December 1985

Structural Evolution of Morocco and New Ideas on Basement Controls of Mineralization

M. BENSAID

Direction de la Géologie, Ministère de l'Energie et des Mines
Agdal-Rab stituts, B.P. 6208
Rabat, Morocco

J. KUTINA

Laboratory of Global Tectonics and Metallogeny
c/o Department of Chemistry, The American University
Washington, D.C. 20016, U.S.A.

A. MAHMOOD

Department of Geology
National School of Mining Engineering (E.N.I.M.)
Agdal-Rabat, B.P. 753
Morocco

M. SAADI

Ministère de Tourisme
Rabat-Chellah
Morocco

ABSTRACT

Examination of geologic and gravimetric maps of Morocco, especially the isostatic anomaly maps by Van den Bosch (1981), indicate the presence of major boundaries in the deep structure of this territory. Two of these structural boundaries, defined in the present paper, extend north-south, transversely to the trend of the Atlas and Anti-Atlas Mountains. Preliminary comparison with the new "Carte des Gîtes Mineraux du Maroc" (1980) indicates that the deep structural boundaries played a role in the genesis and distribution of endogenic ore deposits in Morocco. A major cluster of mineralization, with about 50 deposits of Pb, Cu, Ag, Au and other metals, located within an area of about 40 x 50 km, occurs adjacent to the corner of a lithospheric block defined by intersection of a N-S trending and a E-W trending deep-seated structural boundary.

INTRODUCTION

This paper is an expanded version of a communication presented at the IAGOD/CTOD workshop "Parameters Controlling the Distribution of Large Ore Deposits, Ore Clusters, Mineral Belts and Metallogenic Provinces" which was held at Santa Fe, New Mexico, in September 1985. The purpose of the paper was to demonstrate a new approach to the study of deep-seated controls of mineralization in Morocco, based on a model of block structure of the lithosphere.

The paper gives a brief review of the geology, structural evolution, and the main endogenous ore deposits of Morocco, describes a model of the block structure of the lithosphere which was selected for testing in Morocco, and presents inital observations from the study of the gravimetric maps compiled by Van den Bosch (1981). The examination of a map of isostatic anomalies indicated the presence of major structural boundaries in the lithosphere of Morocco. A comparison of these boundaries with a map of mineral deposits of Morocco suggests that these boundaries may have played a

role in te concentration of metals in the crust.

The study is being conducted under a project "Block Structure of the Lithosphere and Its Role in the Genesis and Distribution of Metallic Ore Deposits", financed by the U.S. Agency for International Development.

GEOLOGICAL AND STRUCTURAL FRAMEWORK OF MOROCCO*

Morocco is situated in the northwestern corner of the continent of Africa. It neighbours Algeria in the east, the Atlantic Ocean in the west, Mauritania in the south and, through the narrow straits of Gibraltar, Spain in the north. The present structural set-up of Morocco is the result of Precambrian (Eburnean and Pan-African), Caledono-Hercynian, and Alpine orogenies (Michard, 1976). The Saharan part of the country had been, by the Early Precambrian, incorporated completely into the vast, inert continental mass or shield area called the West African craton.

Structurally, Morocco may be divided into two parts. The extreme northern part or "Mediterranean Morocco" is the southern extension of the Betic chain in Spain and the western extension of the Tellian chain in Algeria, and belongs to the Alpine-type orogen that hems the west Mediterranean. This part of Morocco is tectonically the most unstable, and is called the Rif domain. The structure of this domain is defined by a series of north to south directed overthrusts or nappes with varying amplitude.

In the south of the Rif domain, the other part of Morocco is a vast territory which belongs to West Africa in terms of its structure. This territory is called African Morocco; it behaved as a rigid, stable block during the Alpine orogeny. African Morocco may be divided into two parts: the pericratonic South Morocco which is structurally homogeneous, therefore, constituting a separate structural domain, called the "Anti-Atlas". The other part of African Morocco is called "Middle Morocco" which is a quasi-cratonic area. It may be distinguished from South Morocco by its lesser rigidity during the Phanerozoic orogenic cycles. The Paleozoic sediments of Middle Morocco and South Morocco are to some extent similar. However, the Paleozoic subsidence with detrital sedimentation of variable thickness was stronger in the southwestern than in the northeastern parts of the Anti-Atlas. The basins of the Anti-Atlas, affected only by epeirogenic movements, are different from those in Middle Morocco where, during the Hercynian orogeny, strong deformation (even with nappes) and a lateral variabilitiy in sedimentation took place. Moreover, the long periods of post-Paleozoic erosion resulted, in south Morocco, in the appearance of a number of Precambrian inliers; Ifni, Kerdous, Tagragras, Bou-Azzer, Siroua, Saghro, and Ougnat. The boundary between Middle Morocco and South Morocco is a fault zone known as South Atlasic fault.

Middle Morocco may be further divided into two sub-domains, very different from each other in terms of stratigraphy and structure. One is the Meseta and the other is the mountain chain of Middle and High Atlas formed of mainly Jurassic sediments. The Middle Atlas consists of the tabular Middle Atlas in the west and the folded Middle Atlas in the east. In the Meseta, the Paleozoic rocks outcrop in several Hercynian massifs: Central, Eastern, Rehamna, Jebilet, Tichka, Tazzeka, and Beni-Snassen.

The Caledono-Hercynian orogen of the Meseta and Anti-Atlas extends southwards into Mauritania, and has its counterpart on the opposite side of the Atlantic in the Appalachians.

In all, the geology of Morocco may be studied in terms of four structurally distinct regions: the Anti-Atlas with its Saharan extension, the Meseta, the Atlas mountain chain, and the Rif.

MINERAL DEPOSITS OF MOROCCO*

Important metallic mineral deposits were formed throughout the geological and structural history of Morocco. Regardless of the age and type of mineral deposits, they are to be found in terranes of all ages. The lithology, tectonics, metamorphism, magmatism and paleogeography of these terranes constitute metallotects for these deposits.

In the oldest Archean rocks of Morocco, important banded iron ores occur. Lower Precambrian alkali granites are traversed by Be, Li, and Nb-bearing pegmatites in the Tazenakht, Iguerda, Agadir-Melloul, Tazeroualt and Kerdous areas. The Middle Precambarian ultrabasic

*By M. Bensaid and A. Mahmood

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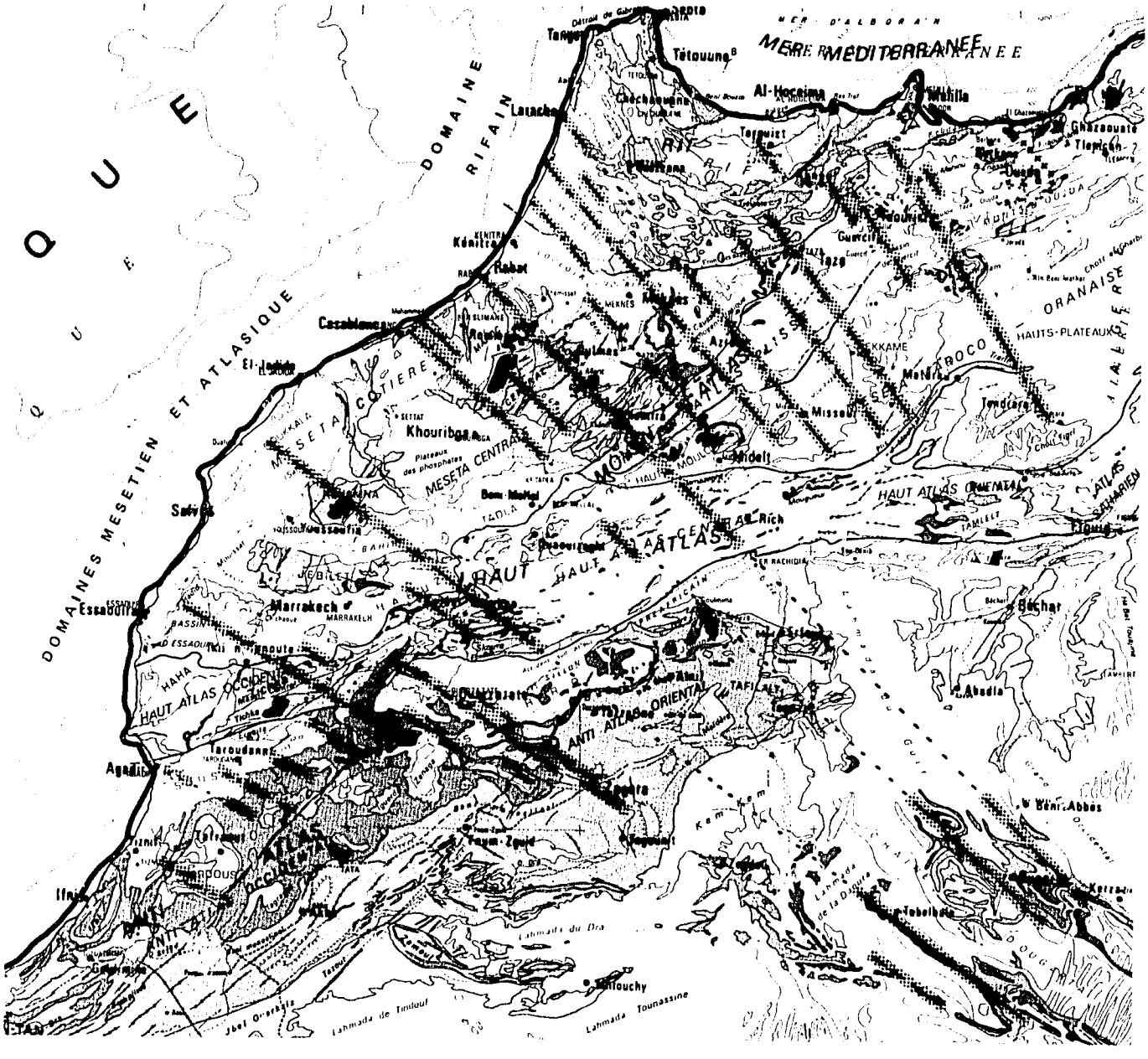

Fig. 1. The convergent NW-SE lineament set (from Saadi, 1982b), superimposed on a part of the structural geological map of Morocco (Saadi, 1982a). Legend to simplified geology of the same area see in fig. 2.

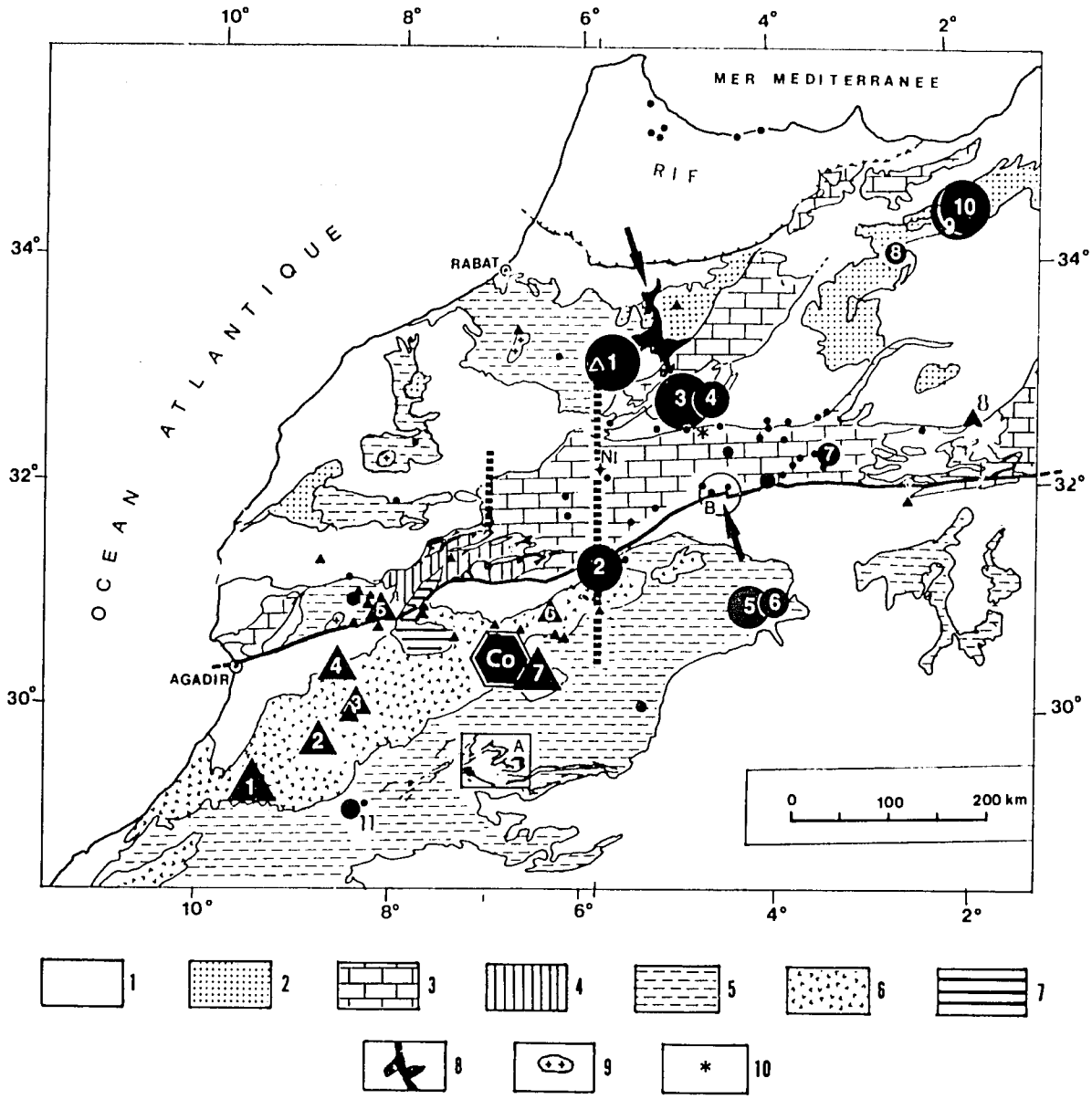

Fig. 2. Geologic scheme of the project area showing the distribution of the main deposits of lead, zinc and silver (black dots), copper (black triangles) and the location of the cobalt district of Bou-Azzer (Co).

The geology is simplified from Saadi's (1982a) 'Carte Structurale du Maroc', the ore deposits are after Saadi's (1982b) 'Carte Minière et Energetique du Maroc'.

The two N-S trending lineaments are structural boundaries distinguished by J. Kutina in Van den Bosch's (1971) isostatic map, reproduced in fig. 4. Note that all of the most important deposits of Pb-Zn-Ag concentrate to the east, and those of Cu to the west of the N-S trending structural boundary which extends close to longitude 6°W.

The rectangular inset A, shown south of the cobalt district of Bou-Azzer, is an area with great accumulation of dolerite sills and dikes.

The area B (open circle) shows the intersection of the South Atlasic Fault with a lineament which is proposed to extend transversely to the High Atlas Mountains (marked by two arrows). The area B may be of special metallogenic interest.

Legend to geology: 1—Neogene and Quaternary; 2—Tabular Jurassic cover; 3—Folded Mesozoic (mostly Jurassic); 4—Triassic continental red beds; 5—Undifferentiated Paleozoic; 6—Undifferentiated Precambrian of the Anti-Atlas; 7—Precambrian granites of the High- and Anti-Atlas; 8—Doleritic dykes of Liassic age (mainly in the Anti-Atlas); 9—Hercynian granites; 10—Calco-alcaline massif of Tamazeght (High Atlas).

Pb-Zn-Ag deposits (shown by black dots): 1—Jbel Aouam Pb-Zn (Ag); 2—Imiter Ag; 3—Zeida Pb-Zn (Ba); 4—Aouli and Mibladen Pb-Zn; 5—Tadaout Pb-Zn; 6—M'Fis Pb-Zn; 7—Bou-Dahar Pb-Zn; 8—Sidi-Lahcen Pb-(Ag); 9—O. Mekta Pb-Zn; 10—Bou-Beker Pb-Zn; 11—Addana Pb-(Ag).

Cu deposits (shown by black triangles): 1—Ouansimi; 2—Tazalaght; 3—Talat-n'Ouamane; 4—Asif-Imider; 5—Tanfit; 6—Bou-Skour; 7—Bleida; 8—Jbel Klakh.

For greater detail, see 'Géologie des Gîtes Minéraux Marocains' (1980).

rocks host chromium and asbestos deposits in El Graara—Bou-Azzer and Siroua inliers. The world famous cobalt deposits are associated with the ophiolites of the Bou-Azzer inlier (Leblanc, 1975). The Middle Precambrian granodiorites have Zn, Ag, Au, Cu and W-bearing veins or disseminations in the Siroua, eastern Saghro and Ougnat inliers. Most of the copper showings of Morocco are found in the Infracambrian volcanic rocks of the Anti-Atlas. The Precambrian, mantle-derived Beni-Boucera peridotite in the Rif domain, too, has economic quantities of graphite, nickel and vermiculite.

The Cambro-Ordovician placers of Zr, Th and Ti are found in the Ougnat inlier. The Ordovician rocks of Morocco are characteristically ferruginous and have yielded large quantities of oolitic iron ores in the Central Massif, High Atlas and eastern Anti-Atlas. The mineralizations in the Hercynian massifs are undoubtedly the most varied and include the iron ores in the Ordovician rocks of the Khenifra area; the Kettara-Guemmassa sulphide masses in the volcano-sedimentary rocks of the Jebilet; manganese deposits in acidic volcanic rocks of the Eastern Massif; magnetite-hematite-pyrite veins at the contact of granodiorites in the western "horsts country"; antimony deposits associated with granite porphyries in the Central Massif, Eastern Massif and High Atlas; economically very important fluorite-bearing veins in the Achmeche and Khenifra areas; and tin and tungsten deposits associated with the Hercynian granites of the same areas.

The Mesozoic rocks of Morocco are also known for their economic potential; in fact, the Pb-Zn-Ag Zeida mine in the Moulouya area, which is, excluding the phosphate mining, the largest open-pit mining area in Morocco, is in the Triassic detrital formations. In Middle Morocco, the Jurassic as a whole is mineralized, primarily with lead and secondarily with zinc, copper and manganese in stratabound deposits which are related to a transgression on the Upper Paleozoic. Stratabound, Pb-containing manganese loads occur in the Cretaceous rocks of the Ouarzazate basin and Sous region.

STRUCTURAL LINEAMENTS OF MOROCCO*

A systematic study of structural lineaments, undertaken by Saadi (1980, 1982a) and Saadi and Mahmood (1984), revealed the presence of four lineament sets in Morocco, trending N-S, E-W, NE-SW, and NW-SE. While the N-S and the E-W lineaments show a more or less constant trend, the lineaments of the NE-SW and the NW-SE sets exhibit strong azimuthal variation. The authors have noticed that the above four general trends correspond to those shown by fractures and lineaments in the rest of Africa and even in other parts of the world, suggesting that the linear structures may be attributed to the regmatic fracturing of continental or global dimensions.

Saadi (1980) and Saadi and Mahmood (1984) have compiled diagrams showing cumulative length of lineaments and known faults in the Rif, Atlas and Anti-Atlas structural domains. A comparison of these diagrams showed similarities, indicating that the faulting caused by the Atlasic orogeny (Pre-Cenomanian and Oligo-Miocene) had largely followed the old Hercynian trends. These trends are clearly visible in the Anti-Atlas domain and in the Paleozoic basement of the Atlas domain, suggesting reactivation of fractures during successive orogenies. Regarding lineament trends in the Ougarta and in the south of Siroua (Anti-Atlas), the authors assume that most if not all of the fractures may be as old as Precambrian. According to Saadi (1980), especially the fractures of the E-W and NE-SW sets played a dominant role in structural evolution of Morocco.

The N-S and NW-SE lineament and fracture trends are oblique to the trend of the Atlas and Anti-Atlas Mountains. While the N-S lineaments are parallel to each other (fig.1 in Saadi and Mahmood, 1984), the NW-SE lineaments converge southeastwardly to a point situated in Ahnet area, NW of Hoggar, Algeria. These lineaments, also referred to as the Ougartian lineaments, are shown in fig.1, where they are superimposed on a structural-geological map of Morocco.

Relationships between structural lineaments and some metal deposits in Morocco have been reported by Saadi (1980) and Saadi and Mahmood (1984). The most prominent relationship is between copper deposits and dolerite dikes, in particular those in the Anti-Atlas with NE-SW trend (Saadi, 1968,1971).

*A review based on papers by M. Saadi, partly summarized in Saadi and Mahmood, 1984.

BLOCK STRUCTURE OF THE LITHOSPHERE— A MODEL TO BE TESTED IN MOROCCO. EXAMPLES FROM OTHER TERRITORIES*

Our task is to test on the Morocccan territory a model of a block structure of the lithosphere, developed by one of us in other parts of the world. If the model proves to be applicable to Morocco, we are supposed to use it in the derivation of new targets for mineral exploration. The model, lately reviewed in Kutina 1983, will be explained with the help of a few examples.

1. The Abitibi area of the Canadian Shield, located south of the Hudson Bay, contains the ore fields of Val d'Or, Noranda, Kirkland Lake, Timmins and others. Structural lineaments of four sets, trending N-S, E-W, NW-SE, and NE-SW are well developed and clearly exposed in the area. The distribution of about 1,300 gold and 700 copper occurrences of the Abitibi Area showed spatial relationship with the intersections of these lineaments (Kutina and Fabbri,1972). Within the individual sets of lineaments, some spacings are structurally more important than the others. For instance, the east-west lineaments with a spacing of 100 miles (about 160 km) are of special importance, being developed not only south of the Hudson Bay, but also within other latitudes, including the Canadian Arctic (fig.1 in Kutina and Fabbri,1972).

A major N-S trending geofracture, the Hudson Bay Paleolineament (HBP), recognized in the Canadian Shield by Kutina (1971), traverses the Abitibi area. A set of fracture zones, extending parallel to the Hudson Bay Paleolineament (with a spacing of over 150 km west of HBP and of less than 150 km east of HBP), intersects the east-west lineaments, defining a pattern of orthogonal blocks. Clustering of major ore deposits occurs near the corners of these orthogonal blocks (fig.1 in Kutina, 1974a, including locations of new mineral discoveries).

Stephenson and Beaumont (1980), who studied the isostatic response of the Canadian Shield, detected two sets of long-wavelength gravity anomalies with an amplitude of 200-600 km, trending N-S and E-W, which have the same directions as the block boundaries in the Abitibi area defined by Kutina and Fabbri (1972)

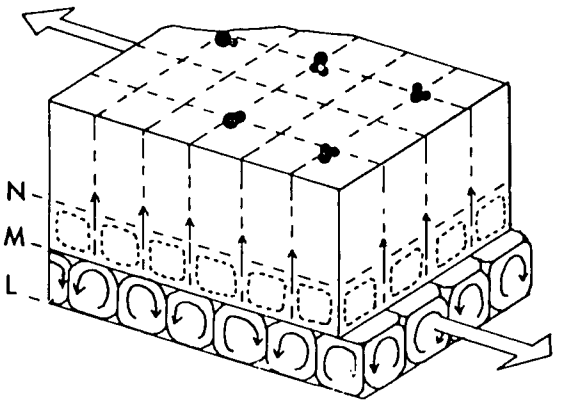

Fig. 3. Model of block structure of the lithosphere, showing melting proceeding preferentially along boundaries of blocks at the base of the lithosphere, finally leading to separation of a layer of convective cells. The arrows indicate the ascent of magmas and the path of ore-forming fluids. The full dots show location of intrusive/volcanic centers and associated ore deposits. From Kutina, 1983.

and Kutina (1974a). According to Stephenson and Beaumont (op.cit.), the anomalies indicate that convective cells of such a size may exist at the base of the lithosphere. Kutina (1983) has noted that the size of convective cells could be different in the geological past than at the present time, because the thickness of the crust has changed. The blocks, defined by Kutina and Fabbri (1972), may reflect the size of 'paleoconvective cells' in the Precambrian era. Both the convective cells considered by Stephenson and Beaumont, and the 'paleoconvective cells' may be related to the same pattern of deep-seated fracture zones or corners of lithospheric blocks.

2. In the Western United States, Kutina (1983), following his earlier studies (1969 and 1980), defined four lithospheric blocks of the size 530 × 600 km, delimited by structural boundaries of an E-W and N-S trend. The presence of the individual boundaries is supported by geophysical data, such as the contours of P_n velocities, residual gravity patterns, alignment of seismic epicenters, location of the intrusive-volcanic centers, etc. Major ore districts such as Bingham, Tintic and Park City in Utah, Butte in Montana, and others, have developed near the corners of some of these lithospheric blocks which provided channelways favorable for the ascent of magmas and ore-forming fluids. The geochemical and geophysical exploration, carried out in an area of repeated magmatic activity occurring close

*By Jan Kutina

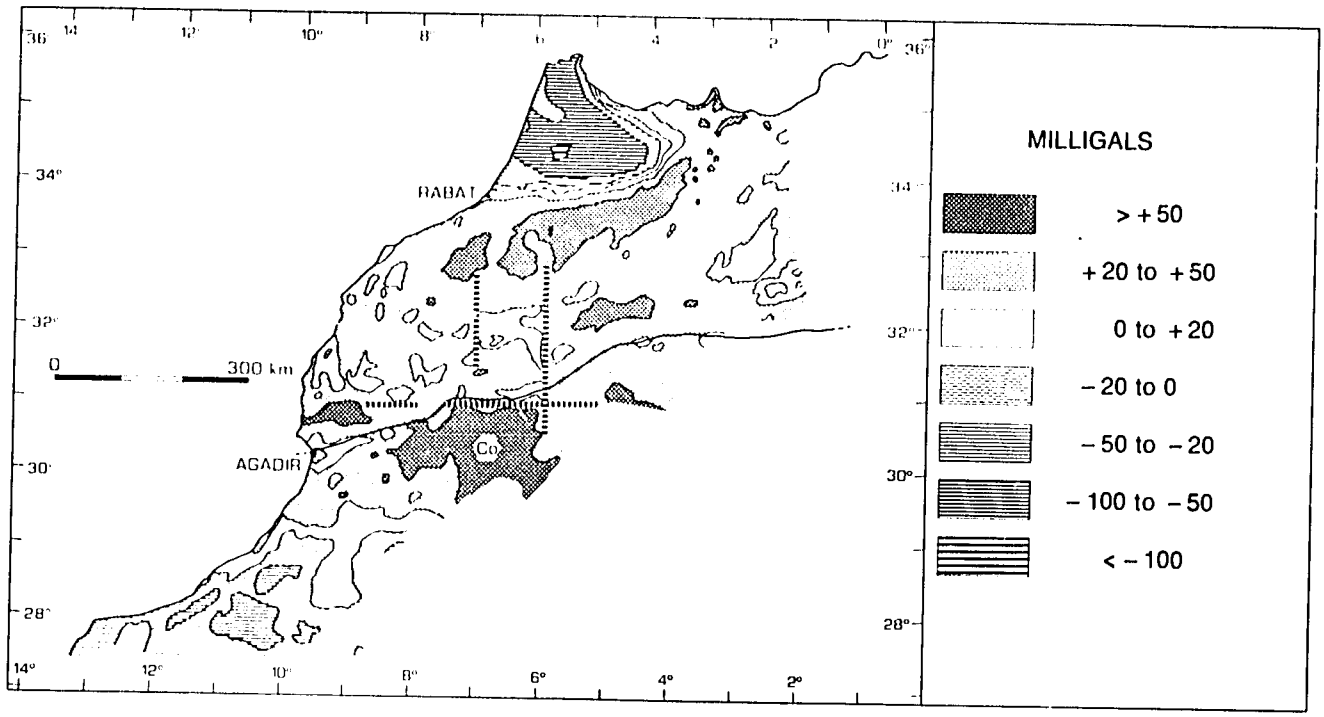

Fig. 4. Generalized isostatic anomaly map of Morocco (Airy hypothesis, T = 30 km) after Van den Bosch, 1971 (the original is in color). The two N-S trending lineaments and one E-W lineament (the latter transferred from fig. 5) are structural boundaries distinguished by Jan Kutina. The South Atlasic Fault, extending east-north-easterly from the Atlantic coast at Agadir, is added from Saadi's (1982a) map. The cobalt deposits occurring in the Bou-Azzer inlier between longitudes 6°30′ and 7°00′W, are jointly shown by a hexagon labeled Co (size exaggerated). The Bou-Azzer district occurs in the western part of this area, between 6°50′ and 6°55′W.

to one of the corners of the lithospheric blocks, resulted in the discovery of a porphyry-type Mo-Cu mineralization in NW-Nevada, confirmed by drilling (Kutina and Bowes, 1982; Bowes et al., 1982).

3. Other examples of preferential clustering of ore deposits near the corners of lithospheric blocks have been described from different parts of the world (Kutina, 1976). In African countries, such a block structure has been described from Madagascar (Kutina, 1975) and from Upper Volta (Kutina, 1974b).

INITIAL OBSERVATIONS FROM THE STUDY OF A BLOCK STRUCTURE OF MOROCCO*

Marçais (1954) noted that the Bouguer anomaly map of Morocco (scale 1:1,500,000) reflects the orographic picture, and the isostatic map (Airy hypothesis, T = 60 km) offers indications of a deep structure of the country.

In 1971, the Service Géologique du Maroc published a set of more detailed Bouguer gravity anomaly maps of Morocco (scale 1:500,000), compiled by Van den Bosch. These maps were followed, ten years later, by a very detailed explanatory text (Van den Bosch, 1981), accompanied by additional maps, especially the isostatic anomaly maps on a scale of 1:5,000,000. These maps provide an excellent basis for the study of possible presence of important boundaries within the deep structure of Morocco.

Fig. 4 is a black and white version of a map by Van den Bosch (1971), showing a simplified pattern of the isostatic anomalies of Morocco (T = 30 km), reduced from a scale of 1:5,000,000. The South Atlasic fault has been added to the map from a map by Saadi (1982a). Two N-S structural boundaries, distinguished in this pattern of isostatic anomalies by Kutina (1984, un-

*By Jan Kutina

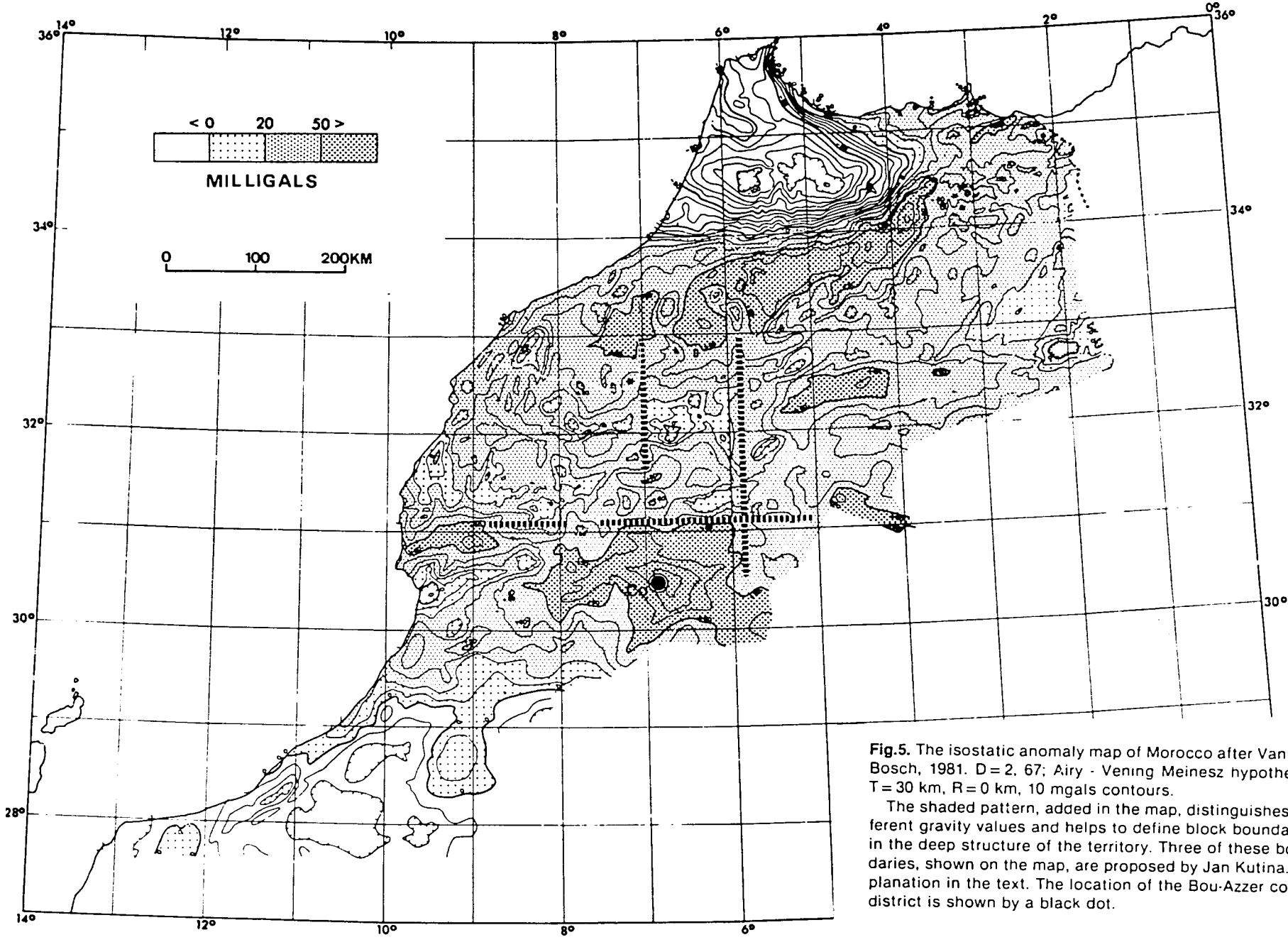

Fig.5. The isostatic anomaly map of Morocco after Van den Bosch, 1981. D = 2, 67; Airy - Vening Meinesz hypothesis, T = 30 km, R = 0 km, 10 mgals contours.

The shaded pattern, added in the map, distinguishes different gravity values and helps to define block boundaries in the deep structure of the territory. Three of these boundaries, shown on the map, are proposed by Jan Kutina. Explanation in the text. The location of the Bou-Azzer cobalt district is shown by a black dot.

publ.**), extend transversely to the Atlas and Anti-Atlas Mountains. The same boundaries, transferred onto a simplified geologic map of Morocco are shown in fig. 2. The distribution of the main endogenic deposits of Morocco, introduced in this illustration from Saadi (1982b), shows that all of the major deposits of lead, zinc and silver (marked by black dots) are located to the east of the main N-S lineament, while all the major deposits of copper (marked by solid triangles) occur to the west of that lineament, being located in another geologic environment than the Pb-Zn-Ag deposits.

The western of the two north-south trending boundaries, shown in fig. 4, has a prominent morphological expression in the shape of the High Atlas Mountains at approximately 7°W longitude. Other criteria indicating that the High Atlas has a block structure have recently been described by Dresen (1985).

Preliminary examination suggests that the above N-S trending structural boundary and its possible extension towards the south deserves special attention. A number of copper and some lead deposits or showings are known along or close to 7°W longitude, within an area north of Ourzazate (between latitudes 31° and 32°N). The major cobalt district of Bou-Azzer is located close to southern projection of the same N-S trending structural boundary shown in fig. 2 at a longitude of 7°W. Further south, along the same longitude, a great accumulation of basic intrusives occurs, labeled as Hercynian dolerites and gabbros in the Carte Geologique du Maroc 1:500,000, sheet Ouarzazate (publ. 1959/1978), and as dolerite sills and dikes of Triassic-Liassic age in the Carte Geologique du Maroc 1:1,000,000 (publ. 1985). The respective area is delineated by a small inset (labeled A) in fig. 2.

The gravity contours in a more detailed isostatic anomaly map of Van den Bosch (1981), reproduced in fig. 5, made it possible to propose the location of the two N-S trending structural boundaries more accurately: the 'eastern' one at a longitude 5°50'W and the 'western' one at 7°00'W as used above. It is possible, however, that the 'eastern' of the two north-south boundaries, plotted at 5°50'W, belongs to a broader zone of tectonic disturbance which may extend through the basement between longitudes 5°30' and 5°50'W.

The gravity contours in fig. 5 indicate that the deeper parts of the Moroccan territory are also penetrated by major structural boundaries of an E-W trend, the most prominent one extending at approximately 31°N. The area of intersection of this latitudinal boundary, extending close to 31°N, with the longitudinal boundary plotted at 5°50'W, defines the NE-corner of a lithospheric block which is characterized by gravity values of +50 mgals and higher (fig. 5). The new 'Carte des Gîtes Mineraux du Maroc' (1980), scale 1:500,000, prepared by a team of geologists of the Geological Survey of Morocco and of Technoexport, USSR, reveals that the area adjacent to the NE-corner of the lithospheric block, defined in the present paper, contains one of the most populated clusters of ore deposits in Morocco: about 50 deposits and a number of additional occurrences of Pb, Cu, Ag, Au and other metals, including the important silver deposit of Imiter, occur within an area of about 40 × 50 km.

The above observations, coming from initial stages of our work on the project confirm that significant structural boundaries occur in the deep structure of Morocco and play a role in the genesis and distribution of endogenic ore deposits of this territory. A more detailed study is being planned, incorporating different geophysical methods.

**First presented in a lecture given at the Ministère de l'Energie et des Mines in Rabat, June 7, 1984

ACKNOWLEDGEMENTS

Thanks are due to William D. Carter for reading the manuscript and valuable comments. Similarly, we are grateful to Mr. Josiah Royce, Coordinator, Mineral Activities, U.S. Trade and Development Program, for encouragement and advice.

Figures 4 and 5 of this paper were prepared, in their final form, in the Cartographic Services Laboratory of the Department of Geography, the University of Maryland.

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Adv. Space Res. Vol. 7, No. 3, pp. (3)87–(3)94, 1987
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THE USE OF LANDSAT IMAGERY IN STRUCTURAL STUDIES OF MIDDLE MOROCCO

M. Bensaid* and A. Mahmood**

*Direction de la Géologie, Ministère de l'Energie et des Mines,
**Department of Geology, National School of Mining Engineering, B.P. 753, Agdal-Rabat, Morocco

ABSTRACT

Preliminary results of a tectonlinear study of Landsat MSS images in bands, 4, 5 and 7 covering Middle Morocco are presented. The relationships between lineaments and large-scale structural patterns are studied and compared with geological and ore deposits distribution data on the area.

Middle Morocco in this article comprises parts of the Moroccan Meseta, Central and Eastern High Atlas and northeastern Anti-Atlas. Rocks of all ages, from Precambrian to Quaternary, are found, and the structural evolution of the area is due to Precambrian, Variscan and Alpine orogenies. Two main lineament sets are recognized on the satellite images. These are NE-SW and NW-SE. The NW-SE set of lineaments is prominent in older Precambrian and Paleozoic terranes, whereas the NE-SW set is observed both in the old inliers and massifs as well as in the younger mountain chains. The NE-SW lineaments therefore represent reactivated fractures that should have played an important role in the tectonics and sedimentary cycles of Middle Morocco. Other lineament trends are seen only in specific regions of the study area.

Several major ore deposits follow lineament trends both in the basement and cover rocks. This is particularly true of endogenic deposits in the Anti-Atlas and in the Central Paleozoic massif.

INTRODUCTION

A common use of the satellite imagery is the study of 'lineaments' that are linear or near-linear features of tectonic origin. These lineaments are often shown to be the expressions of structural evolution /1/ and to be the controlling factors of metallic deposits distribution /2,3/. The tectonic significance of lineaments and their metallogenic influence is however best described in areas of sufficient cartographic information. In such areas, different geological features and ore occurrences may be related to lineament trends. This study analyses lineaments mapped from Landsat images in relation to known geological features and metal deposits in Middle Morocco.

Middle Morocco is located between 5° and 8° West longitude and 30° and 34° North latitude (Figure 2), and comprises parts of the Moroccan Meseta, Central and Eastern High Atlas, Middle Atlas and northeastern Anti-Atlas. Rocks of all ages are found, and orogenic movements of different Precambrian, Variscan and Alpine cycles have shaped the structural facade of the study area.

The Meseta is a coastal plain extending from the Atlantic Ocean to the Atlas mountains. Low reliefs and plateaux form the interior of the plain where Paleozoic basement rocks crop out. The Middle Altas is a NE-SW trending complex mountain chain which has both tabular areas and ridges and valleys /4/. The Middle Atlas offshoot from the Central High Atlas in the Beni Mellal region, and further to the northeast, the two mountain chains are separated by the Moulouya depression. The Central and Eastern High Atlas parts of Middle Morocco are formed of a series of well-projected anticlinal crests and splayed synclinal troughs /4/. South of the High Atlas mountains is a vast territory of relatively low mountains known as the Anti-Atlas which constitute the northwestern fringe of the West African Craton. Precambrian rocks of the Anti-Atlas occur in a few inliers of which only the Saghro and Bou Azzer are included in the study area. The topographic contrasts in the Anti-Atlas are the result of several phases of folding and peneplanation of the Paleozoic cover rocks and upheaval of the Precambrian basement rocks. The geomorphology is also marked by Tertiary to Quaternary volcanic

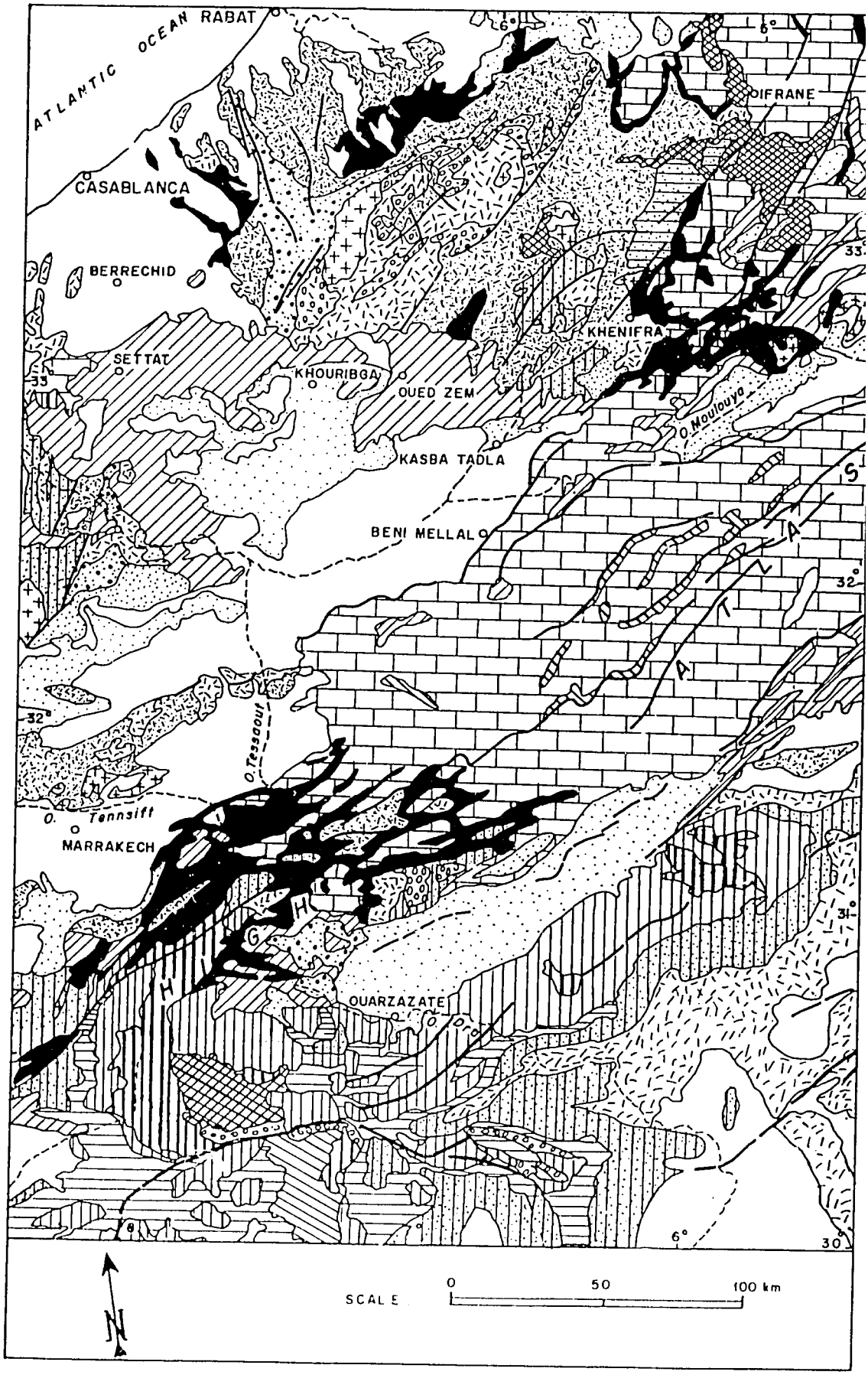

Fig. 1. Geologic map of the study area

vents.

Earlier studies on lineaments are restricted to those of Saadi /5,6/ who worked on 1/500.000 geological map of Morocco for tracing rectilinears, and related these rectilinears to geological, geomorphological and geophysical traits of the country. In 1978, the Geological Survey of Morocco received through a contract with the French compagny BEICIP (Bureau d'Etudes Industrielles et de Coopération de l'Institut français du Pétrole) the first lineament analysis study based on space imagery (Landsat I and II black and white images in MSS bands 5 and 7). Recently, Bensaid, et al /7/ elaborated on lineaments as indicative of deep-seated block boundaries that may have an important control on the occurrence of large ore deposits in Middle Morocco. The study presently undertaken used 1/500.000 maps and satellite images, now reduced to the scale of 1/2.000.000. Reduction of that magnitude necessitated simplification of the maps, but the lineament overlays were not tampered with. All the lineaments traced on the 1/500.000 images are therefore presented here on the reduced scale.

The coloured satellite images in MSS band 4 (yellow), 5 (red) and 6 (blue) from a 1973 Landsat mission were bought with the USAID funds from the US Geological Survey's EROS Center at Sioux Falls, South Dakota. Middle Morocco is covered by seven images that are of good quality generally without snow or cloud cover and sharp colour contrasts. A hand lenz was used while working on the images. In addition to lineaments, fold orientations and circular structures were traced. The article describes the lineament trends and looks into their geological and metallogenic significance.

GEOLOGY (Figure 1 and 2)

The stratigraphic record of the study area starts at the Lower Precambrian, or P_I following the nomenclature proposed by Choubert and Faure-Muret /8/. The Lower Precambrian rocks occur primarily south of the Anti-Atlas megafracture, and in some restricted localities of the Saghro inlier. These are mostly schists containing biotite, garnet and sillimanite ; amphibolites ; migmatites ; gneisses ; and alkali granites. Some of the rocks are more than 2 billion years old. The Middle Precambrian or P_{II} lies unconformably over the Lower Precambrian, and is formed of a thick complex of basic rocks ('Bou Azzer greenstone belt'), acidic lavas, quartzites and limestones. The Upper part of the Middle Precambrian or P_{II-III} rocks cover a vast area of the Saghro and Bou Azzer inliers. From the oldest to the youngest, the P_{II-III} rocks consist of conglomerates, tillites, reworked tuffs with rhyolitic and andesitic dikes and flysch. Quartz diorite and granodiorite intrusions are also present. Succeding the last Pan African orogeny and before the first Paleozoic transgression, rocks of the P_{III} system /8/ were deposited. Both volcanic and sedimentary facies constitute this system.

The Paleozoic rocks occur in the Meseta and in the Anti-Atlas. The earliest are Lower Cambrian sandstones, shales and limestones, locally with rhyolitic and andesitic lava flows /9/. The Ordovician sediments are shaly and sandy, and were deposited during successive transgressions and regressions caused by epeirogenic movements. The Silurian rocks are essentially shaly and are most abundant in the Anti-Atlas. From the Silurian to the Devonian time, an important facies change is noted. The Lower Devonian is shaly and sandy, whereas the Middle Devonian is calcareous and marly. The Carboniferous sedimentation is the most important sedimentary episode in the study area. Flysch prevails among the Lower Carboniferous sediments. The Visean paroxysm of the Variscan orogeny caused instability of the sedimentary basins and resulted in the formation of synsedimentary overthrusts, particularly in the eastern part of the Central Massif. A good deal of lithological diversity is evident in the Visean sediments. The NE-SW Variscan trend is the main tectonic grain that may be observed on aerial or satellite images. At the end of the Variscan orogeny, granitoid plutons were emplaced in all the Paleozoic massifs of the Meseta. Toward the end of the Carboniferous time, a major regression occurred ; the Permian and Triassic facies are consequently of continental type.

After a gap at the beginning of Jurassic, a major Liassic transgression deposited carbonate sediments in the shallow Middle and High Atlas basins. The Meseta and the Anti-Atlas remained emerged areas, and their deformation into horsts and grabens enabled conservation of Triassic facies in some localities. The Alpine orogeny started in mid-Jurassic and continued into Early Cretaceous. This period of time was marked by a general regression of the sea and deposition of red continental beds. In the Cenomanian time, the Middle and High Atlas region of the study area was covered by another transgression. By the Late Cretaceous, this transgression had died down, inundating only the Upper Cretaceous - Lower Tertiary phosphate basins of Middle Morocco. At the end of Tertiary and during the Quaternary, Middle Morocco was the site of strong basic to intermediate volcanism.

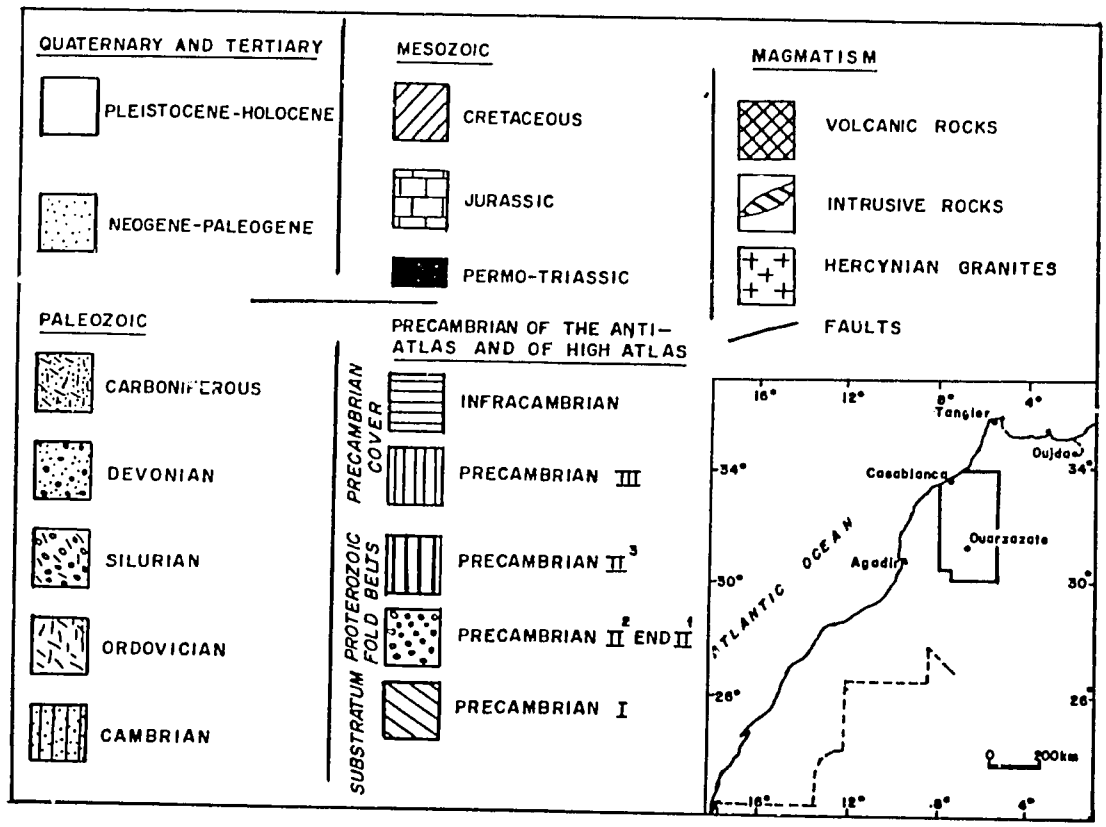

Fig. 2. Locality and legend of the geologic map (Figure 1)

LINEAMENTS (Figure 3)

Lineaments in this study represent rectilinear features expressed on the satellite images as tonal contrasts that may have been caused by lithological variations and traces of faults, dikes and shear zones. Drainage and topographic salients have also been considered for drawing lineaments. Individual lineaments or lineament segments are less than 5 km to over 50 km long. Certain lineament trends are persistent throughout Middle Morocco, others are prominent only in specific regions.

In the Meseta, two lineament sets are clearly visible. One is NW-SE and the other is NE-SW. Lineaments of the first set are generally long and they are present both in the flat or monoclinal areas of Secondary and Tertiary rocks, as well as in the Paleozoic massifs. The NE-SW trend is prevelant only in the Paleozoic terranes. In the Central Massif, the NE-SW lineaments show strong azimuthal variation, but may be broadly grouped into three subsets : NE-SW, NNE-SSW and ENE-WSW. An intersecting relationship between the NNE and ENE subsets can be noted in the southeastern part of the Central Massif. In regard to circular structures, they appear to be related in most cases with exposed or unroofed granite domes.

The NE-SW trend is the most dominent lineament trend in the mountain chains of Middle and High Atlas. The variation in the lineament trend follows closely the regional strike. The NW-SE trend is visible in the westcentral part of the High Atlas. Elsewhere, this lineament trend is only weakly reflected. The circular structures in the Atlas mountains must be associated with Triassic salt domes, though other causes should not be overlooked.

In the Anti-Atlas of Middle Morocco, the NE-SW trending lineaments are observed, however, other lineament sets are also present. In the Saghro inlier, there is an intersecting network of NE-SW and NW-SE lineaments, the former set being denser that the latter one. Outside the Saghro inlier, the NW-SE lineaments are rare. In the Bou Azzer - Tazenakht area (Lower Precambrian), WNW-ESE trending lineaments are most common. These lineaments are broken into segments, each about 50 km long, and they disappear further to the southeast where only the NE-SW lineaments persist.

Geological significance

In Figure 4, major faults are combined with lineaments to check any conformity of trends. It may be readily noted that there is a general identity of trend between faults and lineaments

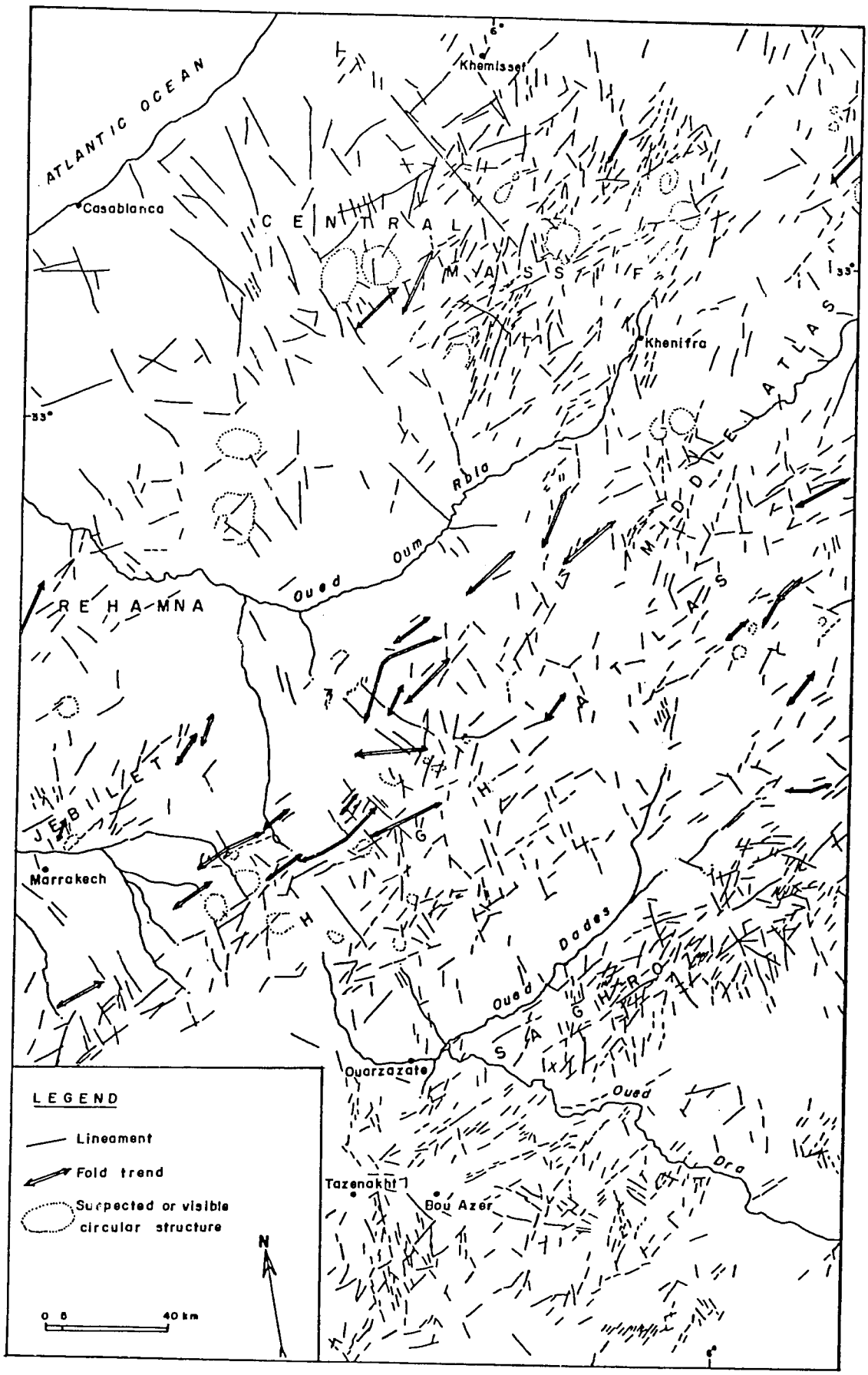

Fig. 3. Lineament map of the study area

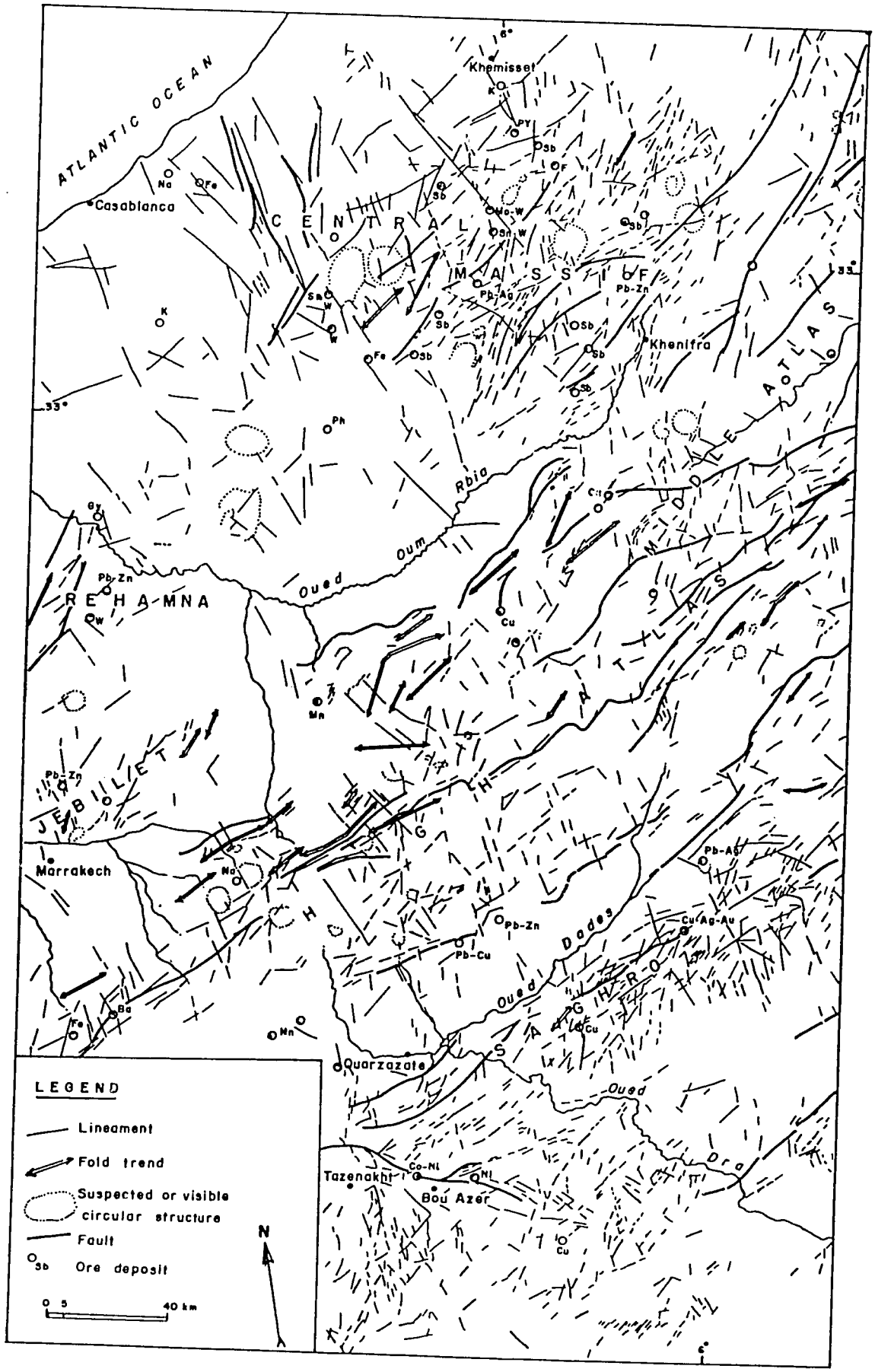

Fig. 4. Lineaments, major faults and ore deposits in the study area

derived from space imagery in all parts of Middle Morocco.

In the Meseta, both the NE-SW and NW-SE lineament trends are followed by faults, particularly in the Central Massif. The fold direction in this Massif is roughly NE-SW, oblique to NNE-SSW and ENE-WSW subsets, and this supports an earlier speculation /10/ that the azimuthal variation in the general NE-SW lineament set may be reflecting trend of the Variscan folds and the associated conjugate fractures.

In the Middle and High Atlas mountains, faults and lineaments follow a common NE-SW to NNE-SSW direction. In fact, a general parallelism may be noted between fold, fault and lineament trends. Lineaments in this part of Middle Morocco, therefore, appear to be the expression of wrench movements of considerable extent.

In the Anti-Atlas, the NE-SW lineaments traverse both the Precambrian inliers as well as Paleozoic cover rocks and follow the main fault direction. The WNW-ESE lineaments, however, are confined only to the area affected by the Anti-Atlas megafracture.

Metallogenic significance

Major ore deposit occurrences are shown on Figure 4 where faults and lineaments have been combined. The type of the ore deposit is shown by chemical symbol (Sb, Pb, Ag, Au, Cu, etc.) or name symbol (Ph : phosphate ; bt : barytes, etc). It may be noted that in many instances a major ore deposit lies on or close to a prominent fault or lineament. This is, for example, true for Co - Ni and Cu deposits of Bou Azzer area, Cu, Au and Ag deposits of the Saghro inlier, and Sb and Pb-Zn-Ag deposits of Central Massif. More important, the deposits are often aligned following a major lineament / fault trend. The endogenic Co-Ni and Cu deposits of the Bou Azzer inlier follow the WNW lineaments. In the Saghro inlier Cu deposits lie on the paths of NE-SW lineaments. Saadi /6/ plotted both minor and major Cu deposits on lineament map to demonstrate their close relationship with NE-SW lineaments. Despite a very high density of lineaments in the Central Massif, a roughly NE-SW alignement of a few major deposits parallel to known faults and deduced lineaments may be appreciated, particularly in the Smala area.Sb deposits are a particularly good case of aligned deposits /10/. The NW-SE lineaments also seem to have controlled the emplacement of ore deposits, though less strongly than the NE-SW lineaments. In the northern part of the Central Massif, for instance, one Sb and two W deposits lie in the proximity of a prominent NW-SE lineament.

CONCLUSIONS

NE-SW and NW-SE trending lineaments are the most common in Middle Morocco. The NW-SE lineaments are observed mainly in the Anti-Atlas and the Paleozoic massifs of the Meseta. The NE-SW lineaments on the other hand pervade terranes of all ages, from the Precambrian inliers of the Anti-Atlas to young Alpine chains of Middle and High Atlas. This set of lineaments must therefore represent fractures that were reactivated, and played an important role in tectonics and sedimentation in the study area. In the Central Paleozoic Massif, the NE-SW lineaments show strong azimuthal variation that was presumably caused by different elements of Variscan deformation. Another set of lineaments trending WNW-ESE traverses the Bou Azzer - Tazenakht area and is related to the Anti-Atlas megafracture.

Several important ore deposits, both in the basement and cover rocks of the Anti-Atlas, and in the Paleozoic massifs of the Meseta follow lineament trends. More work is required before lineaments may be selected as prospecting guides.

ACKNOWLEDGEMENTS

The study is part of the USAID funded project (N° 936-5542) : Block Structure of the Lithosphere and its Role in the Genesis and Distribution of Metallic Ore Deposits. We are grateful to the USAID staff in Rabat and in Washington for their support. Thanks are also due to Mr. Josiah Royce, Coordinator, Mineral Activities, US Trade and Development Program for encouragement. Advice and comments from William D. Carter, Jan Kutina and Moussa Saadi at various stages of the study were very helpful.

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PART IV

THE GABBRO-DOLERITE MAGMATISM OF THE FOUM ZGUID REGION: RELATION TO DEEP STRUCTURE OF MOROCCO AND POSSIBLE POTENTIAL FOR COBALT, NICKEL AND PLATINUM-GROUP METALS*

Jan Kutina
Laboratory of Global Tectonics and Metallogeny
c/o Department of Chemistry, The American University
Washington, D.C. 20016, U.S.A.

Abdelhak Bennani
Division de la Recherche Minière
Ministère de l'Energie et des Mines
Rabat, Morocco

K. Fredriksson and J. Nelen
Department of Mineral Sciences
Smithsonian Institution
Washington, D.C. 20560, U.S.A.

D. W. Golightly, F. W. Brown, Z. A. Brown
Norma Rait and Roosevelt Moore
Branch of Geochemistry
U.S. Geological Survey
Reston, Virginia 22092, U.S.A.

ABSTRACT

The territory of Morocco has been used to test a model of block structure of the lithosphere in which block boundaries guide magmatism and predetermine most favorable places for the concentration of metals. The examination of Van den Bosch's (1971, 1981) isostatic gravity anomaly map has revealed such a

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*Presented at the 7th International Conference on Basement Tectonics held at Queen's University, Kingston, Ontario, Canada, August 1987. To appear in the Proceedings of the Conference.

block structure, with boundaries trending north-south and east-west. In the Triassic and Jurassic time, these boundaries have controlled, to some degree, the shape of a subsiding depression or trough, which is now reflected in the course of the High Atlas Mountains and in the changes in strike of the South Atlas fault zone.

One of the deep-seated N-S trending boundaries, following a longitude close to 7°W, extends farther south toward the northern border of the West African craton. A major concentration of gabbro-dolerite rocks of early Mesozoic age occurs near the intersection of the above N-S boundary with an E-W trending one, in the Saharan part of the Anti-Atlas, south of Foum Zguid.

Quantitative chemical analyses have revealed five differentiates of a basic magma, with two distinct types of dolerite as the prevailing rock type. Significant similarities have been found between the composition of Type-1 and Type-2 dolerite from Foum Zguid and the "Upper contact dolerites" from the Noril'sk-Talnakh region in Siberia, USSR.

In the SW-part of the Foum Zguid region, the process of magmatic differentiation led to a highly differentiated intrusive, over which a potassium metasomatism has been superimposed. The intrusive contains "schlieren" with pyrrhotite and pentlandite, the latter containing 2 to 3% Co. The contact zone of the intrusive, consisting of a serpentinized limestone and hornfels, is very rich in titanium and contains a fine dissemination of a sulfide with about 38% Ni, 17% Fe and 6% Co.

The observations indicate that magmatic differentiation in the SW parts of the Foum Zguid region has reached a stage in which separation and concentration of nickel and cobalt was possible.

It is suggested that a differentiated body of gabbroic rocks, with more substantial concentration of Ni, Co and possibly Pt-group metals may occur beneath the "screen" of dolerites in the SW-parts of the Foum Zguid region, similar to that described from beneath a "screen" of the "Upper contact dolerites" of the Noril'sk-Talnakh region near the western border of the Siberian platform (Vilensky et al., in Smirnov, 1976).

INTRODUCTION

The results presented in this paper are based on the project "Block Structure of the Lithosphere and its Role in the Genesis and Distribution of Metallic Ore Deposits," sponsored by the U.S. Agency for International Development.

The main objective of the project was to test a model of block structure of deeper parts of the lithosphere in which the block boundaries guide magmatism and predetermine most favorable areas for the concentration of metals (fig. 1).

The territory of Morocco provided a special opportunity for testing the above model, because:

1. It is located adjacent to a former junction of three lithospheric plates (North America, Africa and Eurasia), the motion of which could cause rejuvenation of movements along the old intraplate block boundaries, especially in the marginal parts of the plates.

2. The orogenic belt of the Atlas Mountains extends across the entire territory of Morocco, giving good opportunity (a) to examine the relation of the belt to the deep structure of Morocco, and (b) to study intersections of the orogenic belt with structural boundaries extending transversely to it, especially the role of these intersections on the concentration of metals--a phenomenon described from the Appalachians (Kutina, 1981), the Tien Shen Mountains (Favorskaya & Tomson, 1974; Favorskaya & others, 1985) and other orogenic belts.

3. An extensive data base is available in Morocco, including detailed monographs on the geology (Michard, 1976),

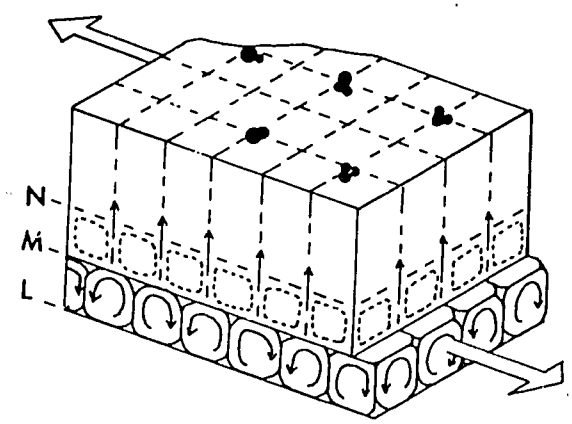

Figure 1. Model of block structure of the lithosphere showing melting proceeding preferentially along boundaries of blocks at the base of the lithosphere, finally leading to separation of a layer of convective cells. The arrows indicate the ascent of magmas and the path of ore forming fluids. The full dots show location of intrusive/volcanic centers and associated ore deposits. From Kutina, 1983.

The isostatic gravity anomaly map of Morocco has revealed structural boundaries compatible with the above model (compare with fig. 4).

mineral deposits (Géologie des Gites Minéraux Marocains, 1980), geotectonic and structural evolution with analysis of structural lineaments (Saadi, 1980), an outstanding gravimetric study (Van den Bosch, 1971, 1981), and excellent geological maps on different scales, published by the Service Géologique du Maroc.

Our study, using geological and geophysical data, especially the isostatic gravity anomaly map, confirms that the lithosphere of Morocco has a block structure, that the orogenic belt of Atlas Mountains is related to it, and that this block structure plays an important role in the concentration of metals. The most interesting target area we have derived to date is the Foum Zguid region in the Saharan part of the Anti-Atlas. Our paper focuses on this area, setting it in the context of the deep structure of Morocco.

THE INITIAL OBSERVATIONS

A preliminary examination of Van den Bosch's (1971, 1981) isostatic gravity anomaly maps of Morocco, carried out by J. Kutina (in Bensaid et al., 1985) has indicated the presence of two north-south trending boundaries in the deep structure of Morocco. These boundaries, superimposed on Saadi's (1982a, 1982b) structural and mineral deposit maps of Morocco have revealed that all the most important deposits of Pb-Zn-Ag concentrate to the east and those of Cu to the west of the main N-S trending structural boundary which extends close to longitude 6°W (fig. 2). The same map has shown that: (1) The major

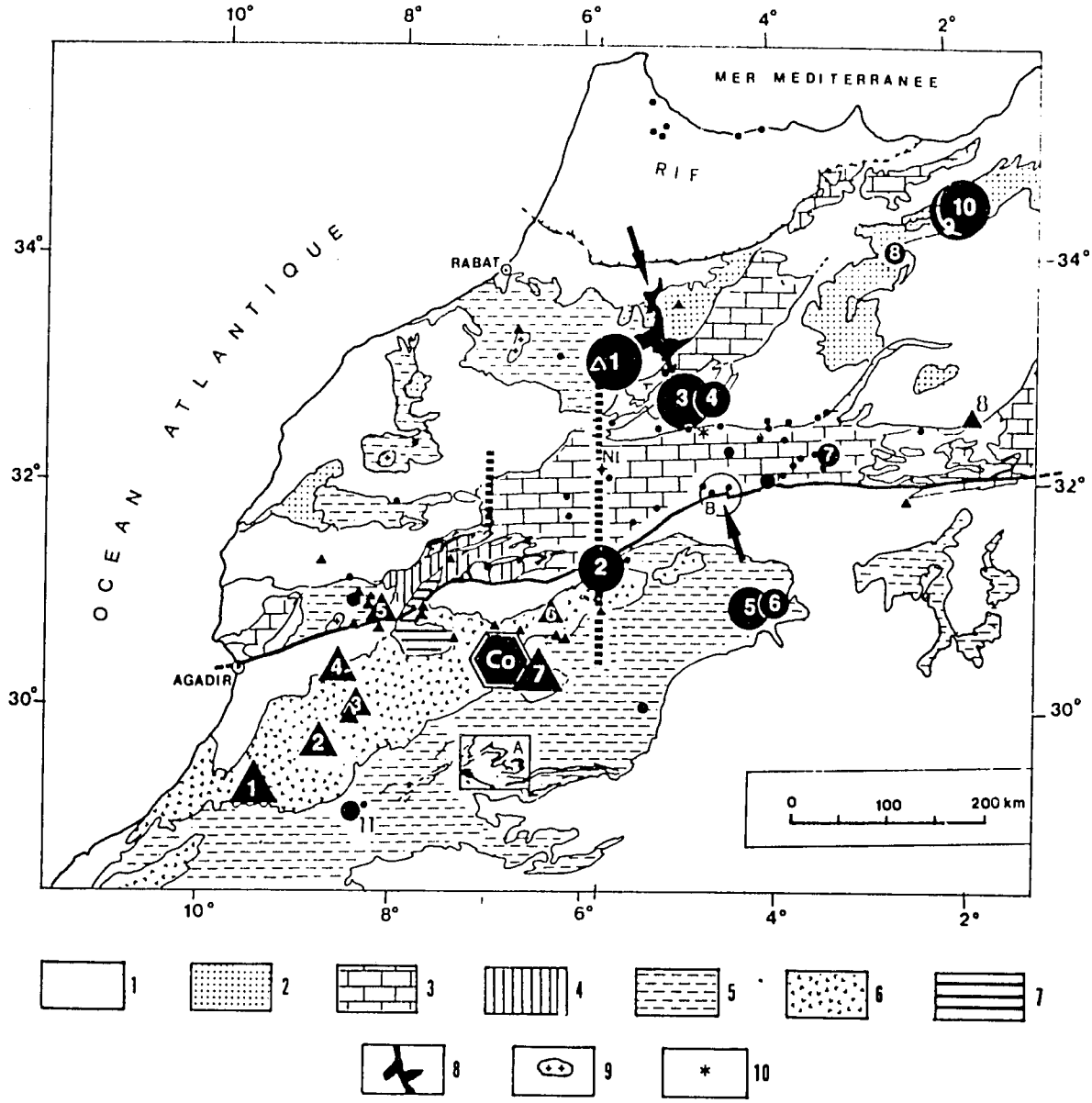

Fig. 2. Geologic scheme of the project area in northern Morocco showing the distribution of the main deposits of lead, zinc and silver (black dots), copper (black triangles) and the location of the cobalt district of Bou-Azzer (Co).

The geology is simplified from Saadi's (1982a) 'Carte Structurale du Maroc', the ore deposits are after Saadi's (1982b) 'Carte Minière et Energetique du Maroc'.

The two N-S trending lineaments are structural boundaries distinguished by J. Kutina in Van den Bosch's (1971) isostatic map, reproduced in fig. 4. Note that all of the most important deposits of Pb-Zn-Ag concentrate to the east, and those of Cu to the west of the N-S trending structural boundary which extends close to longitude 6°W.

The rectangular inset A, shown south of the cobalt district of Bou-Azzer, is an area with great accumulation of dolerite sills and dikes.

The area B (open circle) shows the intersection of the South Atlas Fault with a lineament which is proposed to extend transversely to the High Atlas Mountains (marked by two arrows). The area B may be of special metallogenic interest.

Legend to geology: 1—Neogene and Quaternary; 2—Tabular Jurassic cover; 3—Folded Mesozoic (mostly Jurassic); 4—Triassic continental red beds; 5—Undifferentiated Paleozoic; 6—Undifferentiated Precambrian of the Anti-Atlas; 7—Precambrian granites of the High- and Anti-Atlas; 8—Doleritic dykes of Liassic age (mainly in the Anti-Atlas); 9—Hercynian granites; 10—Calco-alcaline massif of Tamazeght (High Atlas).

Pb-Zn-Ag deposits (shown by black dots): 1—Jbel Aouam Pb-Zn (Ag); 2—Imiter Ag; 3—Zeida Pb-Zn (Ba); 4—Aouli and Mibladen Pb-Zn; 5—Tadaout Pb-Zn; 6—M'Fis Pb-Zn; 7—Bou-Dahar Pb-Zn; 8—Sidi-Lahcen Pb-(Ag); 9—O. Mekta Pb-Zn; 10—Bou-Beker Pb-Zn; 11—Addana Pb-(Ag).

Cu deposits (shown by black triangles): 1—Ouansimi; 2—Tazalaght; 3—Talat-n'Ouamane; 4—Asif-Imider; 5—Tanfit; 6—Bou-Skour; 7—Bleida; 8—Jbel Klakh.

For greater detail, see 'Géologie des Gîtes Minéraux Marocains' (1980).

Reproduced from Bensaid et al.,1985.

silver deposit of Imiter (black dot No. 2, in fig. 2) occurs, on the scale of Figure 2, close to the intersection of the above N-S trending structural boundary with the South Atlas Fault, the latter delineating the High Atlas Mountains on their southern side; (2) The cobalt district of Bou Azzer (symbol Co in fig. 2) occurs close to the southern projection of one of the N-S trending structural boundaries and, farther south, a major concentration of gabbro-dolerite rocks occurs in the Saharan parts of the Anti-Atlas (see the small framed area A in fig. 2); (3) The South Atlas Fault shows significant changes in its strike which may be related to the deep structure of Morocco (figs. 2 & 3).

The above observations suggested that a detailed study of the isostatic anomaly maps may reveal additional regularities reflecting the deep structure of the terrirory and its role in metallogeny.

DEEP STRUCTURE OF MOROCCO AS MANIFESTED IN THE ISOSTATIC GRAVITY ANOMALY MAP

According to the Airy model of isostasy, there is a tendency of lithospheric blocks to compensate the differences in their weight by different degrees of submerging in the plastic, partially molten substratum beneath the base of the lithosphere. It was our expectation that the isostatic adjustment would reflect itself in Van den Bosch's isostatic gravity anomaly maps (calculated for different thickness of the

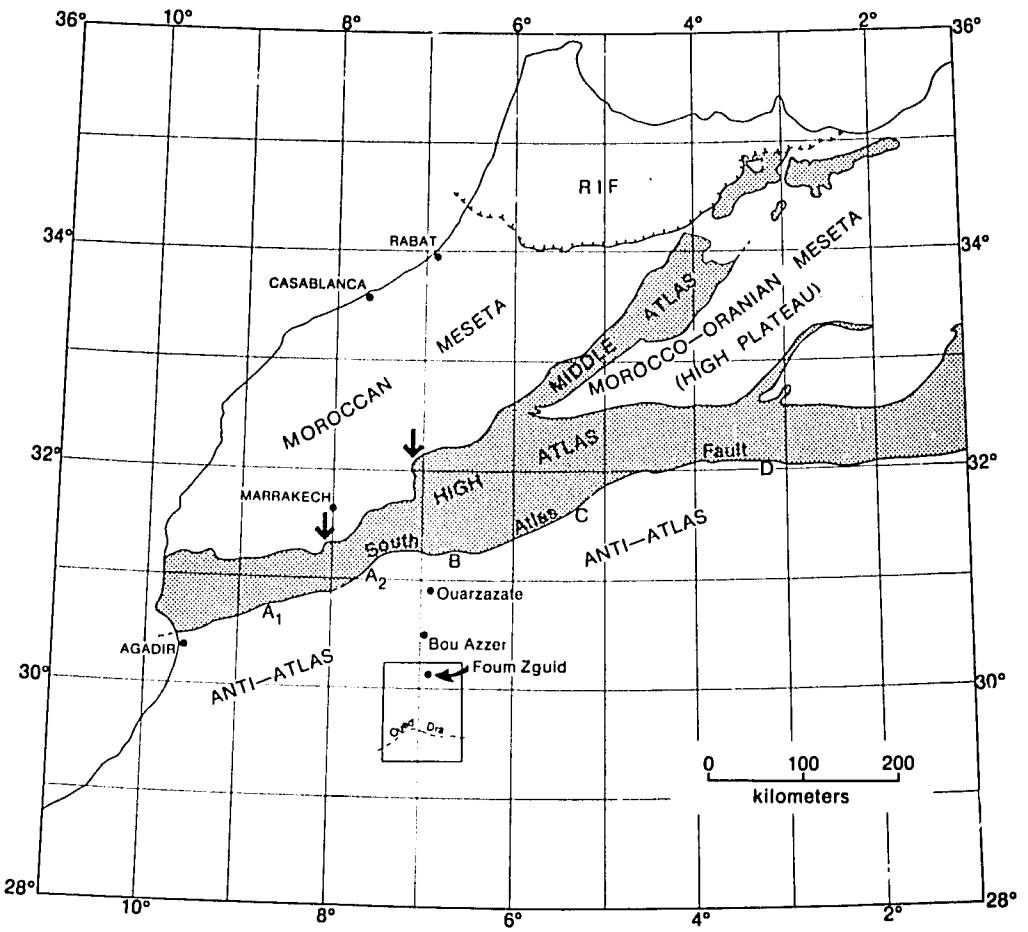

Figure 3. The four principal structural-geological domains of northern Morocco: (1) Meseta (the Moroccan meseta and the Moroccan Oranian meseta), (2) Atlas Mountains, (3) Anti-Atlas, and 4. Rif. (Adopted from Michard, 1976, and Saadi, 1980, 1982a). The course of the Atlas Mountains is after Saadi's (1982a) map. Note the changes in the strike of the South Atlas Fault (the east-west segments B and D and the northeast segments A_1, A_2, and C, and the morphological "steps" on the northern boundary of the Atlas Mountains, marked by arrows).

The Foum Zguid region in the Saharan part of the Anti-Atlas (inside the small frame corresponding to fig. 6) was found to have potential for concentration of nickel, cobalt, and gold (this paper).

lithosphere) and will reveal the most important structural boundaries of Morocco by different gravity values of the blocks.

Figure 4 shows one of the isostatic anomaly maps of Van den Bosch, selected for our analysis. We have distinguished, by different patterns, four groups of gravity values, using the darkest pattern for values higher than 50 milligals (reflecting parts of the lithosphere with the greatest participation of rocks of high density).

The course of the Atlas Mountains (fig. 3), essentially reflecting the shape of the depression or trough in which sedimentation proceeded in the Mesozoic time, has been superimposed on the isostatic anomaly map (shown by heavy contours in fig. 4). A considerable part of the High Atlas Mountains and the Middle Atlas Mountains is made up of folded Mesozoic (mostly Jurassic) rocks and, in the western parts of the High Atlas, the continental Triassic red beds play an important role (fig. 2).

In agreement with the accumulation of a pile of less dense sedimentary rocks, which make up most of the High Atlas Mountains, most of this orogen is characterized by relatively low gravity values. This belt of lower gravity is enclosed between zones of gravity highs, one occurring north of 32°45'N and the other south of 31°N latitude.

The shape of the High Atlas Mountains indicates that the subsidence, giving rise to the elongated depression, had a tendency to follow a NE-direction but that it was also controlled

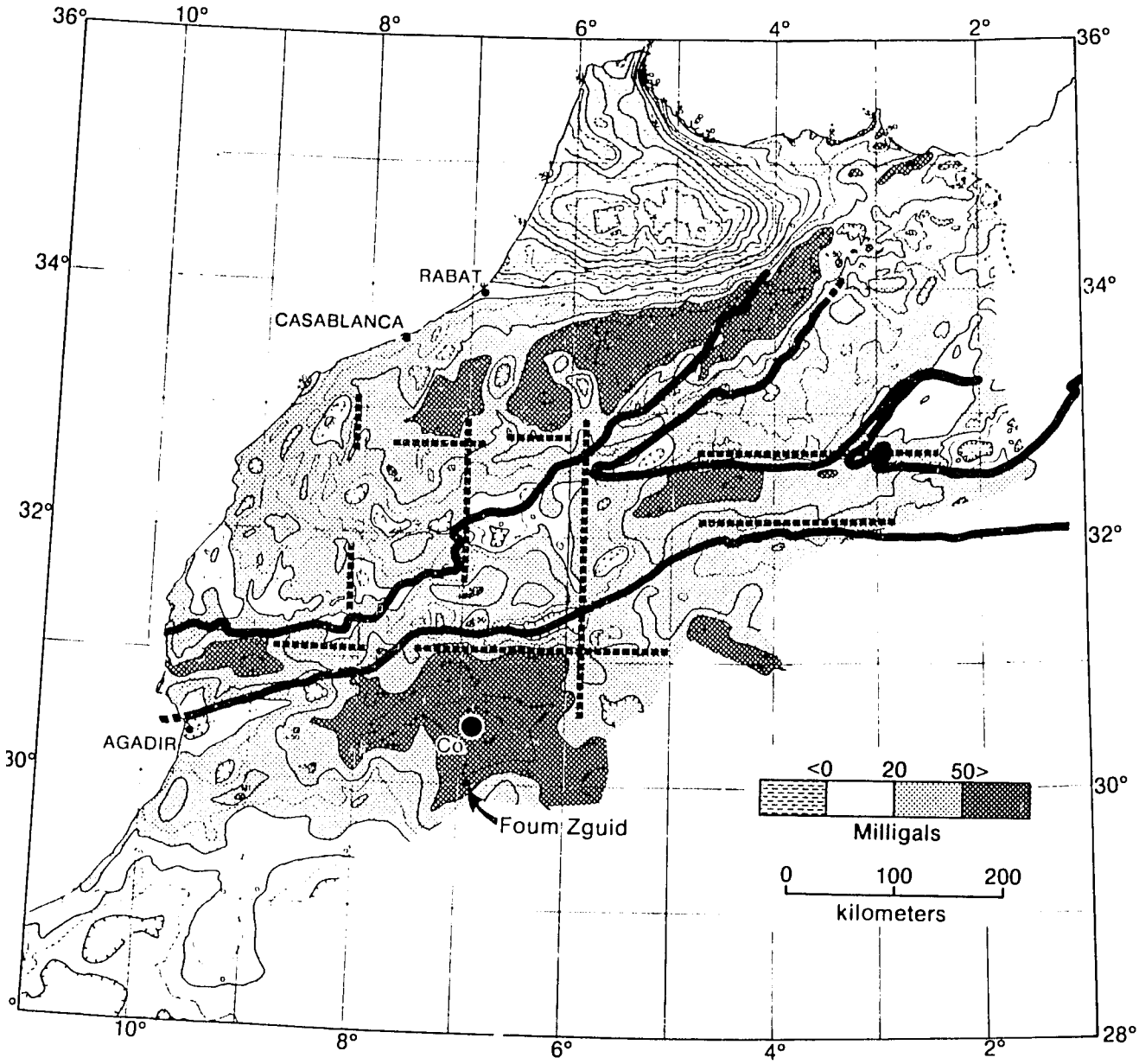

Figure 4. The isostatic anomaly map of northern Morocco, adopted from Van den Bosch (1981). D=2.67; Airy-Vening Meinesz hypothesis, T = 30 km, R = 0 km, 10 mgals contours.

The course of the Atlas Mountains (heavy full lines), superimposed on the isostatic map, is from Saadi's (1982a) "Carte Structurale du Maroc," scale 1:2,000,000.

The N-S and E-W trending boundaries of lithospheric blocks, marked by heavy broken lines, are distinguished by Jan Kutina (this paper). The location of the cobalt district of Bou Azzer is shown by a large dot, marked Co.

by E-W trending structural boundaries. This control is well visible by the changes in the strike of the boundary which delineates the High Atlas Mountains on their southern side. This boundary is a rather complicated one and is, in the literature, referred to as the "Accident sud-atlasique" (Michard, 1976), South Atlas fault zone, or simply the South Atlas Fault. This boundary consists of segments trending ENE to NE (segments A_1, A_2 and C) and those trending E-W (segments B and D). The northern limitation of the High Atlas Mts. also exhibits important changes in its course, of which especially two N-S "steps" (marked by arrows in fig. 3) are significant.

The isostatic gravity anomaly map (fig. 4), onto which the course of the Atlas Mountains has been transferred, helps to explain the above observations:

1. The E-W trend of the High Atlas Mountains at 32°N (between longitudes about 2°W and 4°30'W) correlates with the east-west contours in the isostatic anomaly map.

2. The change from NE to E-W which occurs on the southern boundary of the High Atlas Mountains (i.e., on the South Atlas Fault zone at about 31°N, near the longitude 6°W), correlates with the northern limitation of a major zone of gravity highs (shown dark in fig. 4). This zone apparently acted as a rigid block, limiting a sedimentary depression or trough which developed to the north of this block. The gravity contours of the isostatic map indicate that the northern limitation of this zone of gravity highs is part of a major latitudinal boundary which extends from the Atlantic coastal area towards the east.

Two zones of gravity highs which occur SE of Rabat and SE of Casablanca respectively (fig. 4), terminate at a latitude approximately 32°45'N, essentially correlating with the northern border of a sedimentary basin shown in the Carte Géologique du Maroc, scale 1:1,000,000 published in 1985.

Within the High Atlas Mountains, between longitudes 4° and 5°30'W, there occurs a rather narrow zone of gravity highs (>50 milligals) which is more than 100 km long. This zone is not manifested by any larger block of basic rocks in the surface area. It may reflect a larger body of basic or ultrabasic rocks beneath the surface, either uplifted as a rigid upper mantle block (similar to the blocks of basic or ultrabasic rocks in the east-trending fracture zones of the equatorial Atlantic described by Bonatti, 1971; Bonatti & Honorez, 1971; Bonatti 1973; and others), or an intrusive body not reaching the Earth's surface. The relatively small calco-alkaline massif of Tamazeght, shown by asterisk in Figure 2, correlates with the northern boundary of the zone of gravity highs.

Besides the east-trending structural boundaries, shown by broken lines in Figure 4, there are, in the same map, structural boundaries trending north-south. These boundaries intersect with the east-west ones and extend transversely to the orogenic belt of the High Atlas Mountains. Two of these N-S trending boundaries are manifested as "steps" on the northern border of the High Atlas Mountains (one at a longitude close to 7°W, and the other at 8°W)--compare with Figure 3.

The recognition of a set of N-S trending boundaries in the deep structure of Morocco is of extraordinary importance for mineral exploration and is described in the next section.

THE ROLE OF DEEP STRUCTURE OF MOROCCO IN THE GENESIS OF METALLIC ORE DEPOSITS

The metallogeny of Morocco has been studied by many scientists and the main results summarized in "Géologie des Gîtes Minéraux Marocains, Tome I" (1980). Special attention has been paid to the relationship between metallogeny and geotectonic evolution of Morocco (Saadi, 1980), and between mineralization and structural lineaments (Saadi, 1971, 1980, 1982a; Saadi & Mahmood, 1984, and Bensaid & Mahmood, 1986).

The isostatic anomaly map (fig. 4) reveals two features which are of basic importance for further analysis of deep controls of mineralization in Morocco: (1) Intersection of deep-seated structural boundaries of two trends (north-south and east-west), defining lithospheric blocks of orthogonal shape; (2) Intersection of the orogenic belt of the High Atlas Mountains with a set of deep-seated, north-south trending structural boundaries, extending transversely to this belt.

The spacing of the three N-S trending structural boundaries is about 110 km (fig. 4). The two E-W trending boundaries (one extending close to latitude of 31°N and the other at approximately 32°45'N) intersect with the boundaries trending north-south. There are indications suggesting that another E-W boundary exists half-way between the above two, so that the

spacing in the E-W set of structural boundaries would be slightly smaller than 100 km.

A similar size of structural blocks has been found in the Precambrian of the Abitibi area in the southern part of the Canadian Shield (Kutina & Fabbri, 1972). The lithospheric blocks, distinguished in the isostatic anomaly map of Morocco may also reflect a block structure of the Precambrian basement. In the Abitibi area, the distribution of approximately 1,500 gold and about 700 copper occurrences (as well as deposits of other metals) has shown a pronounced tendency to concentrate near the corners of lithospheric blocks (documented by statistical methods). In Morocco, a major cluster of about fifty occurrences and deposits of metals, including the large silver deposit of Imiter, occurs near the intersection of the N-S trending structural boundary which extends close to 6°W longitude and the E-W trending boundary following the 31°N latitude (fig. 4).

The following observations have been made regarding the intersection of the High Atlas Mountains with the N-S trending structural boundaries: (1) The N-S trending boundary at longitude west of 8°W (fig. 4), manifests itself as a morphological "step" on the northern border of the High Atlas Mountains (fig. 3), but does not show up, on the scale of Figure 3, on the course of the South Atlas Fault which constitutes the southern boundary of the mountains. However, the major magnetic lineament in Demnati's (1979) "Carte Magnetique du Maroc" (fig. 5), which reflects the South Atlas Fault, provides

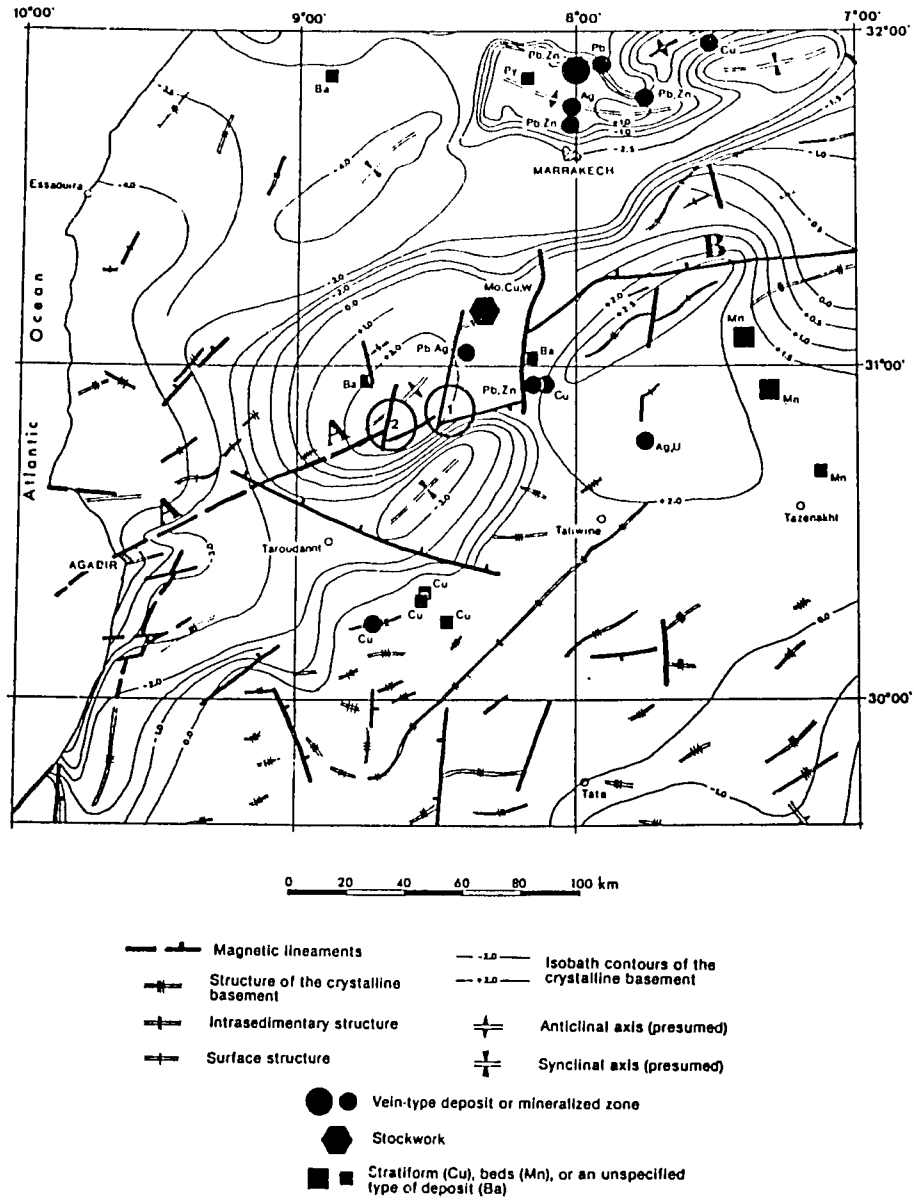

Figure 5. A cluster of ore deposits SW of Marrakech, developed in places where the South Atlas Fault zone intersects with a set of N-S trending faults.

The South Atlas Fault zone, extending east-north-easterly from Agadir, is shown by a major magnetic lineament (with segments A and B of different strike), on the background of isobath contours giving the depth and indicating structure of the crystalline basement.

The interpretation of magnetic data and the isobath contours are after A. Demnati's (1979) 'Carte Magnétique du Maroc,' sheet Marrakech; the location and relative size of mineral deposits are after the 'Carte Géologique du Maroc' (1985), and the types of mineral deposits are distinguished after the 'Carte de Gîtes Minéraux du Maroc' (1980). The areas enclosed by circles Nos. 1 and 2 are local targets defined (this paper) inside the broader area of intersection which is understood as having potential for concentration of metals.

evidence that the South Atlas Fault, at a longitude west of 8°00'W, is also intersected by the N-S trending fault, and, west of it, by other two NNE-striking faults. (2) A cluster of ore deposits has developed in the area of this structural intersection. This indicates that the intersection of the South Atlas Fault with the above N-S trending structural boundary provided channelways for the ascent of magmas and ore-forming fluids.

The above observation is of importance for evaluation of the intersection of the High Atlas Mountains with the other north-south trending structural boundary which extends close to 7°W. In this case, a still bigger morphological "step" has developed on the northern border of the mountain belt (figs. 3 and 4) and, also, no comparable step occurs on its southern border. With regard to the previous case, one should expect that the N-S trending structural boundary, extending at a longitude close to 7°W, also intersects with the South Atlas Fault (at least at a deeper level beneath the Earth's surface) and could guide heat, magma and mineralizing fluids towards the surface. The most probable place of metal concentration, controlled by the above structural intersection, can be expected in the area NNW of Ouarzazate, adjacent to the South Atlas Fault.

THE GABBRO-DOLERITE MAGMATISM OF THE FOUM ZGUID REGION

Geology and Structural Control

The Foum Zguid region, as defined in this paper, is located in the Saharan part of the Anti-Atlas, extending across the Morocco-Algerian border (fig. 3). It occupies about 80 x 60 km on the inner, southern side of Jbel Bani, a mountain range made up of resistant Ordovician rocks (fig. 6). The Foum Zguid region is comprised of Paleozoic sediments (Ordovician to Upper Devonian), of which especially the Devonian sediments are extensively penetrated by dikes, sills and other bodies of gabbro-dolerite rocks. The age of these basic rocks, originally considered Hercynian (for example, in the Carte Géologique des L'Anti Atlas Central, 1970), is now classified as early Mesozoic (Triassic-Liassic in the Carte Géologique du Maroc, 1:1,000,000 of 1985).

The arcuate structure of Jbel Bani is, in the places of its biggest curvature, cut by a deep north-south trending valley. The town of Foum Zguid is located adjacent to the southern end of the valley.

The gabbro-dolerite magmatism, marked in black in Figure 6, tends to penetrate toward the north along direction F_2 (localities No. 13 and 14). The importance of a N-S direction in this region is also manifested by the shape of the Hamsailikh anticline, the axis of which changes its strike from NE-SW to N-S. This change in the strike, occurring between 29°50'N and 30°00'N, can be explained by tectonic movements along a deep-seated, north-south trending boundary, following direction F_1

Figure 6

Geological map of the Foum Zguid region,* Saharan part of the Anti-Atlas, showing a locality with concentration of nickel and cobalt (No. 8, Ni, Co) and an area with opalites containing anomalous contents of gold (Nos. 3, 4 and 5), discovered under the AID-funded project.

The geology is after the "Carte Géologique des Plaines du Dra au sud de l'Anti-Atlas Central" and the "Carte Géologique de l'Anti-Atlas Central et de la zone synclinale de Ouarzazate," both on the scale 1:200,000, published by the Service Géologique du Maroc in 1971 and 1970 respectively.

Legend: 1 - Precambrian (Infracambrian); 2 - Lower Cambrian; 3 - Middle Cambrian; 4 - Ordovician; 5 - Silurian, partly covered by Quaternary sediments; 6 - Lower Devonian; 7 - Middle and Upper Devonian; 8 - Carboniferous; 9 - Quaternary sediments of Oued Dra; 10 - Gabbros and dolerites of Liassic age; 11 - Localities of samples collected by J. Kutina and A. Bennani in 1986 and 1987; 12 - E-W trending structural boundaries (S_1 and S_2) in the southern part of the map, and possible positions of north-south trending, deep-seated structural boundaries (F_1 and F_2) in the northern part of the map, proposed in this paper.

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*Shown by a small frame in Figure 3.

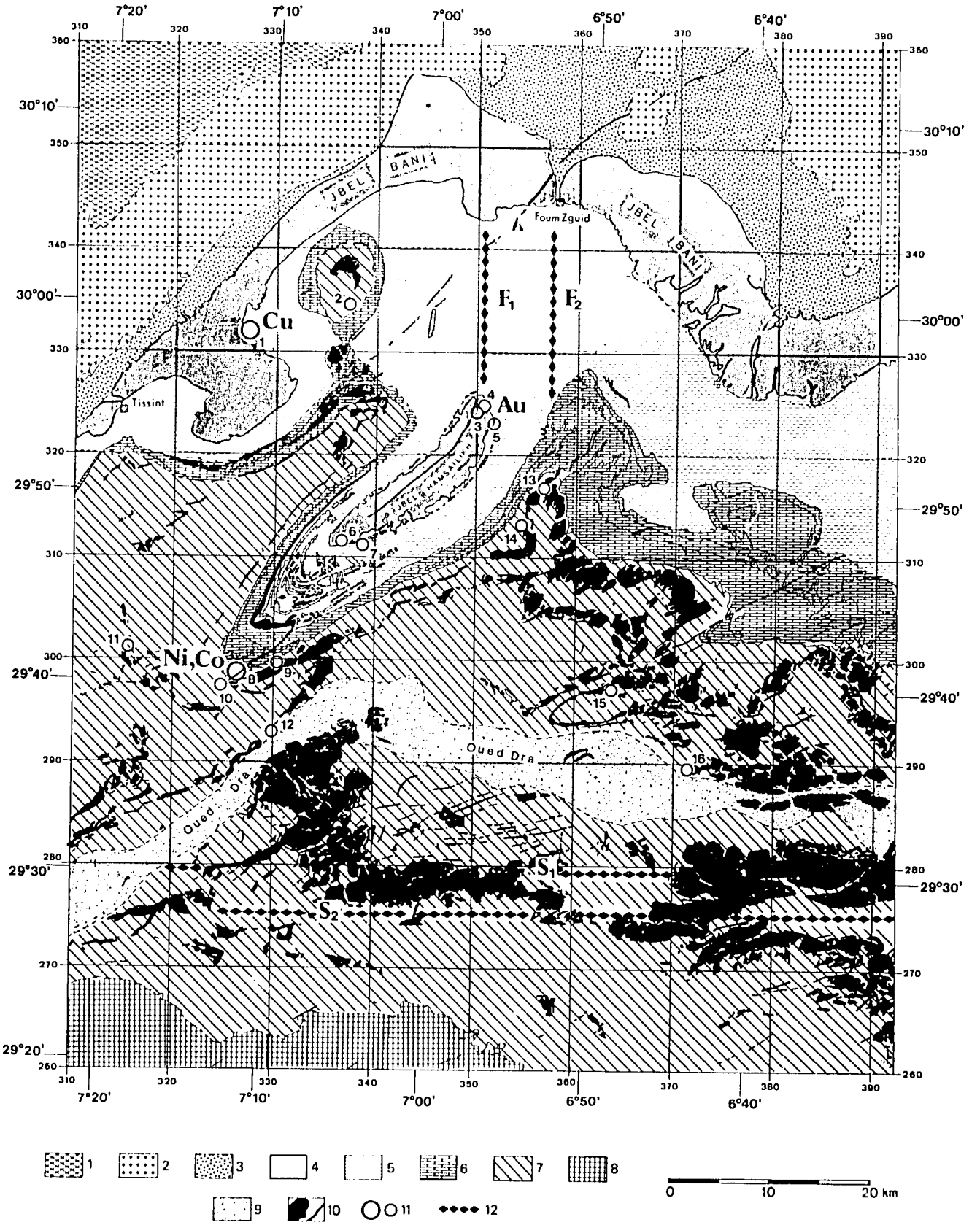
7°20'
7°10'
7°00'
6°50'
6°40'
30°10'
30°00'
29°50'
29°40'
29°30'
29°20'
JBEL BANI
JBEL IBANI
Foum Zguid
Tissint
Cu
Au
Ni,Co
F1
F2
S1
S2
Oued Dra
1
2
3
4
5
6
7
8
9
10
11
12
0
10
20 km

Figure 6

(fig. 6). The positions of F_1 and F_2 show a good correlation with the longitude of the meridional structural boundary which has been distinguished in the isostatic gravity anomaly map at 7°W (fig. 4). These observations indicate that the above meridional boundary may extend southward into the Foum Zguid region. The arcuate curvature of the Jbel Bani is symmetrical to the course of the suspected N-S trending deep-seated boundary.

Supporting evidence for extension of the above structural boundary into the Foum Zguid region is found in the residual Bouguer gravity anomaly map with a wavelength cutoff of 100 km (scale 1:2,000,000) prepared by T. G. Hildenbrand, R. P. Kucks, M. F. Hamouda and A. Bellot (1987, to be published). A N-S trending deep-seated boundary at a longitude close to east of 7°W is indicated by the distribution of zones of gravity highs and lows, and correlates with directions F_1 and F_2 in Figure 6. The cobalt district of Bou Azzer occurs close to the boundary between a zone of gravity highs and a zone of gravity lows.

In the southern part of the Foum Zguid region, close to latitude 29°30'N, the gabbro-dolerite rocks exhibit a prominent E-W trend, shown in Figure 6 by lineaments S_1 and S_2. These lineaments correlate with the east-west contours of the isostatic anomaly map between longitudes 7°30' and 10°00'W (fig. 4). This correlation shows that a major E-W trending structural boundary, following a latitude close to 29°30'N, extends for a long distance away from the Atlantic coastal region. In places where this E-trending boundary intersects with the meridional one (which extends into the Foum Zguid region

from the north, following a longitude close to 7°00'W), a huge concentration of basic igneous rocks occurs.

The local concentration of such an amount of gabbro-dolerite rocks, as seen in the Foum Zguid region, requires structural control by deep-seated channelways which the above structural intersection could provide. Moreover, this intersection occurs in the vicinity of the northern border of the West African craton. Therefore, we consider the basic magmatism of the Foum Zguid region as the product of an early Mesozoic tectono-magmatic reactivation that occurred in a structurally favorable area near the border of the West African craton. The opening of deep-seated channelways, which guided the basic magmatism, occurred during the process of rifting, associated with the evolution of the Atlantic Basin.

Comparison with Structural Setting of the Noril'sk-Talnakh region, Siberia

On a global scale, there are several cases of tectono-magmatic reactivation that occurred in specific areas near the borders of old cratons or platforms. For comparison with the Foum Zguid region, the most important case is the gabbro-dolerite magmatism of the Noril'sk-Talnakh region in the USSR which is also of an early Mesozoic age and occurred near the western border of the Siberian platform. Using a simplified map of extensional structures of the Siberian platform (Kozlovsky, 1986), one can see that the basic magmatism of the Noril'sk-Talnakh area occurred in places adjacent to the intersection of the meridional, western border of the platform

with an essentially east-west trending paleorift. Thus, the concentration of the gabbro-dolerite rocks in both the Noril'sk-Talnakh and the Foum Zguid regions is related to a deep-seated magmatism which was guided by intersection of the border zone of an old craton (or platform), with a deep-seated structural boundary extending transversely to it.

A large concentration of Cu-Ni ores, with a substantial amount of Pt-group metals, which is known in the Noril'sk-Talnakh region, is of great interest for evaluation of a possible mineral potential of the Foum Zguid region.

According to the observations by Vilensky et al. (in Smirnov, 1976, p. 100), the most promising areas for copper-nickel sulphide ores in the Noril'sk district are "the thick (more than 100 meters), gently sloping, differentiated lopolith-like intrusions of the alkaline-earth branch of basaltic magma differentiation, which have a small aureole of contact metamorphosed rocks lying beneath a 'screen' of lavas or dolerites."

A question arises: Can the dolerite rocks of the Foum Zguid region also represent a 'screen', beneath which intrusive bodies with economic concentrations of metals, in this case mainly nickel, cobalt and platinum-group elements, may occur?

To answer the above question, we have undertaken two expeditions to the Moroccan part of the Foum Zguid region (north of the valley Oued Dra in fig. 6), and searched for signs of differentiation and alteration of the gabbro-dolerite rocks.

Chemical Composition of the Foum Zguid Magmatic Rocks and their Comparison with those from the Noril'sk-Talnakh Region

The quantitative chemical analyses of 17 samples of igneous rocks from the Foum Zguid region reveal a process of magmatic differentiation. Fourteen of the samples correlate significantly with the "Upper contact dolerites" of the Noril'sk region, USSR (Tables 1, 2 and 3). Among these 14 samples one can distinguish two distinct groups of dolerites, further referred to as "Type 1" and "Type 2." The difference in the composition between these two groups is best seen when comparing the ranges of contents of the individual elements (Tables 1 and 2). The "Type 2" dolerites have distinctly lower contents of FeO, Fe_2O_3, TiO_2 and MnO, representing a relatively less basic magmatic differentiate, still within the composition range of dolerites. The difference between the two types of dolerites is also seen in the contents of some minor and trace elements (Table 4). In particular, the Type-2 dolerite has lower contents of Cr, slightly lower contents of Co, Ni and Cu, and higher contents of Ba, Sr and Pb, which is in line with the increased acidity of the rock. The quantitative analyses of three Pt-group metals (Pt, Pd and Rh) of 14 dolerite samples show that the Type-2 dolerite has a relatively lower average content of platinum than the Type-1 dolerite.

The contents of zirconium and magnesium in the two types of dolerite from Foum Zguid fit with the pattern of regularity described from the Noril'sk area by Zolotukhin (1982).

Three of the seventeen samples from the Foum Zguid region belong to other differentiates of basic magma than the Type-1 and Type-2 dolerites. These rocks are further referred to as Types 3, 4 and 5 respectively. Reserving the assignment of definite names to these rocks until the microscopic study is completed, we are preliminarily comparing the quantitative chemical analyses of these rocks with the composition of some magmatic differentiates from the Noril'sk-Talnakh region.

The "Type 3" from Foum Zguid: the nearest composition among the Noril'sk-Talnakh rocks given by Dodin et al. (1971) has the gabbro-diorite from Talnakh and the gabbro-dolerites from the Noril'sk and Morongo intrusives. The Foum Zguid rock has a distinctly lower CaO content. The total Fe of all the rocks under comparison is very similar, but the higher Fe^{3+} and the lower Fe^{2+} contents of the Foum Zguid sample are due to oxidation (this only sample coming from gravels, with iron oxydation products megascopically visible).

The Type-4 from Foum Zguid reasonably correlates with the composition of a melanocratic basalt from Noril'sk, but our sample belongs to an intrusive rock.

The Type-5 from Foum Zguid is an intrusive rock with superimposed potassium metasomatism and requires a detailed microscopic study to determine the nature of the original rock. The chemical analysis, especially the high contents of SiO_2, Al_2O_3, Fe_2O_3 and FeO show similarity with a plagiodolerite from Noril'sk, but the rock from Foum Zguid has a considerably higher K_2O and considerably lower CaO and MgO contents which,

at least partly, are related to the superimposed K-metasomatism (observed microscopically).

On a regional scale, all the four samples of Type-2 dolerite come from locations closer to the Oued Dra Valley, it is closer to the east-west trending structural boundary expressed by lineaments S_1 and S_2 (fig. 6). The northernmost localities such as Nos. 2, 13 and 14 belong exclusively to Type-1 dolerite. The other magmatic differentiates, Types 3, 4 and 5, come from an area adjoining the SW-limb of the Hamsailikh anticline, it is also from the southern part of the Foum Zguid region.

The above zonal distribution of igneous rocks, with the Type-1 dolerite found only in the northern parts of the Foum Zguid region (fig. 6) indicates that the emplacement of the individual differentiates of a basic magma was controlled by and proceeded away from the main chanelway, located closer to the West African craton.

Separation and concentration of parts of the cobalt, nickel and platinum metals, originally distributed in the basic magma, required magmatic differentiation. Therefore, better chances for finding concentrations of the above metals might be in the southern parts of the Foum Zguid region, where several differentiates of the basic magma have been found, including an intrusive with superimposed potassium metasomatism. In accordance with this theoretical assumption is our discovery of concentration of nickel and cobalt at locality No. 8, within an area where rock types Nos. 2, 3, 4 and 5 occur.

Rock type	Type 1											
No. in Fig. 6	2	2	11	13	13	14	14	14	14	15	Range	Average
Field No.	45	46	42	14	15	19	20A	20B	20C	13	%	%
SiO_2 %	50.7	50.6	50.5	50.5	49.1	50.6	50.3	50.3	50.0	50.5	49.1 - 50.7	50.31
Al_2O_3 %	13.2	13.1	13.3	13.7	13.4	13.5	13.3	13.5	12.8	13.0	12.8 - 13.7	13.28
Fe_2O_3 %	2.7	3.3	3.1	2.8	5.0	2.8	3.1	4.4	4.6	3.3	2.7 - 5.0	3.51
FeO %	13.0	12.8	12.3	12.7	10.4	12.6	12.5	11.0	11.4	12.6	10.4 - 13.0	12.13
MgO %	5.4	5.3	5.5	5.5	5.1	5.4	5.1	5.2	5.2	5.2	5.1 - 5.5	5.29
CaO %	9.8	9.7	9.6	9.8	9.5	9.7	9.4	9.6	9.6	9.5	9.5 - 9.8	9.62
MnO %	0.25	0.25	0.25	0.26	0.24	0.25	0.25	0.24	0.25	0.25	0.24 - 0.26	0.25
Na_2O %	2.3	2.3	2.3	2.3	2.2	2.3	2.3	2.3	2.2	2.2	2.2 - 2.3	2.28
K_2O %	0.56	0.62	0.64	0.52	0.61	0.58	0.66	0.59	0.62	0.58	0.52 - 0.66	0.60
TiO_2 %	1.5	1.6	1.5	1.5	1.5	1.4	1.6	1.4	1.6	1.6	1.4 - 1.6	1.52
P_2O_5 %	0.20	0.18	0.17	0.18	0.19	0.18	0.24	0.14	0.21	0.20	0.14 - 0.24	0.19
CO_2 %	0.16	0.20	0.05	0.03	0.34	0.05	0.08	0.02	0.22	0.02	0.02 - 0.34	0.12
H_2O^+ %	0.39	0.40	0.81	0.53	1.0	0.55	0.62	0.78	0.70	0.71	0.39 - 1.0	0.65
H_2O^- %	0.04	0.06	0.04	0.08	0.22	0.04	0.06	0.12	0.10	0.11	0.04 - 0.22	0.09
Total %	100.20	100.41	100.06	100.40	98.80	99.95	99.51	99.59	99.50	99.77		99.84
Pt ppb	11	9.5	12	18	11	11	14	8.5	11	14	8.5 - 18	12
Pd ppb	6.4	5.8	6.7	8.6	3.5	2.8	7.1	2.3	3.3	8.1	2.3 - 8.6	5.5
Rh ppb	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5
Au ppb	<10	<10	<10	40	<10	<10	<10	<10	<10	<10	<10 - 40	

Table 1. Chemical composition of type-1 dolerite from the Foum Zguid region, Saharan part of the Anti-Atlas, Morocco. Location of samples given in Figure 6.

Major components determined by inductively coupled argon plasma spectrometry (for method see Montaser and Golightly, 1987). Analysts: F. W. Brown and Z. A. Brown. Determination of Pt, Pd, Rh and Au by atomic absorption spectrometry; following a fire-assay pre-concentration. Analysts: Norma Rait (Pt-group metals) and Roosevelt Moore (Au).

H_2O^- determined by weight loss at 105-110°C

H_2O^+ determined by measurement of hydrogen liberated at 1000°C on a Perkin-Elmer analyzer (for method see Skinner et al., 1981)

CO_2 total carbon determination as CO_2 by the Perkin-Elmer elemental analyzer

Rock type	Type 2						Types 3	4	5
No. in Fig. 6	16	8	8	12	Range %	Average %	10	9	8
Field No.	12	32	30	23			41	40	31B
SiO_2 %	52.0	53.5	53.4	53.1	52.0 - 53.5	53.0	46.6	50.7	54.0
Al_2O_3 %	14.8	14.1	14.4	14.2	14.1 - 14.8	14.4	15.5	12.6	20.0
Fe_2O_3 %	2.3	3.5	2.2	2.8	2.2 - 3.5	2.7	8.3	2.2	1.1
FeO %	7.5	7.8	8.6	8.2	7.5 - 8.6	8.0	5.6	7.7	4.4
MgO %	7.5	5.7	5.9	6.1	5.7 - 7.5	6.3	5.7	11.0	3.0
CaO %	10.9	9.5	9.6	9.8	9.5 - 10.9	9.95	7.4	12.3	3.5
MnO %	0.17	0.18	0.18	0.18	0.17 - 0.18	0.18	0.21	0.18	0.15
Na_2O %	2.0	2.5	2.5	2.4	2.0 - 2.5	2.35	3.1	1.6	3.1
K_2O %	0.64	0.91	0.83	0.81	0.64 - 0.91	0.80	1.6	0.37	4.8
TiO_2 %	1.0	1.3	1.2	1.2	1.0 - 1.3	1.18	2.4	0.87	0.90
P_2O_5 %	0.15	0.20	0.16	0.17	0.15 - 0.20	0.17	0.35	0.11	0.07
CO_2 %	0.05	0.23	0.08	0.10	0.05 - 0.23	0.12	0.29	0.08	0.41
H_2O^+ %	1.1	0.80	0.70	0.72	0.70 - 1.1	0.83	2.8	0.62	2.9
H_2O^- %	0.17	0.07	0.07	0.10	0.07 - 0.17	0.10	0.10	0.02	0.13
Total %	100.38	100.29	99.82	99.88		100.03	99.95	100.35	98.46
Pt ppb	7.6	8.0	11	8.5	7.6 - 11	8.8	<0.5	12	0.9
Pd ppb	5.6	3.7	5.7	6.5	3.7 - 6.5	5.4	<0.5	6.1	0.8
Rh ppb	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5
Au ppb	<10	<10	<10	<10	<10	<10	<10	80	<10

Table 2. Chemical composition of type-2 dolerite from the Foum Zguid region, Saharan part of the Anti-Atlas, Morocco. Location of samples given in Figure 6.

Analytical methods and names of analysts the same as in Table 1.

		Foum Zguid		Norilsk	
		Dolerite		"The upper contact dolerite"	
		Type 1	Type 2	Norilsk I	Norilsk II
SiO_2	%	50.3	53.0	51.61	51.10
Al_2O_3	%	13.3	14.4	14.98	15.38
Fe_2O_3	%	3.5	2.7	3.57	2.58
FeO	%	12.1	8.0	5.92	7.70
MgO	%	5.3	6.3	6.65	6.05
CaO	%	9.6	9.95	9.15	8.48
MnO	%	0.25	0.18	0.18	0.13
Na_2O	%	2.3	2.35	3.26	2.73
K_2O	%	0.60	0.80	1.10	1.29
TiO_2	%	1.5	1.18	1.64	1.66
P_2O_5	%	0.19	0.17	0.36	0.26
CO_2	%	0.12	0.12		
H_2O^+	%	0.65	0.83		
H_2O^-	%	0.09	0.10		

Table 3. Comparison of chemical composition of the dolerites (type 1 and type 2) from the Foum Zguid region, Morocco (average values from Table 1 and Table 2) with the composition of the "Upper contact dolerites" from the Noril'sk region, Siberian platform, USSR (from Dodin et al., 1971, p. 30).

	Dolerite		Hornfelse	Shear zone
	Type 1	Type 2		
No.in Fig.6	14	12	8	
Field No.	20C	23	25	21A,B,C
Ag	0.53	0.32	0.44	n.d.
B	n.d.	n.d.	69	15-20
Ba	110	240	210	150-300
Be	n.d.	n.d.	2.6	3
Ce	n.d.	n.d.	150	-
Co	51	47	19	0-15
Cr	70	27	84	150-200
Cu	150	130	6.0	30-50
Eu	n.d.	n.d.	5.7	-
Ga	11	14	12	-
La	n.d.	n.d.	120	30-70
Mn	3200	2600	1300	50-150
Mo	6.6	5.3	12	n.d.
Nb	16	11	9.4	0-20
Nd	n.d.	n.d.	/**	-
Ni	91	88	79	5-20
Pb	n.d.	19	30	70-100
Sc	54	46	11	7-20
Sn	n.d.	n.d.	/**	n.d.
Sr	200	380	540	150-500
Ti	9300	8500	3900	3000
V	300	260	39	150-300
Y	48	32	44	10-20
Yb	5.4	3.5	3.8	-
Zn	230	130	210	n.d.
Zr	140	120	110	70-200

n.d.= not detected - = not analyzed

MAJOR COMPONENTS:

Dolerite

See Tabs.1 and 2

Hornfelse (Sample 25)
(serpentinized and silicified limestone)

XO %: Si,Ca
X %: Al,Fe,Mg
0.X%: Ti,Mn

Shear zone

(Samples 21A,B,C)

XO %: Si
X %: Fe,Al,K,Na
0.X%: Mg,C a,Ti,P

/* = detected in heavy fraction:

Nd 41 ppm

Sn 6.1 ppm

Table 4. Minor and trace element contents in selected samples of dolerite, hornfels and a shear zone from the Foum Zguid region, Morocco. Location of samples given in Figure 6.

Semiquantitative emission spectrographic analysis. Samples of dolerite and hornfels analyzed by the Jarell-Ash 3.4 meter Ebert plane grating spectrograph ("Mark IV"), with a d.c arc and computerized evaluation of spectra (D. W. Golightly, Geochemical Branch, U.S. Geological Survey). The samples of shear zone analyzed by the Wadsworth mounted Jarell-Ash 1.5 meter spectrograph, using d.c.arc (G. Shannon, Specom Services, W. A. Bowes,Inc., Steamboat Springs, Colorado).

Besides magmatic differentiation, however, the separation of cobalt, nickel and Pt-group metals may also be conditioned by other factors. One of them is tectonic uplifting of blocks of basic or ultrabasic rocks from deeper levels, followed by their hydrothermal alteration (serpentinization and other). The occurrence of both the cobalt district of Bou Azzer and the Foum Zguid region within the same broad field of gravity highs (fig. 4) may indicate metallogenic specialization of the underlying upper mantle and requires further study.

Concentration of Nickel and Cobalt in the Southwestern Part of the Foum Zguid Region

At locality No. 8, near the southwestern limb of the Hamsailikh anticline, we have discovered a small outcrop of a relatively acidic intrusive, referred to as "Type-5" in this paper. The following criteria indicate that this intrusive represents a relatively acidic differentiate of the same basic magma from which the dolerites of the Foum Zguid region originated: (1) The intrusive occurs in the immediate vicinity of Type-2 dolerite, the prevailing magmatic rock in this part of the Foum Zguid region; (2) Two other basic rocks, Type-3 and Type-4 (localities Nos. 10 and 9), occur in the vicinity; (3) Concentration of sulfides of nickel and cobalt took place inside and outside the intrusive; (4) The contact aureole of this intrusive, with concentration of titanium-rich minerals, is typical for differentiates of a basic magma. The above characteristics give the Type-5 intrusive a special importance for appreciation of mineral potential of the Foum Zguid region.

As explained in the preceding section, the composition of the Type-5 intrusive shows similarity with plagiodolerite from the Noril'sk area, but has lower contents of CaO and MgO and a higher content of K_2O. The higher content of K_2O and, possibly, the lower content of CaO are related to the introduction of potassium and the removal of part of the calcium by the process of superimposed K-metasomatism.

The intrusive (Type-5) is of a rather light to medium grey color, with "schlieren" hosting pyrrhotite $Fe_{1-x}S$ and associated pentlandite $(Ni, Fe)_9S_8$, the latter with Co-contents of 2 to 3% (electron microprobe analysis, K. Fredriksson).

While the changes of the Devonian limestones are insignificant at the contact with the Type-2 dolerites, there is a strong alteration aureole at the contact with the Type-5 intrusive. The alteration manifests itself as hydrothermal serpentinization passing over into a silicate hornfels. The electron microprobe study (K. Fredriksson) has revealed high concentration of titanium in the alteration zone (perovskite $CaTiO_3$ in association with wollastonite $CaSiO_3$, two varieties of andradite $Ca_3Fe_2Si_3O_{12}$, one with about 13% TiO_2 (melanite or schorlomite* and other minerals.

A fine dissemination of a sulfide, mostly in grains of a few micron size, occurs in the contact aureole of the Type-5 intrusive and is of special interest for high contents of nickel and cobalt (Table 5).

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*Full analysis will be given in a separate paper.

The ratio of (Ni+Fe+Co) to sulphur in grain No. 4 (Table 5), approximately $(Ni,Fe,Co)_{8.2}S_8$, is similar to the metal to sulphur ratio in pentlandite, while grains Nos. 2 and 3 are deficient in metal; No. 3 approximately $(Ni,Fe,Co)_{8.1}S_9$. This latter phase may be the high-temperature (rare) monosulfide solid solution polymorph of pentlandite or a new mineral. An X-ray study is needed.

The above concentration of nickel and cobalt inside the intrusive body (pyrrhotite-pentlandite association) and in the contact zone (in a disseminated Ni-Fe-Co sulfide), indicate that differentiation of basic magma occurred beneath the SW-part of the Foum Zguid region and led to separation of a part of cobalt and nickel from the melt. The Type-1 and Type-2 dolerites can be considered as products of early stages of differentiation and the Type-5 intrusive as belonging to a later stage, during which separation of a part of Ni and Co occurred. The above observations indicate that a more substantial separation of these metals may have taken place at a depth beneath the area hosting locality No. 8 (fig. 6). Drilling is needed to check for the possible presence of a major intrusive body with economic concentrations of Ni, Co and possibly Pt-group metals, similar to that in Noril'sk, where such a body occurs beneath a "screen" of dolerites (Vilensky et al., in Smirnov, ed., 1976, p. 100).

Results of spectrochemical analysis of a homogenized sample of the hornfels (with serpentinization of the original limestone) from the contact zone of the Type-5 intrusive is

Analysis No.	Fe	Co	Ni	Cu	S	SiO_2	CaO	CO_2 *	Total %
1	19.2	5.4	37.1	tr.	33.8	0.3	0.8	0.6	97.2
2	17.7	5.8	38.0	tr.	35.5	0.7	0.9	0.7	99.3
3	16.2	6.0	37.5	tr.	36.4	1.4	1.0	0.8	99.3
4	19.3	4.8	38.6	n.d.	33.9	n.d.	n.d.		

n.d.= not determined * = calculated

tr. = traces ($\lesssim$0.3%)

Table 5. Electron microprobe analyses of Ni-Fe-Co sulfide grains, disseminated in the contact zone of Type-5 intrusive (Table 2) from Foum Zguid region, Morocco. Analysts: J. Nelen and K. Fredriksson.

The contents of SiO_2, CaO and CO_2 indicate heterogeneous admixtures of silicified limestone (hornfels).

shown in Table 4. Of particular interest are: The content of chromium (84 ppm), which is higher than in the Type-1 and Type-2 dolerites; the presence of a group of rare earth elements (Ce, La, Y, Yb and Eu); detection of Be and Mo which are characteristic for later stages of differentiation; detection of boron (69 ppm) which is known from the serpentinized ultrabasics hosting the cobalt ores of the Bou Azzer district (Leblanc, 1981).

Trace amounts of nickel (5 to 20 ppm) and cobalt (up to 15 ppm), as well as of chromium (150-200 ppm) and boron (15-20 ppm), have also been found in samples of a shear zone of argillitic material developed near the boundary between the Ordovician and Silurian sediments in the inner parts of the Hamsailikh anticline (locality No. 7 in fig. 6, and Table 4).

Low-level Gold Concentrations in the Foum Zguid Region

Type-1 dolerites: Out of 10 samples analyzed, only one shows gold content above the detection limit of 0.01 ppm (Table 1). It is a sample from locality No. 13 (fig. 6) with 0.04 ppm Au and the highest contents of Pt and Pd.

Type-2 dolerites: None of the four samples analyzed has revealed a gold content higher than the detection limit of 0.01 ppm.

Types-3, 4 and 5 basic magma differentiates: Type-4 basic rock has revealed a gold content of 0.08 ppm. which correlates with the relatively highest contents of Pt and Pd. The rock

has, at the same time, the highest Ca and Mg contents of all the 17 samples of magmatic rocks of the Foum Zguid region.

Gold contents in the vein quartz and in silicified limestones: In the northeastern tip of the Hamsailikh Range, where the axis of the anticline (followed by a fault) changes its strike from NE-SW to N-S, structural conditions were favorable for opening of fractures in the brittle Ordovician quartzites. The fractures were filled in by a low temperature hydrothermal quartz, often containing considerable amounts of a yellow-brown limonite, giving rise to what is referred to in the German literature as the "Eisenquarz" (localities Nos. 3 and 4 in fig. 6). Adjacent to the slope of the Hamsailikh Range, in the flat desert area, a large amount of a low-temperature opalite-like silica occurs (locality Nos. 5 in fig. 6). This type of silica resembles some of the opalites from the low-grade gold deposits in northern Nevada. The high CaO and Co_2 contents, together with the contents of Si and Mg indicate that the opalite-like silica from locality No. 5 (fig. 6) is a partially silicified dolomitic limestone (samples 50A and 50B).

The gold contents of the vein quartz (samples Nos. 48, 49A and 49B) are in the range of 0.02 - 0.06 ppm, and the opalite-like silica (sample No. 50A) gave 0.03 ppm Au. Although these gold contents are very low, they represent an anomalous concentration of Au. Similarly low gold contents were found in some opalites in northern Nevada and were used as one of the indicators in the prospecting for gold deposits. For instance, the first gold contents detected in the opalites from the Jasperoid

Peaks in Pershing County, Nevada, were in two ranges of values 0.05 - 0.08 ppm and 0.15 - 0.64 ppm Au (J. Kutina, 1980; W. A. Bowes & J. Kutina, in preparation). The gold contents in the vein quartz and the opalite-like silica from the northern tip of the Hamsailikh Range (0.02 - 0.06 ppm Au) correlate with the first group of gold values in samples from the Jasperoid Peaks, Nevada. The locality deserves further study.

CONCLUSIONS

1. Two sets of structural boundaries, one trending north-south and the other east-west, have been distinguished in the isostatic gravity anomaly map of Morocco. These boundaries are deep-seated, defining blocks in the structure of Morocco.

2. The shape of the High Atlas Mountains (fig. 3), superimposed on the isostatic gravity anomaly map (fig. 4), shows that the trough or subsiding depression in which Triassic and Jurassic sedimentation proceeded, was controlled, to a considerable degree, by a pattern of deep-seated structural boundaries.

3. The intersections of some of the N-S and E-W boundaries guided magmatism and predetermined favorable places for concentration of metals.

4. Two of the N-S boundaries, extending transversely to the High Atlas Mountains, are manifested as "steps" in the morphology of the mountain belt (fig. 3). An example is presented, showing concentration of metals at the intersection of one of

these boundaries with the South Atlas Fault which delineates the High Atlas Mountains on the southern side (fig. 5).

5. One of the N-S trending boundaries, following a longitude close to 7°W, extends farther south into the Saharan parts of the Anti-Atlas. Here, south of the town Foum Zguid, major concentration of gabbro-dolerite rocks of early Mesozoic age occurs. The location of this center of magmatic activity correlates with the intersection of the above N-S trending boundary with a major boundary of a latitudinal trend, the latter extending close to 29°30'N.

6. Five differentiates of a basic magma, with two distinct types of dolerite as the prevailing rock have been distinguished. The more basic Type-1 dolerite occurs in the northern parts and the less basic Type-2 dolerite is the prevailing rock type in the southern parts of the Foum Zguid region (Tables 1 and 2, fig. 6).

7. Significant similarities have been found between the composition of the two types of dolerite from Foum Zguid and the "Upper contact dolerites" of the Noril'sk-Talnakh region in Siberia (Table 3). The latter, according to Vilensky et al. (in Smirnov, 1976), form a "screen" above a major intrusive body hosting the Cu-Ni sulfide ores. The above similarity is of particular interest for the Foum Zguid region, because the sulfide ores of the Noril'sk-Talnkah region contain significant concentrations of Pt-group metals.

8. There is also an important similarity in the structural setting of the Foum Zguid and the Noril'sk-Talnakh

gabbro-dolerite magmatism: both are products of an early Mesozoic tectono-magmatic reactivation that occurred near the border of an old craton or platform (the West African craton in the case of the Foum Zguid and the Siberian platform in the case of Noril'sk-Talnakh).

9. One of four magmatic differentiates, occurring in the SW-part of the Foum Zguid region (near the SW-tip of the Hamsailikh anticline, fig. 6), contains local concentrations of pyrrhotite $Fe_{1-x}S$ and pentlandite $(Ni, Fe)_9S_8$, the latter with 2 to 3% Co. A dissemination of a sulfide with high contents of Ni and Co (Table 5) occurs in the contact zone of the intrusive, where the Devonian limestones were subjected to hydrothermal serpentinization and transformation into hornfels. An electron microprobe study has revealed high concentrations of titanium in the contact zone, rich in perovskite $CaTiO_3$, occurring in association with wollastonite $CaSiO_3$, andradite $Ca_3Fe_2Si_3O_{12}$ (one variety containing about 13% Tio_2) and other minerals.

Spectrographic analysis of the serpentinized limestone has revealed a trace element association with several rare earths (Ce, La, Y, Yb, Eu). Of special interest is the content of boron (69 ppm) which is also known from the serpentinized body of ultrabasics in the cobalt district of Bou Azzer (Leblanc, 1981). Boron (15-20 ppm) has also been detected, along with traces of cobalt, nickel and chromium, in a shear zone in the SW-part of the Foum Zguid region (Table 4).

10. The above similarity in the tectonic setting and chemical composition of magmatic differentiates which exists between the Foum Zguid and the Noril'sk-Talnakh regions, indicates that a differentiated body of gabbroic rocks may also occur beneath the "screen" of dolerites of the Foum Zguid region. The occurrence of Ni- and Co-bearing sulfides inside and outside one of the magmatic differentiates suggests that the differentiation of the basic magma had, in the SW-part of the Foum Zguid region, achieved a stage capable to concentrate these metals. A drilling at locality No. 8 (fig. 6) is needed to examine the nature of magmatic differentiates beneath the screen of dolerites,and a possible, more substantial concentration of Ni, Co and Pt-metals at deeper levels.

11. It is of particular interest that both the gabbro-dolerite magmatism of the Foum Zguid region (which is of early Mesozoic age and contains a Ni-Co target), and the serpentinized ultrabasics of the Bou Azzer region (which are of Precambrian age and host a superimposed cobalt-arsenide mineralization), occur within the same field of gravity highs of the isostatic gravity anomaly map (fig. 4). This may reflect geochemical specialization of the underlying upper mantle and a potential for concentration of cobalt and nickel in the crust during tectono-magmatic processes at different periods of time. A broader regional study is recommended.

ACKNOWLEDGMENTS

The study was conducted under the project "Block Structure of the Lithosphere and its Role in the Genesis and Distribution of Metallic Ore Deposits," funded by the U.S. Agency for International Development (Grant No. PDC-5542-G-SS-5073-00 through The American University, and Grant No. 936-5542 through the Geological Survey of Morocco). We express our sincere thanks to the Office of the Science Advisor, AID, Washington, in particular Dr. M. Rechcigl and Dr. Irvin M. Asher, and to the AID Mission in Rabat,in particular Dr. Robert A. Kahn, for the interest in our work and the support we have received.

Our gratitude also belongs to Mr. Josiah Royce, Coordinator of Mineral Activities at the U.S. Trade and Development Program, for numerous discussions about the methodology used in our study and for valuable advice.

The Geological Survey of Morocco, in cooperation with the Geological Offices in Marrakech and Ouarzazate, have facilitated our two expeditions to the Saharan parts of the Anti-Atlas. Best thanks are given, in particular, to Dr. Mohammed Bensaid, Director, and Mr. M. F. Hamouda, Associate Director of the Survey.

Mr. Byron Berger, Chief of the Branch of Geochemistry, U.S. Geological Survey, gave support to the analytical work presented in this paper. This support is gratefully acknowledged.

Thanks to Mr. Pete Dunn, Department of Mineral Sciences, Smithsonian Institution, for X-ray identification of a titaniumrich variety of andradite from the Foum Zguid region.

The study, since its early stages, has received valuable support from Mr. Moussa Saâdi, then-Minister of Energy and Mines, Rabat, and benefited from numerous discussions with Dr. M. Bensaid, Director of the Geological Survey of Morocco.

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PART V

Bouguer Gravity Map and Related Filtered Anomaly Maps of Morocco

by

Thomas G. Hildenbrand, Robert P. Kucks, Mohamed F. Hamouda*
and Abderrahmanne Bellot*

Résumé

La plupart des données gravimétriques couvrant les provinces Nord du Maroc ont été collectées à partir de levés réalisés dès 1949.

La carte gravimétrique du Maroc au 1/500.000 en sept feuilles (Province du Nord) a été publiée en 1969, et sa notice explicative en 1984 (Van Den Bosch: Notes et Mémoires du Service Géologique du Maroc, n° 234 et 234 bis)

D'autres levés systématiques complémentaires de semi-détail ont été réalisés par la Direction de la Géologie et on interessé essentiellement le Rif occidental et les régions de Zagora et de Foum Zguid (Anti-Atlas Oriental).

Dans le cadre du projet "Block structure of the lithosphère and its rol in the distribution of metallic ore deposits" réalisé en collaboration entre le Service Géologique du Maroc et l'U.S.G.S l'ensemble des levés gravimétrique a été intégré dans la nouvelle version de la carte gravimétrique du Maroc au 1/1.000.000 (Provinces du Nord), et ont ainsi abouti à la réalisation des cartes suivantes:

- Carte gravimétrique de l'Anomalie de Bouguer au 1/1.000.000,
- Carte gravimétrique de l'Anomalie de Bouguer au 1/2.000.000,
- Carte gravimétrique du Rif Occidental au 1/2.000.000,
- Carte du gradient vertical au 1/1.000.000,
- Carte de distribution des points de mesures au 1/1.000.000,
- Carte gravimétrique de l'Anomalie de Bouguer au 1/1.000.000 (Couleur),

- Carte regionale et résiduelle (R = 100 km) au 1/2.000.000 (Couleur),
- Carte regionale et résiduelle (R = 250 km) au 1/2.000.000 (Couleur),
- Carte du gradient vertical au 1/2.000.000 (Couleur),
- Carte du gradient horizontal au 1/2.000.000 (Couleur),
- Carte du gradient vertical (vue oblique NE) au 1/2.000.000 (Couleur),
- Carte du gradient vertical (vue oblique SW) au 1/2.000.000 (Couleur)

Parmi ces documents, sept cartes sont présentées dans cette publication (cartes B à H).

Introduction

A set of gravity anomaly maps of Morocco are presented here to assist in identifying the boundaries and extent of major tectonic provinces No attempt is made to interpret these maps. Rather, the maps are shown as a data source for regional geologic and geophysical framework studies of Morocco.

In addition to an index map (Map A) and the simple Bouguer gravity map (Map B), various filtered gravity anomaly maps (Maps C-H) are provided. Analysis of geophysical data by filtering involves conversion of the data into a form that enhances particular anomaly characteristics, such as wavelength and trend. Three 3 filtering operations were made: (1) regional-residual anomaly separation by wavelength filtering; (2) first vertical derivative, to sharpen or resolve anomalies of small areal extent; and (3) horizontal gradient magnitudes, to delimit lithologic or structural boundaries. Although a considerable amount of information can be obtained by studying these filtered anomaly maps, each has limitations and thus should be used with caution and only in a qualitative analysis. More detailed discussions on the usefulness of the compiled filtered anomaly maps are given below.

*Ministère de l'Energie et des Mines, Direction de la Geologie, Agdal Ouest BP 6208, Rabat, Maroc

Data Reduction

The primary source of data is from a gravity study by Van den Bosch (1971). The data shown here were in two forms -- digital form and analog form (shown by black dots and yellow dots, respectively on Map A). In the digital data file, 8501 stations are from Van den Bosch's work and 2392 stations were collected by the Moroccan Ministère de l'Énergie et des Mines (Bellot, 1985; Bellot and Hamouda, 1988) in two small regions (near lat. 35°30'N and long. 5°30'W; and lat. 30°15'N and long. 6°30'W). Principal facts (observed gravity, elevation, latitude, and longitude) for the total 10,893 stations were provided by the Moroccan Ministère de l'Énergie et des Mines. On compiled simple Bouguer gravity maps Van den Bosch displayed several areas where the coverage was very dense; the data in those areas were available only in analog contour form. In order to incorporate the information in these areas of dense coverage, the simple Bouguer gravity contours on Van den Bosch's maps were digitized and combined with the digital data base of 10,893 stations discussed above. To avoid problems in merging the two different data types, the regions of digitization of the analog data were trimmed back 5 km from any gravity station with known principal facts.

All gravity values are referenced to the International Gravity Standardization Net of 1971 (Morelli, 1974). Bouguer gravity anomaly values were computed using the 1967 gravity formula (International Association of Geodesy, 1967) with a reduction density of 2.67 g/cm^3. No terrain corrections were made. A grid with an interval of 2 km was derived from the irregularly spaced Bouguer anomaly values by means of a computer program (Webring, 1981) based on minimum curvature (Briggs, 1974). The data were plotted on a Lambert conformal projection with standard parallels of 33°N and 45°N and with a

central meridian of 6°W. All data sets were plotted using Applicon Incorporated[1] color proprietary software.

Bouguer Gravity Map

The following short discussion is intended to give the reader a sense of significance of Bouguer gravity anomalies. It leaves out many technical details of the gravity reduction process. For a more complete discussion, the reader is referred to Dobrin (1976) and Nettleton (1976).

Measurements of gravity are normally compared with the values that would theoretically be obtained if the measurements were made on an idealized surface (the reference ellipsoid) approximated by sea level. If only the latitude and the vertical distance of the gravity observation above sea level are compared, the difference between observed and theoretical gravity is known as the "free-air" anomaly; if the mass between the point of observation and sea level is also taken into account, then the difference is known as the "simple Bouguer" anomaly. Simple Bouguer anomalies of Morocco are shown in Map B.

Filtered Gravity Anomaly Maps

Regional-residual gravity anomaly separation

A Bouguer gravity anomaly map exhibits the effects of source bodies of varying densities, shapes, dimensions, and burial depths. In any region the gravity field is usually caused by the superposition of the overlapping gravitational effects of many bodies whose individual gravity anomalies may be difficult to separate. The terms "residual" and "regional" are somewhat arbitrary, depending upon the map scale and source bodies of interest, but are commonly used to make a distinction between anomalies arising from local, thin

[1]Use of a specific brand name does not necessarily constitute endorsement of the product by the U.S. Geological Survey

masses and those arising from larger and usually thicker features, respectively. There are many methods for preparing regional and residual maps (Grant, 1972). For our study we have chosen a general wavelength (or frequency) filtering method to obtain a separation of long-wavelength anomalies (regional) that are associated with large-crustal or subcrustal features, from short-wavelength anomalies (residual) that are associated with shallow features. It should be noted that the separation is not complete and, in particular, long-wavelength anomalies can be caused by broad, shallow features. The short wavelength anomalies on the residual maps emphasize the contributions of shallow sources, but in many cases the anomaly amplitudes are distorted by the removal of the long wavelengths (Kane and Godson, 1985).

The gridded data were transformed to the wave number domain using the fast Fourier transform and then were low-pass filtered (Hildenbrand, 1983). The low-pass filter was a simple rectangular window (passing long wavelengths), modified so that the gain of the filter drops from one to zero along a ramp centered at the cut-off wavelength. The ramp was located between 75 and 125 km; the cutoff wavelength was 100 km. The regional (low-pass) field (Map C) was calculated by taking the inverse Fourier transform of the product of the low-pass filter and the Fourier transformed Bouguer gravity field. The residual field (Map D) was calculated by subtracting the computed regional field from the unfiltered gravity field.

The effectiveness of the wavelength filtering process in calculating regional-residual gravity fields is partly a function of the relation of the cut-off wavelength of the filter and the maximum depth of sources. The residual gravity map (Map D), composed of wavelengths of 100 km and less, exhibits anomalies which probably are associated primarily with sources within the crust; the effects of broad, shallow sources, however, are not present on

this map. Conversely, the complementary low-pass map composed of wavelengths of 100 km and greater (Map C) generally represents the effects of deeper sources, such as the shape of the crust-mantle boundary and anomalous masses in the mantle and middle and lower crust, although the contributions of any broad, shallow masses are also included.

A similar set of regional-residual maps using a cutoff wavelength of 250 km is shown in Maps E and F.

First vertical derivative

In areas of steep, broad gravity gradients, low-amplitude and spatially restricted anomalies (related to near-surface features) and other subtle features or trends tend to escape notice on the Bouguer gravity map. This is especially the case for features having amplitudes less than 5 mGal, which is the color contour interval of Map B. To resolve short-wavelength anomalies, a first vertical derivative filter (Bhattacharyya, 1965) was applied to the gravity data. The vertical derivative anomaly map shown in Map G thus enhances local features and reduces the effects of broad regional gradients.

Horizontal gravity gradient

The magnitude of the horizontal gravity gradient g' is determined by a computer program (R. W. Simpson, U.S. Geological Survey, unpub. computer program) using the following equations:

$$|g'(x,y)| = \sqrt{\frac{\partial g}{\partial x}^2 + \frac{\partial g}{\partial y}^2},$$

$$\frac{\partial g}{\partial x} = \frac{g_{i+1,j} - g_{i-1,j}}{2\Delta x}$$

$$\frac{\partial g}{\partial y} = \frac{g_{i,j+1} - g_{i,j-1}}{2\Delta y}$$

where x is the longitudinal coordinate, y is the latitudinal coordinate, and $g_{i,j}$ is the pseudo-gravity field defined at grid point i,j. Grid intervals in the x-direction and y-direction are Δx and Δy, respectively.

Gravity gradient maxima occur immediately over steep or vertical boundaries separating rock masses of contrasting densities. On the gravity gradient map, lines drawn along ridges formed by enclosed high horizontal gradient magnitudes correspond to these boundaries. If the boundaries dip, or if contributions from adjacent sources are significant, the maximum gradient will be shifted a certain distance from the boundary (Grauch and Cordell, 1987).

Acknowledgement

The maps are result of cooperation between the Branch of Geophysics, U.S. Geological Survey, and the Geological Survey of Morocco. The work has been accomplished under a joint U.S. - Moroccan project "Block Structure of the Lithosphere and Its Role in the Genesis and Distribution of Metallic Ore Deposits" funded by the U.S. Agency for International Development (Grant No. PDC-5542-G-SS-5073 00). Geological results of the same project, using Van den Bosch's (1971, 1981) isostatic anomaly maps to distinguish boundaries of lithospheric blocks, are given in Bensaid and others (1985) and Kutina and others (1988).

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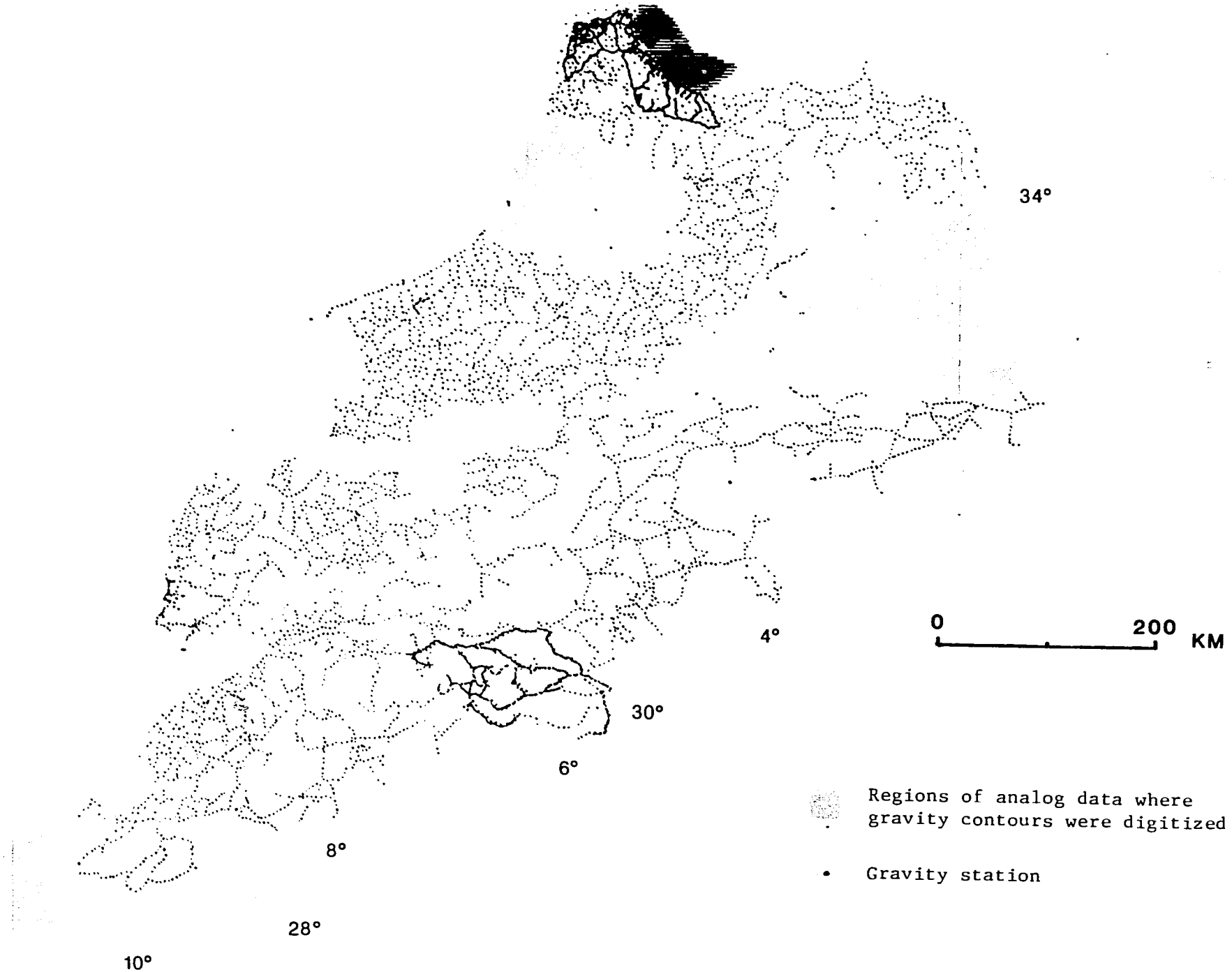
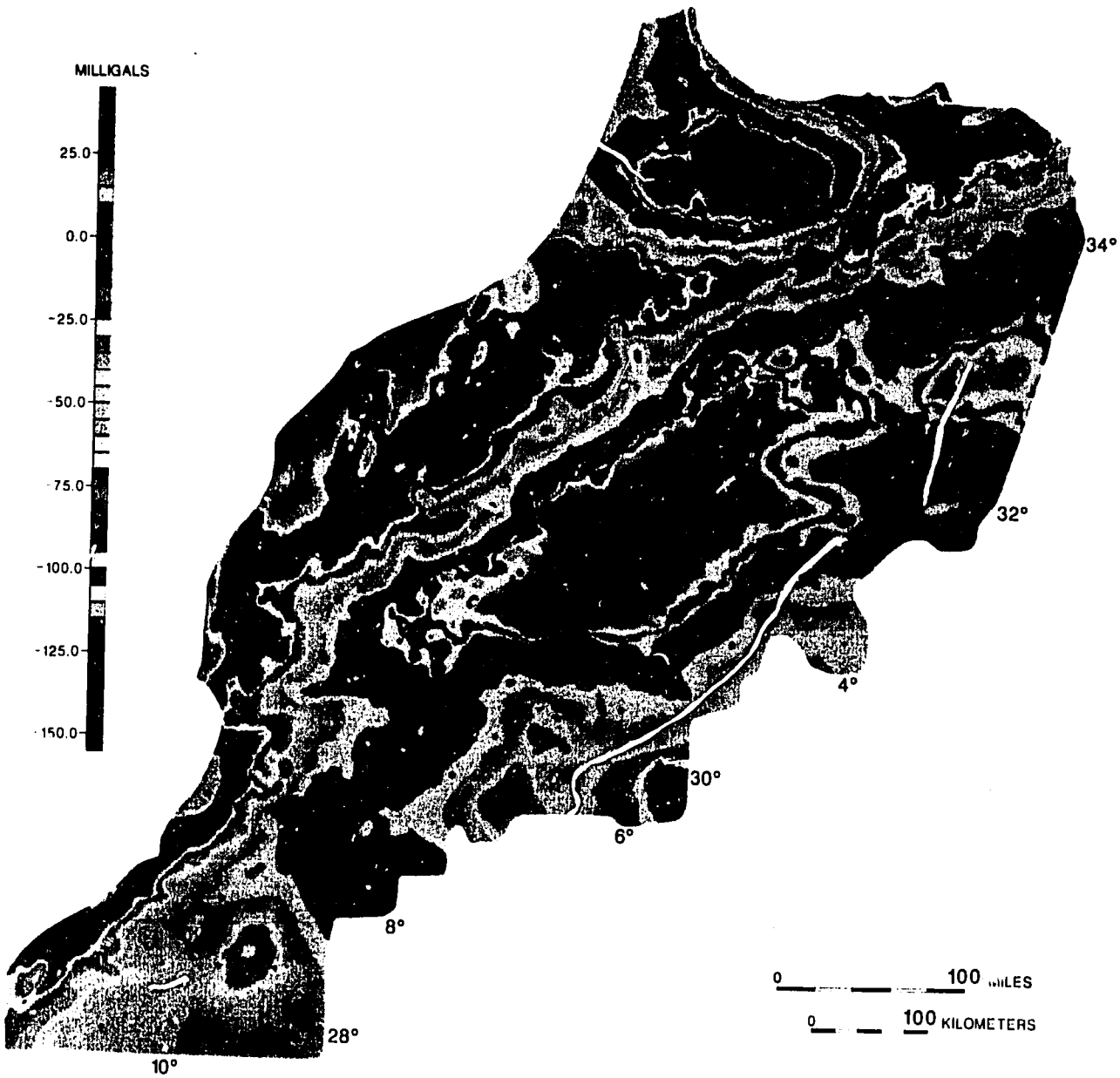
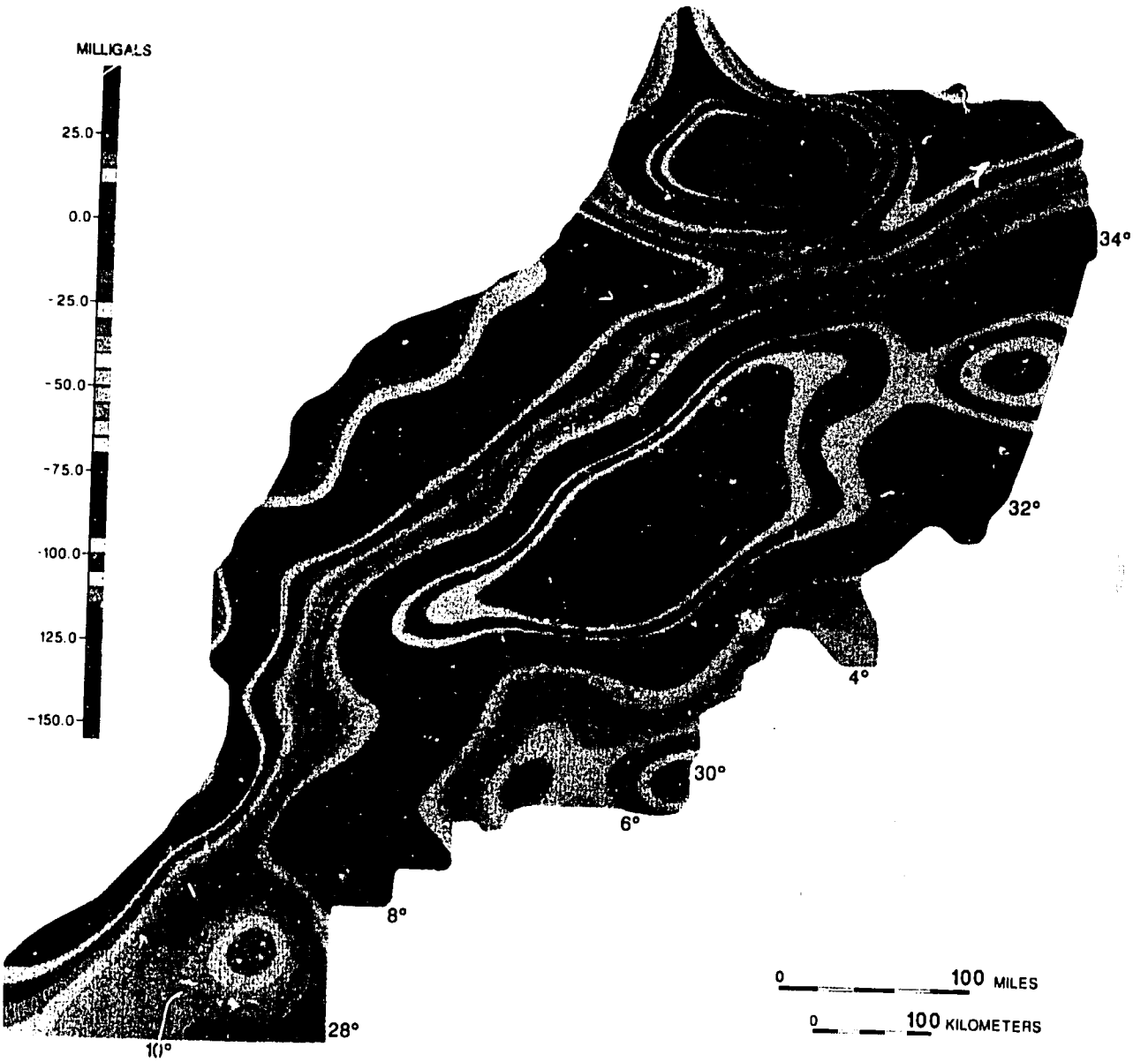


MAP A - INDEX MAP

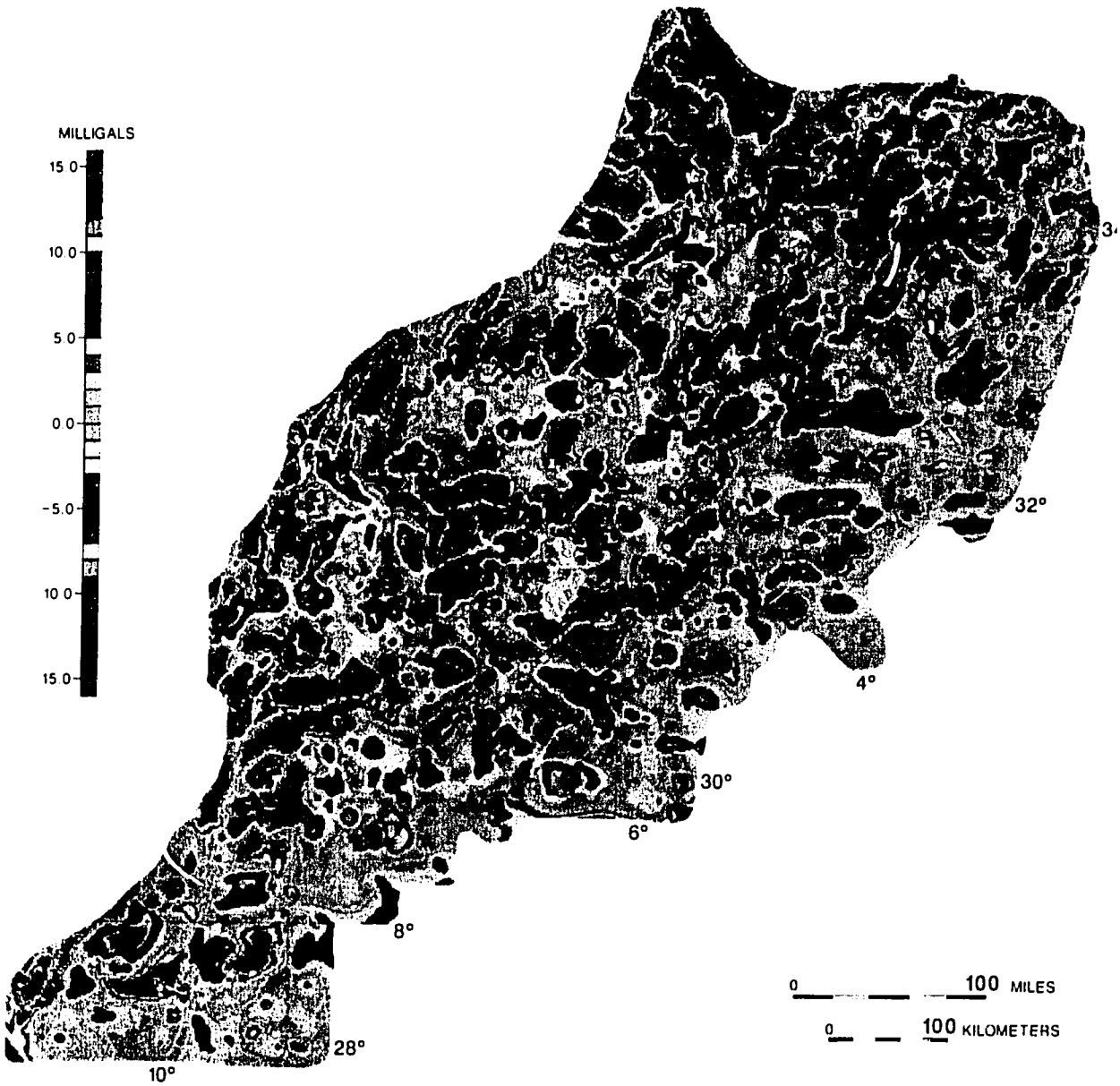
MAP B - BOUGUER GRAVITY



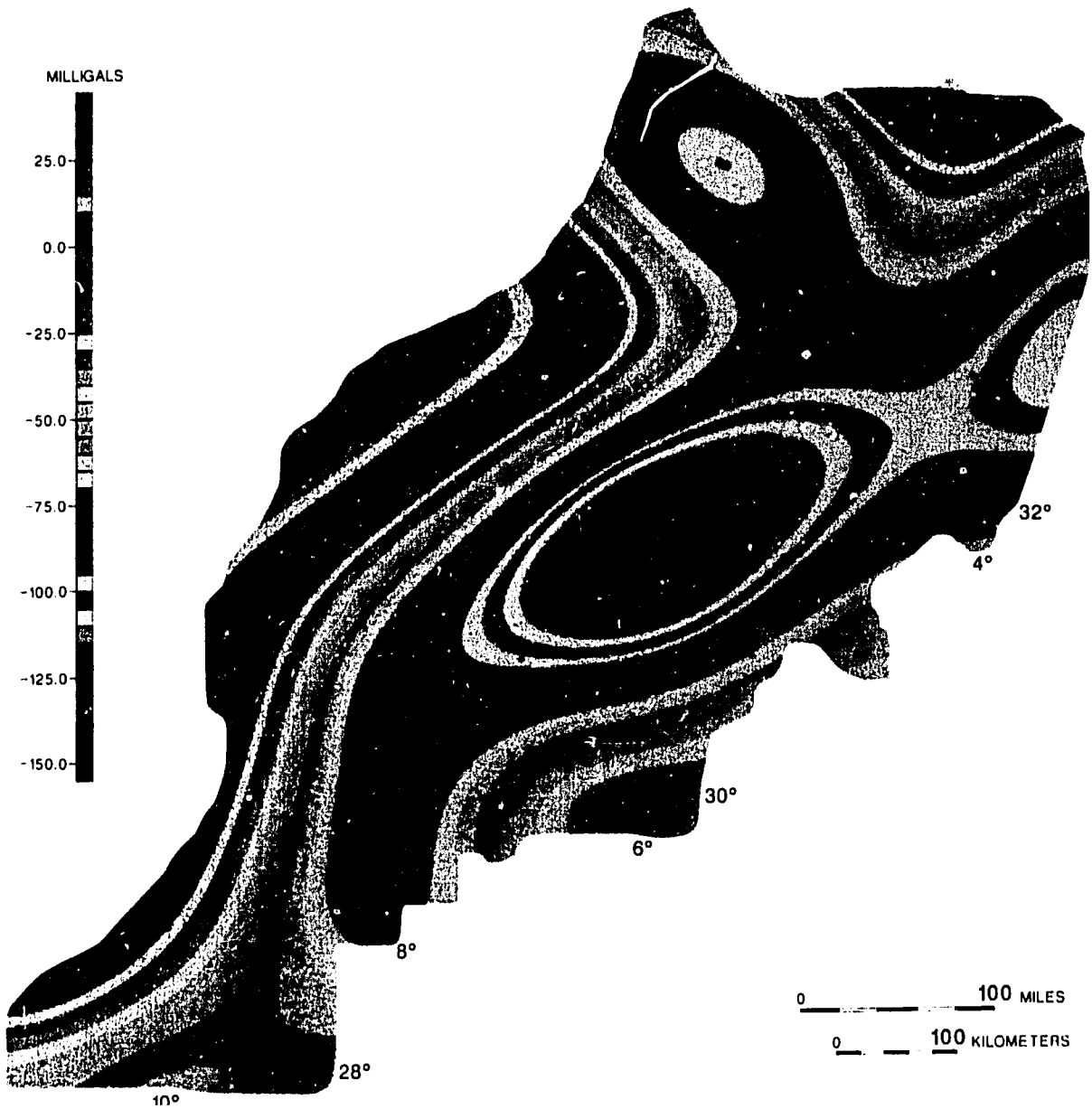
MAP C - REGIONAL GRAVITY: WAVELENGTHS >100 KM



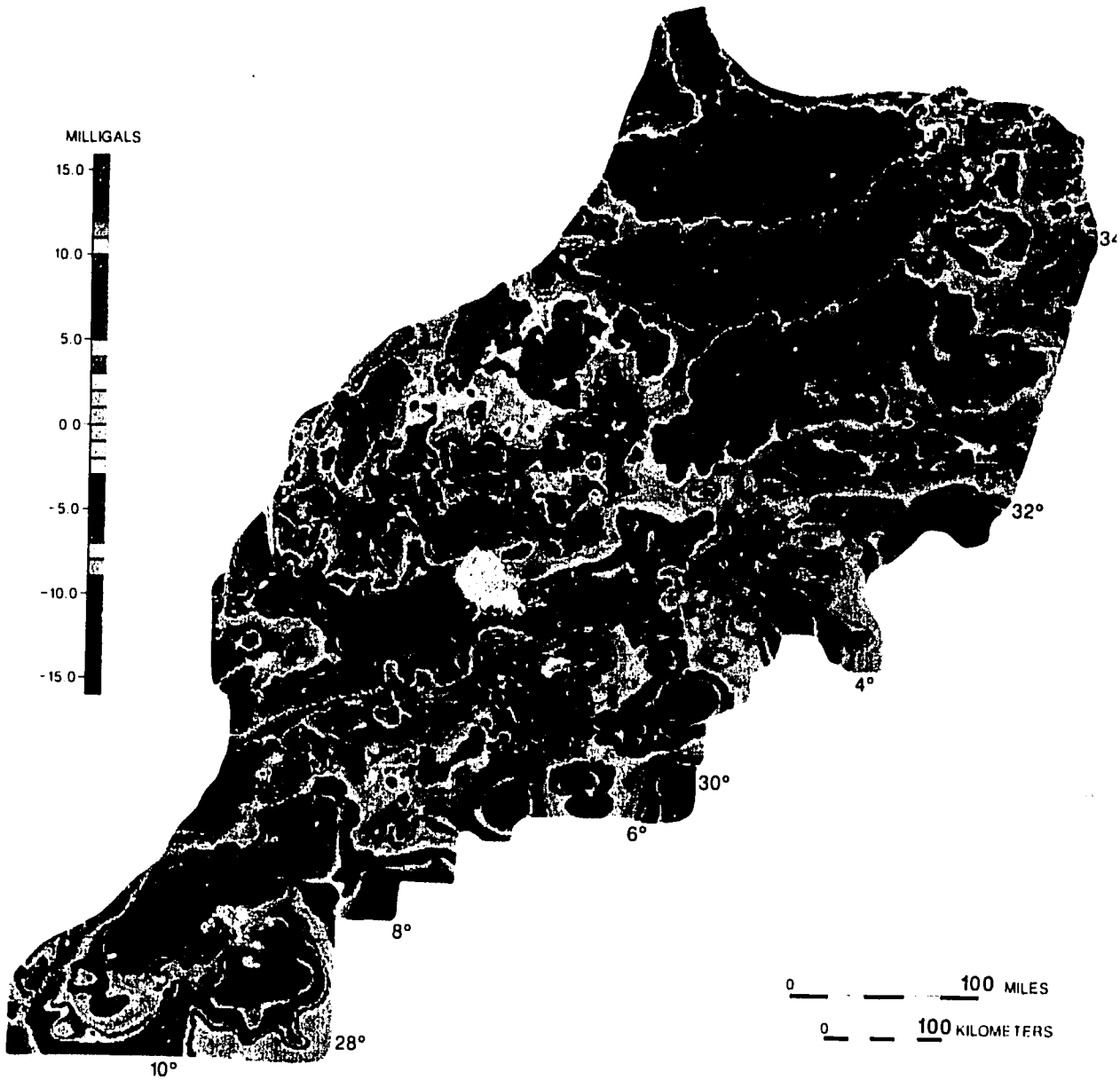
MAP D - RESIDUAL GRAVITY: WAVELENGTHS <100 KM



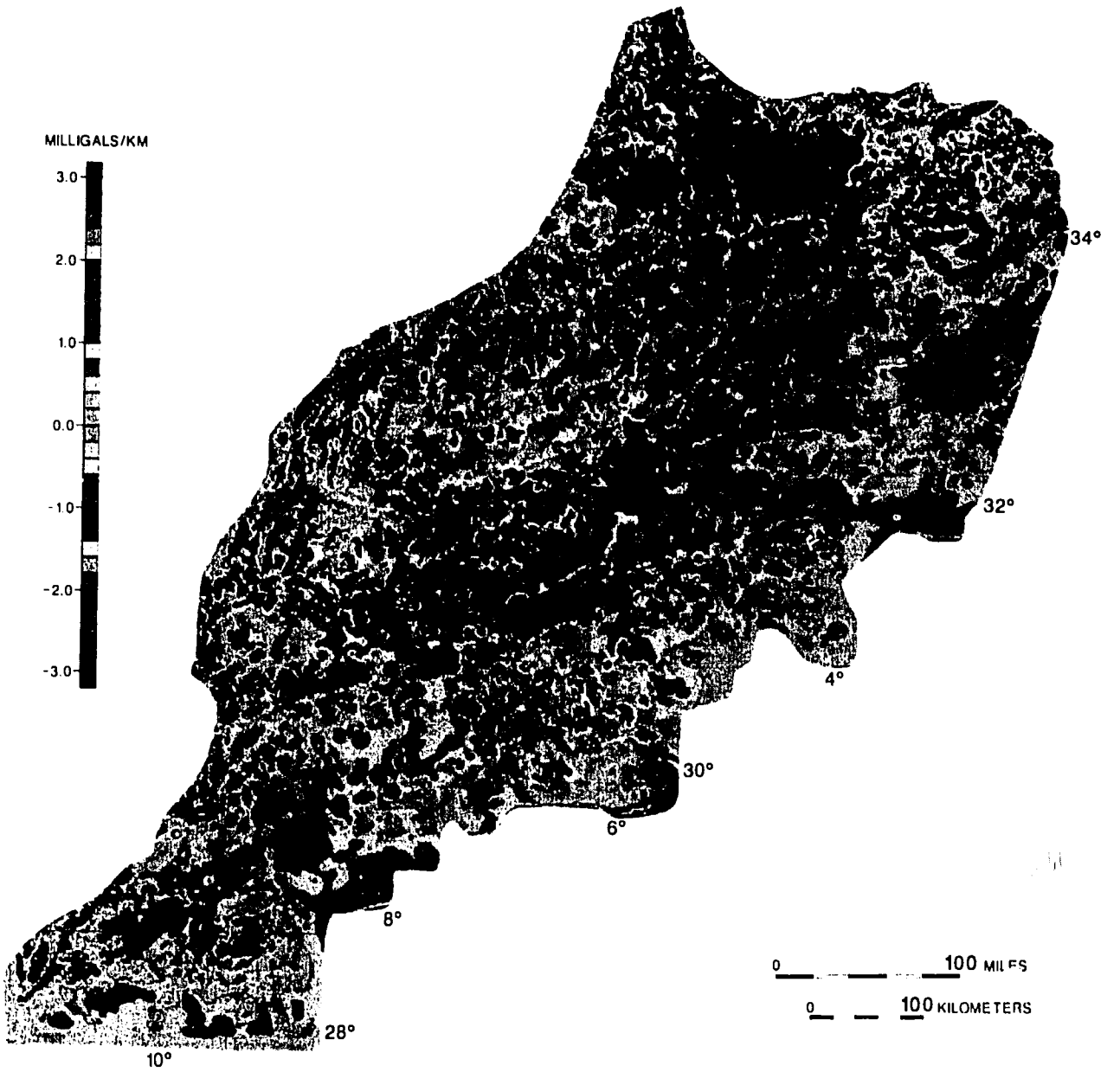
MAP E - REGIONAL GRAVITY: WAVELENGTHS >250 KM



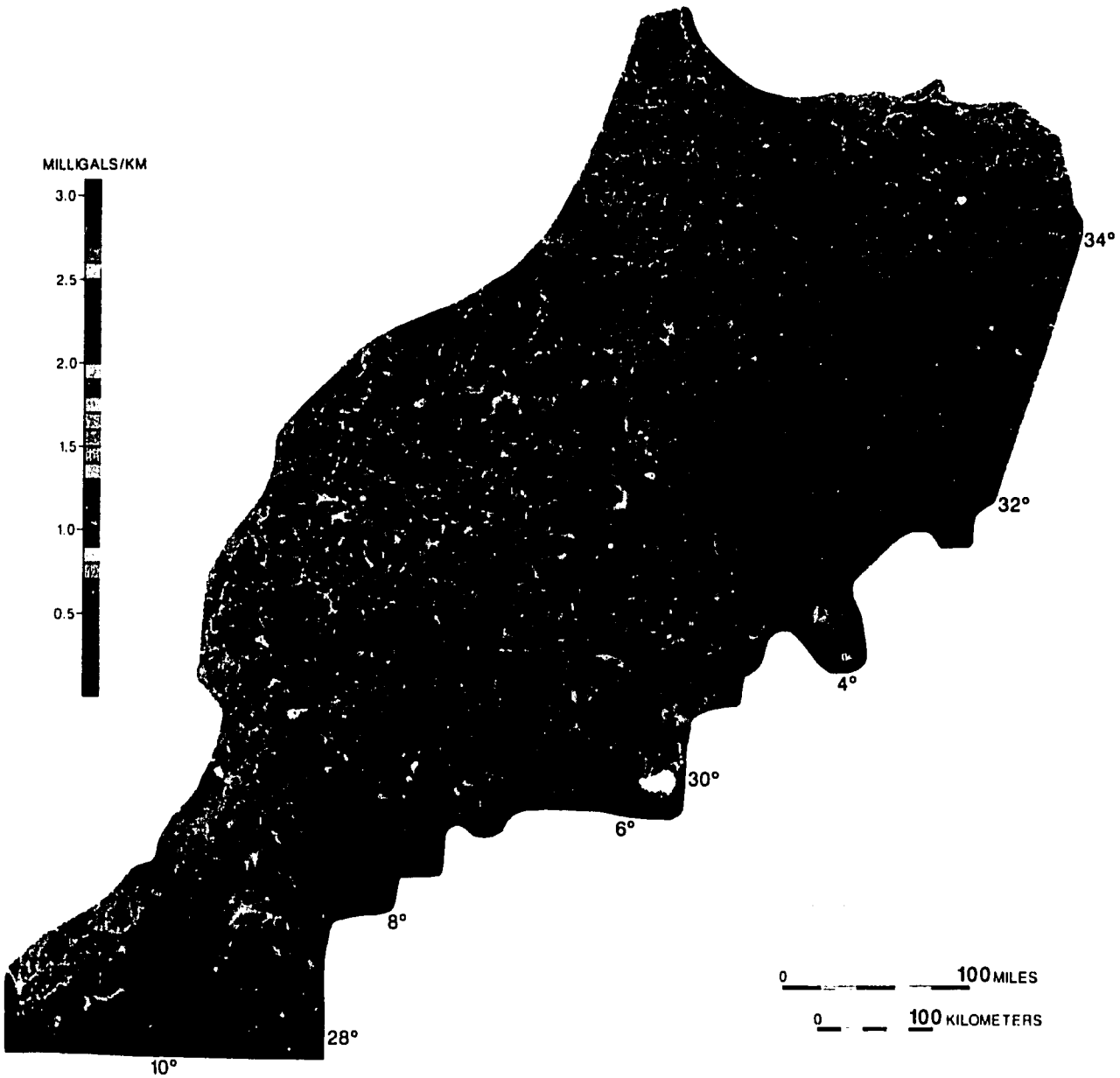
MAP F - RESIDUAL GRAVITY: WAVELENGTHS <250 KM



MAP G - GRAVITY: 1ST VERTICAL DERIVATIVE



MAP H - GRAVITY: HORIZONTAL GRADIENT



PART VI

Criteria indicating a block structure of the upper mantle and its role in metallogeny

Jan Kutina

Laboratory of Global Tectonics and Metallogeny, c/o Department of Chemistry, The American University, Washington, DC 20016, USA

With 6 figures

Abstract. A correlation has been found between the spacings of the deep-seated E-W boundaries of the basement of the United States, the E-W fracture zones of the East Pacific basin, and the transform faults at the crest of the Mid-Atlantic Ridge. This correlation indicates that a uniform stress distribution existed in the upper mantle of both the respective oceanic and continental areas and resulted in the origin of a quite uniform set of "through-going" E-W dislocations. Movements of blocks, proceeding along these boundaries, have caused their upward propagation through both the continental and oceanic crust.

Intersections of the E-W structural boundaries with deep-seated boundaries of other trends delineate lithospheric blocks. The edges and corners of these blocks provided pathways favorable for the ascent of magmas and ore-forming fluids. Examples are given from the United States, northern China and Central Asia.

Introduction

The progress made in geophysics during the last decade has revealed major heterogeneities in the deeper parts of the crust and in the mantle. In the field of metallogeny, these data provide an invaluable basis for the analysis of parameters controlling the distribution of large concentrations of metals.

In this paper, I will focus, in particular, on criteria indicating (1) that the uppermost mantle, which is part of the lithospheric plates, has a block structure; (2) that the boundaries of the blocks propagate upward through the crust due to movements of the blocks; (3) that these boundaries guide heat, magmas, and ore-forming fluids toward the Earth's surface and pre-determine, to some degree, the loci where, under favorable geochemical conditions, the metals may concentrate. I have selected examples from three areas of the globe, all from a belt following the 40°N Parallel.

Example from the western and eastern United States

Fig. 1 shows the pattern of apparent P_n velocities in the uppermost mantle of a part of the United States after Archambeau et al. (1969). Kutina (1980) observed, that the contours of the apparent P_n velocities show significant curvature at a latitude close to 40°N (marked on Fig. 1 by a dotted line) indicating a major E-W boundary in the uppermost mantle, extending from California across Nevada and Utah as far east as the Rocky Mountain Front in Colo-

Proceedings of the Seventh Quadrennial IAGOD Symposium
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rado. This upper mantle lineament correlates with the position of a crustal fracture zone, suggested on the scale of the United States by Fuller (1964) and Affleck (1970) on the basis of interruption of magnetic anomalies. The residual Bouguer gravity map with cutoff wavelengths of 250 km (Hildenbrand et al. 1982) reflects an E-W trending structural boundary in the crust, extending at the same latitude (Kutina 1983). Additional evidence, supporting the presence of a major structural break at a latitude close to 40°N is found on more detailed scales (summarized in Kutina 1980, 1986; Kutina & Bowes 1982).

The line A-A' in Fig. 1 shows the position of a vertical profile across the crust and the mantle, compiled by Archambeau et al. (1968) and shown in Fig. 2. The upper boundary of the low velocity zone (LVZ), distinguished in the upper mantle, shows remarkable near-vertical steps (marked 1, 2, 3, and 4), interpreted by Kutina (1980) as boundaries reflecting a block structure of the upper mantle, delineating blocks with different degrees of melting. The metallogenic importance of these blocks is indicated by the presence of a major ore cluster in the Salt Lake City area (including the mining districts of Bingham, Tintic, Park City, and others), essentially correlating with the position of the near-vertical, 40-km step no. 3, and its intersection with the E-trending boundary distinguished along the 40°N latitude.

The residual Bouguer gravity anomaly map with cutoff wavelengths of 1,000 km (Hildenbrand et al. 1982) reveals that the ore cluster of the Salt Lake City area occurs along the edge of a major field of gravity highs, the latter correlating with a thinning of the crust shown in a map by Smith (197[illegible]). It means that the ore cluster originated along the eastern edge of an upper mantle updoming (Kutina & Hildenbrand 1987).

The E-trending boundary recognized in the upper mantle and crust as extending near the 40°N latitude, as well as other significant E-W-trending structural boundaries are shown together in Fig. 3A. A comparison of this illustration with a map of the modern stress provinces (shown in Fig. 3B, after Zoback & Zoback 1980) reveals that the E-trending lineaments of the basement extend across the boundaries of the modern stress provinces.

Fig. 4 (after Archambeau 1983, unpubl. illustration) shows variations of relative body wave magnitudes δm_b[1] in part of the United States (based on data in Butler 1983) and give strong support to the E-trending structural boundary no. 7 (Fig. 3A) distinguished by Kutina & Norton (1978) along the southern tips of Lake Michigan and Lake Erie.

The spacing of the E-trending structural boundaries, shown in Fig. 3A, correlates with the spacing of the E-W fracture zones of the East Pacific floor and the spacing of the transform faults at the crest of the Mid-Atlantic Ridge (Kutina & Norton 1978, Kutina 1985).

[1] δm_b is a measure of the amplitude (or magnitude) of the seismic compressional (P) wave from a seismic event at a particular point relative to the observed world-wide average. A positive value indicates a greater absorption of the seismic energy at depth (e.g. correlating with a "hot" mantle or high heat flow and low upper mantle velocities). A negative value is just the opposite (C.B. Archambeau, pers. comm.).

Comparison with China

The upper part of Fig. 5, reproduced from a model of block structure of the western United States (Kutina 1983), shows two major structural blocks (C and D) enclosed between two E-W trending structural boundaries marked 2 and 3 in Fig. 3A. The size of these blocks is about 530 x 600 km. The N-S boundary delineating block D on its eastern side is based on a Bouguer gravity map and essentially correlates with the Rocky Mountain Front. The N-S boundary between blocks C and D is essentially based on the N-S trending Intermountain Seismic Belt (Smith 1978) and, partly, on the Wasatch Fault System. The N-S boundary

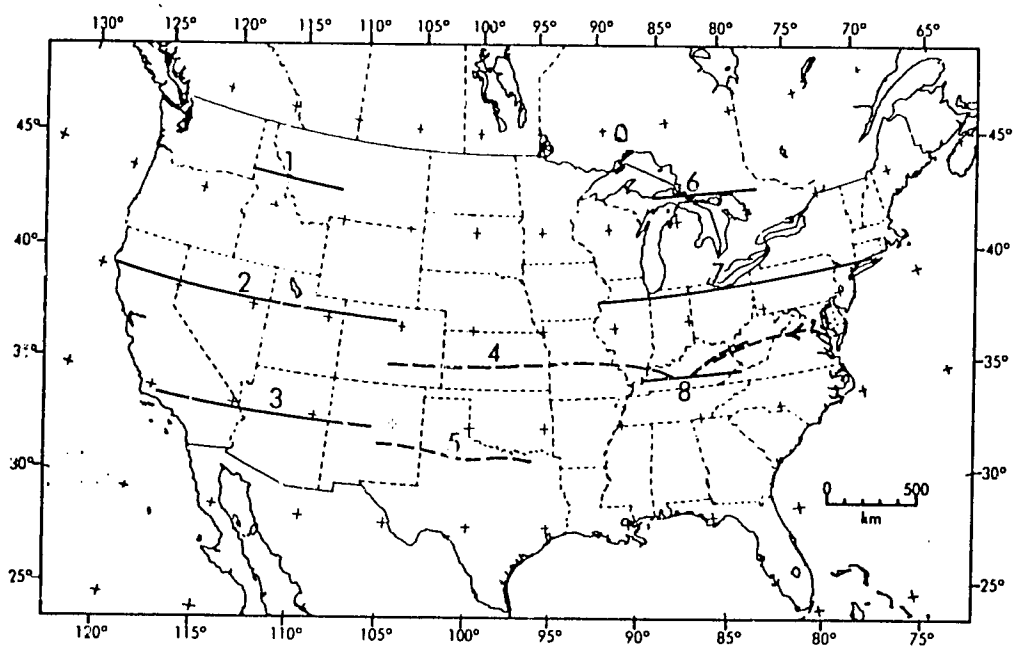

Fig. 3A. The major E-W lineaments of the conterminous United States (nos. 1–3 from Kutina 1983; nos. 4 and 5 after Heyl 1972, 1983; nos. 6–8 after Kutina & Norton 1978) are interpreted as a pattern of very old structural boundaries in the Precambrian basement, originated under a uniform stress distribution and, later, propagated through the crust.

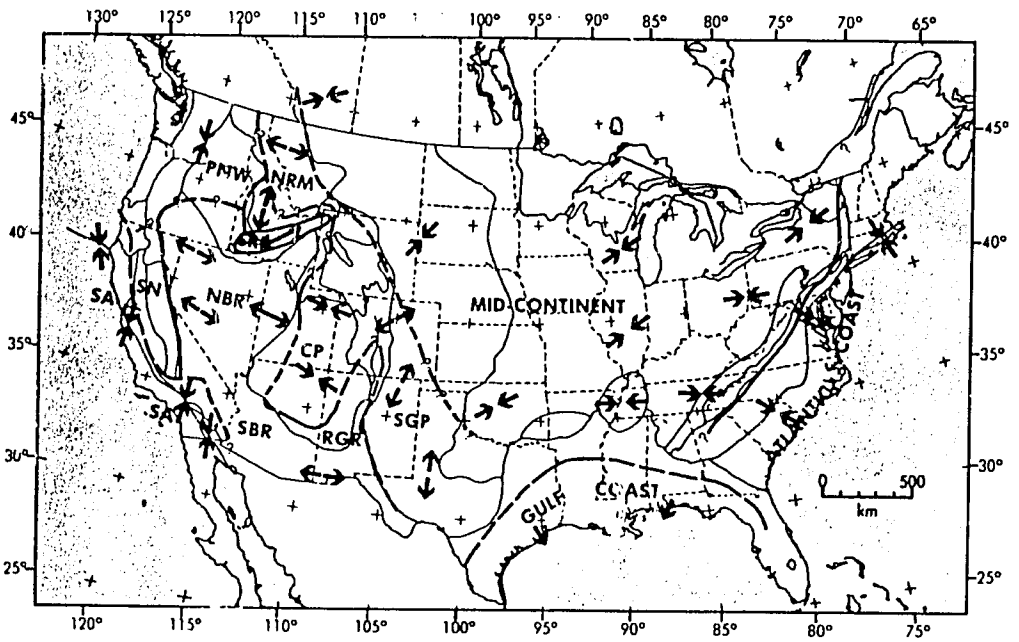

Fig. 3B. The modern stress field provinces of the conterminous United States, with arrows showing the principal horizontal stress orientation (primarily Quaternary in the western United States and Tertiary and younger in the East). After Zoback & Zoback (1980), redrafted to another geographic base map.

Fig. 4. Variations of relative body wave magnitudes in the eastern United States (after C. B. Archambeau 1983, unpubl. illustration, based on data in Butler 1983, and contoured by Archambeau). The contours give strong support to the E-trending structural boundary distinguished by Kutina & Norton (1978) along the southern tips of Lake Michigan and Lake Erie and shown as lineament no. 7 in Fig. 3A.

limiting block C on its western side essentially correlates with the Buena Vista Lineament in Nevada (Kutina 1980) and extends parallel to the former continental margin of western North America, as shown, for instance, by Oldow (1983). The Colorado Plateau[2] is marked by horizontal ruling. The cluster of ore deposits in the NW corner of block D is the group of major ore deposits of the Salt Lake City area, and the two major deposits in the NE corner of block D are the molybdenum giants Climax and Henderson, located in places where the NE-trending Colorado Mineral Belt approaches the vicinity of the 40°N Parallel (Kutina 1986). The exact NE corner of block D is marked by about 100 kimberlites, indicating mantle involvement (A. V. Heyl, pers. comm.).

The lower part of Fig. 5 shows the Yishan (Ordos) structural block in northern China. This block is enclosed between two major E-W trending structural boundaries, the spacing of which remarkably correlates with that of the E-trending basement boundaries in the western United States (Kutina 1983).

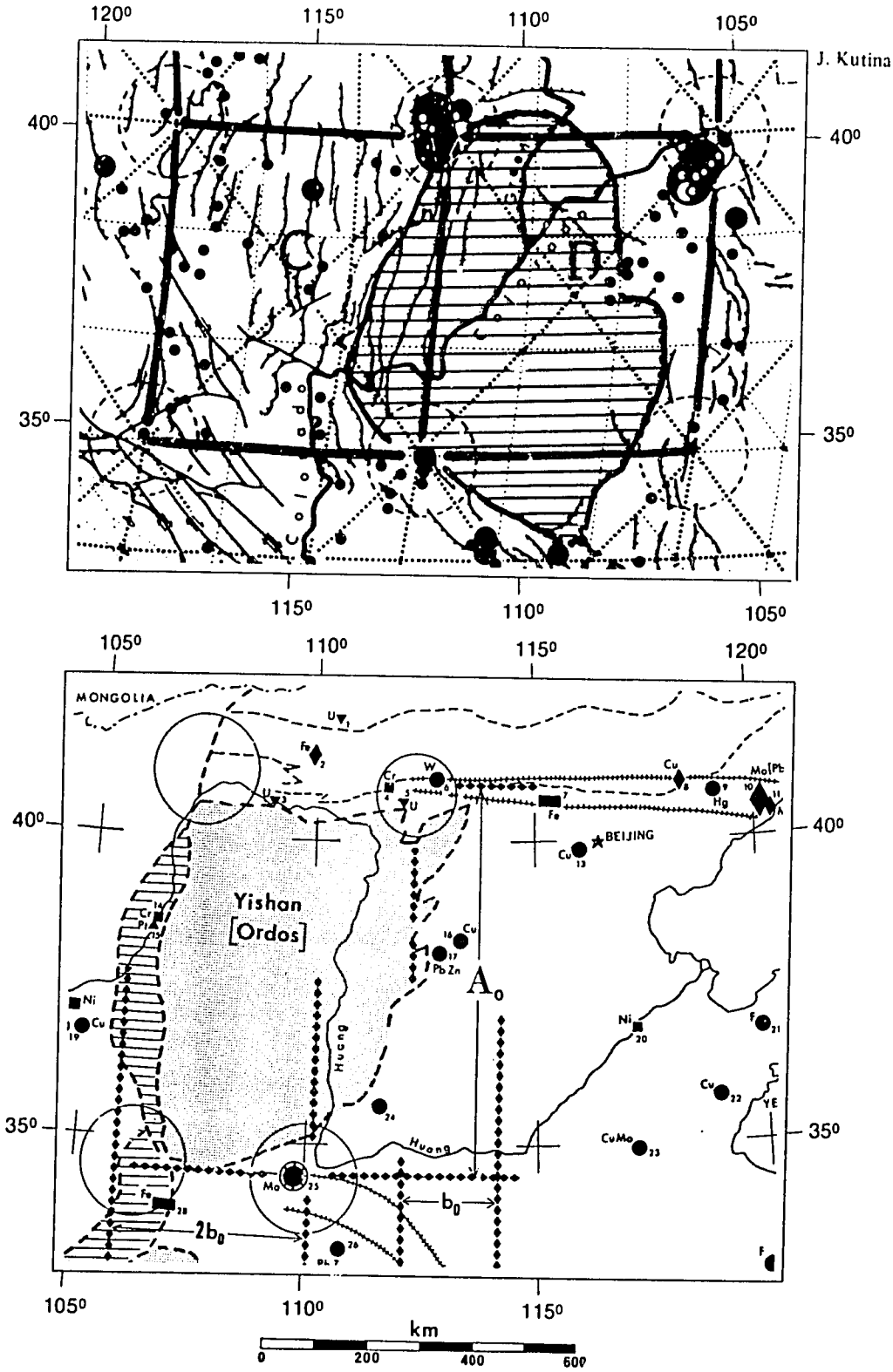

Fig. 5. Similarity in the spacing of major E-W trending structural boundaries between the western United States (upper illustration) and northern China (lower illustration), with major ore deposits near the corners of structural blocks. Based on Kutina 1983, with references. Explanation in the text.

The magnetic and gravity lineament maps of China (Jiang Mei & Ma Kaiyi 1984) show a pattern of major E-W lineaments extending across the entire territory of the P.R. of China. The spacing of these lineaments is very similar to that in the United States, shown in Fig. 3A.

[2] The outline of the Colorado Plateau is based upon the map of major physiographic provinces in the western United States (A.D. Howard and J.W. Williams in "Geologic Atlas of the Rocky Mountain Region", Denver 1972).

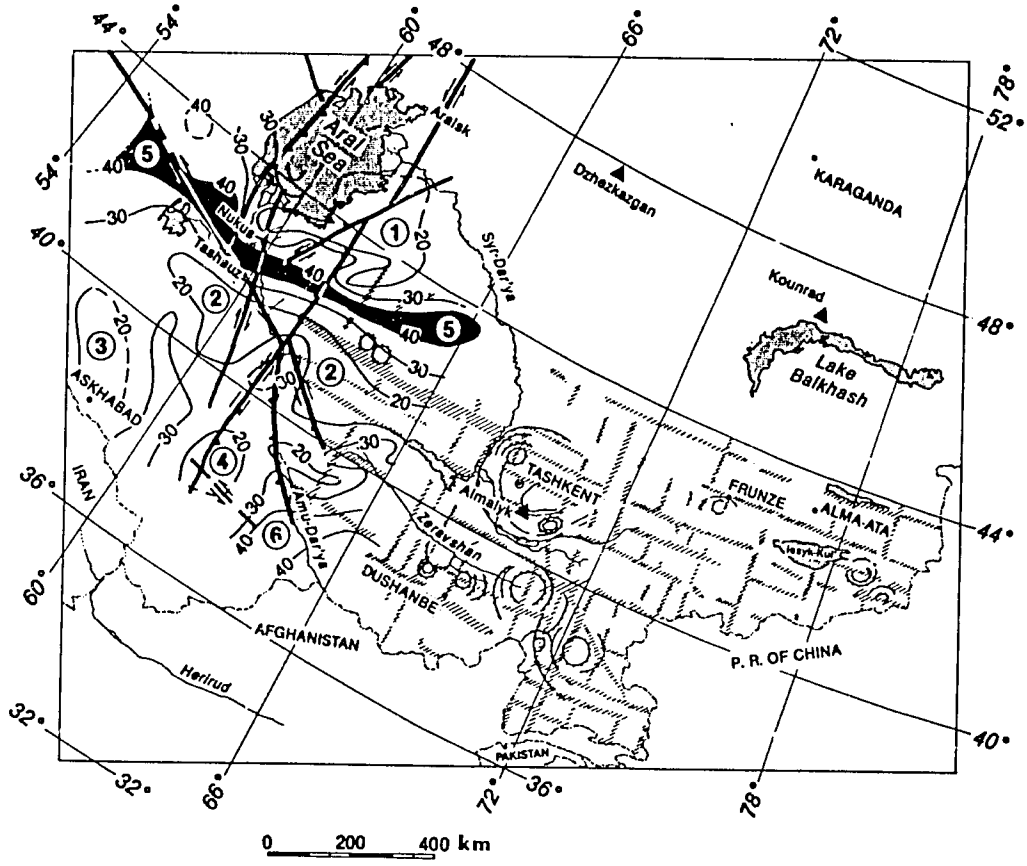

Fig. 6. The contours of Curie point isotherms (from Khaimov et al. 1985) reveal the presence of E-W trending boundaries in the basement of the Karakum and Kyzylkum deserts south and southeast of Aral Sea. These boundaries indicate that some of the E-trending, deep-seated zones of fracturing, recognized in the vast region of Alma-Ata – Tashkent – Dushanbe by Sapozhnikova & Volchanskaya (in Favorskaya et al. 1985, simplified, marked by oblique ruling), may extend westward and intersect with the major N-S faults (from Peive et al. 1977) which represent a southern extension of the Ural Mountains structure.

Example from Central Asia, USSR

The studies of ore-controlling lineaments of Asia, conducted by Favorskaya & Tomson (1974) and Favorskaya et al. (1983), have shown that an extensive magmatic activity and associated metallogenesis occurred in areas where the latitudinal belt of Tethys intersects with major structural lineaments trending N-S.

Another structural belt of a N-S trend, extending through Eurasia, is the Ural Mountains. This structure is well expressed in the global gravity map (Bowin et al. 1982) as a belt of gravity highs, with local interruptions indicating the course of transverse lineaments or structural boundaries. The question is: Does the N-S trending deep-seated structure, which controls the Ural Mountains, extend southward into the latitudes of 40–45°N within which, in other parts of Asia, important magmatism and metallogenesis occurred?

The respective area along the southern projection of the Ural Mountains is in the region south of the Aral Sea. The crystalline basement of this area is covered by Tertiary and Quaternary sidiments and sands of the Karakum and Kyzylkum deserts. Fig. 6, prepared by the author of this paper, covers a vast region and consists of three kind of data:

(1) A scheme of the most important faults of the Turan platform, adopted from Peive et al. (1977). The major faults which extend N-S represent a southern extension of the Ural Mountains structure. Of them, the fault in the western part of the Aral Sea has been documented by geophysical studies, especially by Kunin (1978).

(2) A pattern of major E-W and N-S trending deep-seated zones of fracturing or tectonic weakness ("skvoznye zony") distinguished by Sapozhnikova and Volchanskaya (in Favorskaya et. al. 1985). Some of these E-W zones are documented as far west as about 62°E longitude, and their further extension toward the west can be expected.

(3) Contours of Curie point isotherms, covering the broad area south of Aral Sea (from Khaimov et al. 1985). These data, giving the depth (km) at which rocks are loosing their magnetic properties, reveal a prominent E-W trend within the latitudes of 40–43°N. As emphasized by Khaimov et al. (1985), the zones nos. 1, 2, 3, and 4, enclosed by 20 km depth isotherm contours, represent relatively "warmed" zones, whereas zones nos. 5 and 6, enclosed by 40 km depth isotherm contours, reflect relatively "cold" zones. It means that rocks of the latter zones lose their magnetic properties at a greater depth than the former zones, an observation which may indicate a compositional difference between the two groups of zones. The E-W trending zone no. 5 (marked in black in Fig. 6) extends parallel to the interruptions of gravity highs in the N-S trending structure of the Ural Mountains.

The E-W boundaries occurring in the pattern of the Curie point isotherms (Fig. 6) require a detailed comparison with the segmented structure of the Ural Mountains. Preliminarily, the intersections of some of these E-trending boundaries with the major N-S faults deserve special attention as possible targets where metals may have concentrated.

Global regularity

The examples from the western and eastern United States, China and Central Asia, described in the preceding sections, show a similarity in the control of ore deposits: Important ore clusters occur in some places where a major latitudinal boundary, following the 40°N latitude, intersects with deep-seated zones of fracturing or tectonic weakness of a meridional trend or other trend transversal to the latitudes. Additional examples can be given from areas between those chosen as examples:

For instance, major concentrations of metals occur in the Caucasus, where the latitudinal Tethyan-Eurasian Belt, developed close to 40°N latitude, intersects with deep-seated zones of fracturing of a meridional trend (Favorskaya 1977). Farther west, fracture zones of a N-S trend traverse the Mediterranean and the adjoining parts of Europe and Africa (Burollet & Byramjee 1974, Favorskaya 1974, and others). Most recently, Maneva & Touhami (1986) concluded that the meridional boundary between the Tunisian Atlas and the Eastern Platform is a suture lineament separating two megablocks, and is of metallogenic importance.

Conclusions

The deep-seated structures which control the distribution of some major ore clusters in the United States, China and Central Asia show remarkable similarities. All the three areas reveal a block structure with major E-trending structural boundaries within the same latitudes. The spacing between the E-trending structural boundaries in the western and eastern United States and in China is very similar and correlates with the spacing between the E-W fracture zones in the East Pacific floor and the transform faults at the crest of the Mid-Atlantic Ridge. These observations indicate that the respective E-trending boundaries and fracture zones of both the continental and oceanic areas originated in the mantle under a uniform stress distribution that prevailed at the time of their origin. The author assumes that these E-trending fracture zones are very old, Precambrian, were rejuvenated during later geological history and propagated upward through the crust. The forces causing the E-trending global fracturing of the Earth may be related to the changes in the speed of the rotation of the Earth as discussed by Stovas (1963), Stovickova (1966) and others, or related to other parameters such as the changes in the size of the Earth's body, and require further study.

With regard to the plate tectonic concept, the similarities in the spacing of the E-trending structural boundaries, described in the present paper, do not give support to a major rotation of the North American plate, but do not exclude its westward movement away from the Mid-Atlantic Ridge. The observations provide additional data for the analysis of the motion of lithospheric plates, a question recently revived by Lowman (1985).

Acknowledgements. The paper was prepared under the project "Block Structure of the Lithosphere and Its Role in the Genesis and Distribution of Metallic Ore Deposits" funded by the U.S. Agency for International Development (AID). The presentation at the 7th IAGOD symposium in Luleå, Sweden, was made possible by a travel grant provided by the International Association on the Genesis of Ore Deposits. Best thanks are given to President Gunnar Kautsky and the Chief Treasurer Charles B. Sclar.

The author thanks Charles B. Archambeau of the University of Colorado in Boulder for permission to use Figs. 2 and 4 in this paper.

Technical preparation of the illustrations has received financial support from William A. Bowes, Steamboat Springs, Colorado. The assistance provided by J. R. Miller, Director of Cartographic Services, The University of Maryland Baltimore County, is greatly appreciated. The final version of the manuscript benefited from suggestions by Allen V. Heyl and J. K. Hartsock.

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PART VII.

NEW MINERAL TARGETS DEFINED UNDER THE PROJECT

By

Jan Kutina and Abdelhak Bennani

1. A Nickel-Cobalt Target in the Foum Zguid Region, Saharan Part of the Anti-Atlas

On the scale of Morocco, there is a major concentration of dolerites and gabbros in the region south of Foum Zguid, in the Saharan Part of the Anti-Atlas. This area is shown by a small frame in the lower part of Fig.2, and the same rocks (south of Foum Zguid) marked in green in the geological map - Figure 1 (both in Part II of this Report). On a more detailed scale, the gabbro-dolerite rocks of the Foum Zguid region are shown in black in Fig.6 of Part IV of this Report.

This major concentration of basic rocks has been explained, in Part IV, as an early Mesozoic magmatic reactivation guided by intersecting deep-seated structural boundaries in a region adjacent to the northern border of the West African craton. This structural setting and the time of reactivation correlate with a major concentration of gabbro-dolerite rocks in the Norilsk-Talnakh area near the western border of the Siberian Platform (Kutina and Bennani, 1987).

In the Norilsk region, a major concentration of copper-nickel ores with valuable amounts of platinum-group metals occur within a body of gabbroic rocks beneath a sheet of dolerites. We have discussed the question whether a situation similar to Norilsk can also exist in the Foum Zguid region, with major metal concentration beneath the gabbro-dolerite rocks.

The quantitative chemical analyses of the basic rocks we have collected in the Foum Zguid area are given in Tables 1-3 in Part IV of this Report. The analyses show similarities with the rocks of the Norilsk-Talnakh region. Secondly, a trend in magmatic differentiation of the basic magma has been recognized and gives hopes

that further differentiation could lead to separation of parts of some metals, in particular nickel and cobalt, from the magmatic melt.

In the course of our field work we have discovered, at locality No.8 (Fig.6 in Part IV), a relatively less basic magmatic differentiate (referred to as Type 5 intrusive) with signs of a superimposed potassium metasomatism. This intrusive contains "schlieren" with pyrrhotite and pentlandite $(Ni,Fe)_9S_8$ containing 2-3 % cobalt. The Devonian limestones around this intrusive are altered into a silicate hornfelse (very rich in titanium) and are partly serpentinized (by hydrothermal fluids). A dissemination of a Ni-Fe-Co sulfide with high contents of nickel (37--39 %) and cobalt (5-6%) (Tab.5 in Part IV), occurring in minute grains in the hornfels and serpentinized limestone indicates that part of the nickel and cobalt of the magmatic melt was separated and transported in hydrothermal fluids.

The above intrusive may represent connection with a larger magmatic body beneath the gabbro-dolerite rocks which are outcropping. The suspected larger body of basic rocks may contain greater concentration of some metals which could separate from the parent magma. Unlike Norilsk, there are, in the case of Foum Zguid region, better chances for concentration of cobalt (along with nickel). Figure 4 in Part IV of this Report shows the location of the cobalt district of Bou Azzer in the central part of a huge field of high gravity values of the isostatic gravity anomaly map. The Foum Zguid locality which we have discovered is in the southern, peripheral part of the field of high gravity values, SW of Foum Zguid. With regard to the existence of still other cobalt localities in the same area of high gravity (A.Bennani, unpubl.data), a possibility of geochemical specialization of the upper mantle beneath the respective region of high gravity values seems to be realistic and deserves further study.

The location of our locality with Type 5 intrusive and the concentration of Ni and Co is shown, on the background of a topographic map in Figure 1 of this chapter.

Figure 1. Location of Type-5 intrusive with concentration of nickel and cobalt (shown by a black/white dot enclosed in a triangle) in the southwestern peripheral part of the Hamsailikh Anticline, SW of Foum Zguid. (corresponds to locality No.8 in the geological map, Fig.6 in Part IV of this Report).

The Type-5 intrusive is partly exposed on the slope of a hill (see the photograph, Fig.2) which is located between southwestern projection of Jebel Ikalloula and Jebel Anhsour.

The location is shown on the background of 'Carte du Maroc 1:100,000, Feuille NH-29-XI-4, sheet Tissint, published by the Institut Geographique National, Paris, 1969. The geographic coordinates of the locality are, approximately, 29°40' - 29°41'N and 7°12'W (Moroccan coordinates 298.8 N and 326.4 E).

Note: The lines in Fig.1 are not geographic coordinates, but plotted when reading the coordinates. The numbers in pencil are field numbers. The same localities have received other numbers in Fig.6, Part IV of this Report.

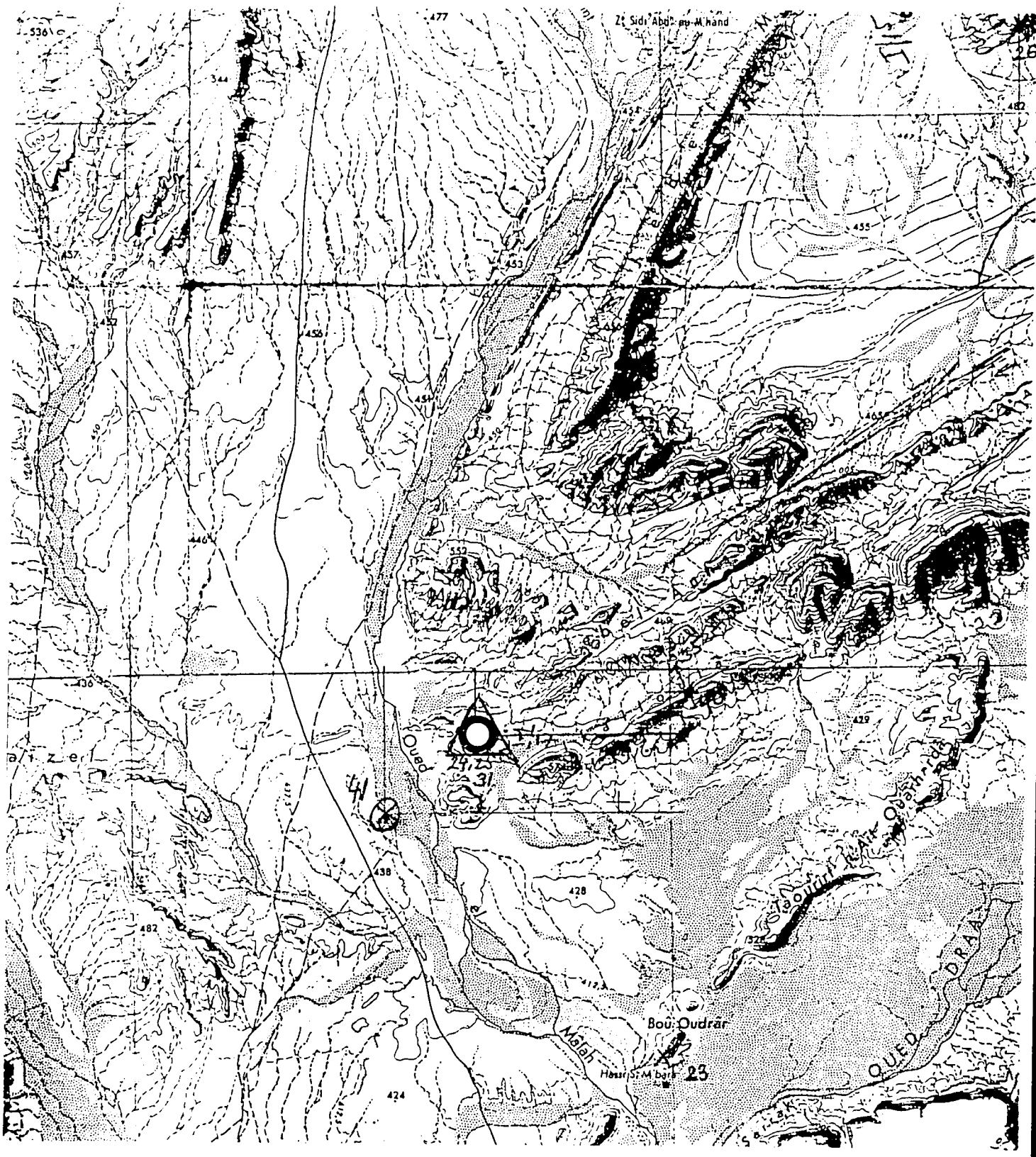

Figure 1

See caption on opposite page

Figure 2 (photograph) is a general view of the locality. The Type 5 intrusive was followed for a distance of about 50 m on the slope of the hill, between the landrover and the dolerites which form the top of the hill.

Regarding the strategy of a follow-up mineral exploration program, a soil geochemistry would not be easily applicable because a real soil is mostly missing. The rocks are covered, in this place, by sand which was blown by air. The analysis of rock chips would be applicable. The following scheme of an initial approach may be considered:

1. To make 2 or 3 trenches about 3 meters deep across the outcroping Type 5 intrusive and carry out a systematic study of samples.

2. To make 2 diamond drillholes at selected locations, about 200 m deep, and carry out a detailed laboratory study of samples.

If the results from the above trenches and drillholes give encouraging results, a deeper drilling and a regional study can be considered. The task of the regional study would be, in particular, to find location of additional sites with the Type-5 intrusive and possibly other rock types promising for the concentration of nickel, cobalt and possibly of platinum-group metals. The persons who would be assigned to perform the regional study have to get well acquainted, at the onset of the study, with criteria of visual distinguishing of the Type-5 intrusive. The color of the Type-5 intrusive is, on a fresh break considerably lighter than dolerite or gabbro, with rather large feldspar phenocrysts, but has a quite dark color, similar to dolerite, on the rock surfaces which were exposed to weathering. A characteristic feature of the Type-5 intrusive of our locality is the presence of many small crystal grains which were resistant to weathering and occur on the rock surfaces subjected to surface weathering. This feature helps to recognize the intrusive visually and distinguish it from the dolerite.

It should be noted that our field work has been limited to the area north of the valley of Oued Dra shown by a dotted pattern in Figure 6 in Part IV of this Report.

The region south of Oued Dra has not been accessible to us and may be of special interest for a comparative study in the future.

Figure 2. The locality of Type-5 intrusive with concentration of nickel and cobalt in the southwestern peripheral part of the Hamsailikh Anticline, SW of Foum Zguid, in the Saharan part of the Anti-Atlas, Morocco.

The Type-5 intrusive is partly exposed over a distance of about 50 m (parallel to the longer side of the picture), in the area between the top of the hill (made up of dolerites) and the landrover. Viewed approximately toward the north.

Photo by Jan Kutina, June 1988. Photograph No.88/II/6.

2. The Occurrence of Serpentinized Ultrabasic Rocks Northeast of Foum Zguid

Some of the dolerite dikes extend far away from the large concentration of the gabbro-dolerite magmatism which occurred in the region south of Foum Zguid. These dikes were subject to study of some investigators, especially by Saadi (1971) * who described their association with copper mineralization. The most important of these dikes is "The Great Dike of Dolerite" (or, "The Great Dike of Foum Zguid"), as referred to, e.g., by Leblanc (1973) and Michard (1976, p.82). It extends for a distance of about 300 km.

The upper section of Fig.6 (Part IV of this Report) shows the Great Dike of Dolerite to cross Jbel Bani ** just west of Foum Zguid and to extend farther northeast. In the area between longitudes 6°45' and 6°50'W and close to (north of) latitude 30°10'N, the continuity of the Great Dike is, in the surface area, interrupted and the dike changes its strike.

The Great Dike is well expressed in the morphology of the region, due to the resistivity to weathering of the dolerite. Two segments of the dike are apparent on the topographic map reproduced in Figure 3 of this chapter: One of the segments is represented by the range Jbel ed Dala which extends northeasterly from the town Lamhamid (north of Foum Zguid). The other segment forms a shorter range that extends southwest from Oçar-en-Nkheyla (NE corner of Figure 3). Two photographs (Figs. 4 and 5) show the Great Dike composing the above mentioned Jbel ed Dala. Figure 4 is a general view of the dike as seen from north of Foum Zguid, and Fig.5 is a view of the same dike from a close distance at Amzzrou.

We have visited the area between Es Smeyra and Oçar-en-Nkheyla (Fig.3) which is adjacent to the places where the Great Dike is interrupted and changes its strike.

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* References to other papers by M.Saadi on the same subject are given in Saadi and Mahmood (1984).

** Jbel = range (mountain range)

In places marked 57 and 58 (Fig.3) we have found, in the flats, a considerable amount of rounded fragments of ultrabasic rocks with different degree of serpentinization. Visually, many of the samples seem to be entirely serpentinized and contain magnetite. The rounded shape of the samples indicates transport from a primary source. The question arises whether the samples could have been transported by streams from some part of the Bou Azzer - El Graara Precambrian block which contains serpentinites and occurs 35-40 km to the north. Another possibility is that the rounded fragments of the serpentinized ultrabasics come from another, closer source which has not yet been known.

The study of the above question and finding the primary source of the serpentinized ultrabasic rocks is of great importance, because the locality is adjacent to places where the Great Dike is interrupted and changes its strike, it is near places structurally favorable for reopening of deep-seated channelways and multiple ascent of magmas. Leblanc (1973, quoted from Michard,1976) noted the presence of gabbroic rocks in the central parts of the Great Dike, indicating that the dike need not be made up just of dolerite.

The 'Great Dike of Rhodesia' (now, Zimbabwe) extends for a distance of about 500 km and also changes its strike. Important deposits of chromite as well as concentrations of Pt-group metals are associated with the dike.

Our discovery of the serpentinized ultrabasics has been done during the last expedition, in the last days of the AID-sponsored project. We strongly recommend a follow-up study to determine the primary source of the serpentinized ultrabasic rocks and to examine the area of the interruption of the Great Dike between Es Smeyra and Oçar-en-Nkheyla.

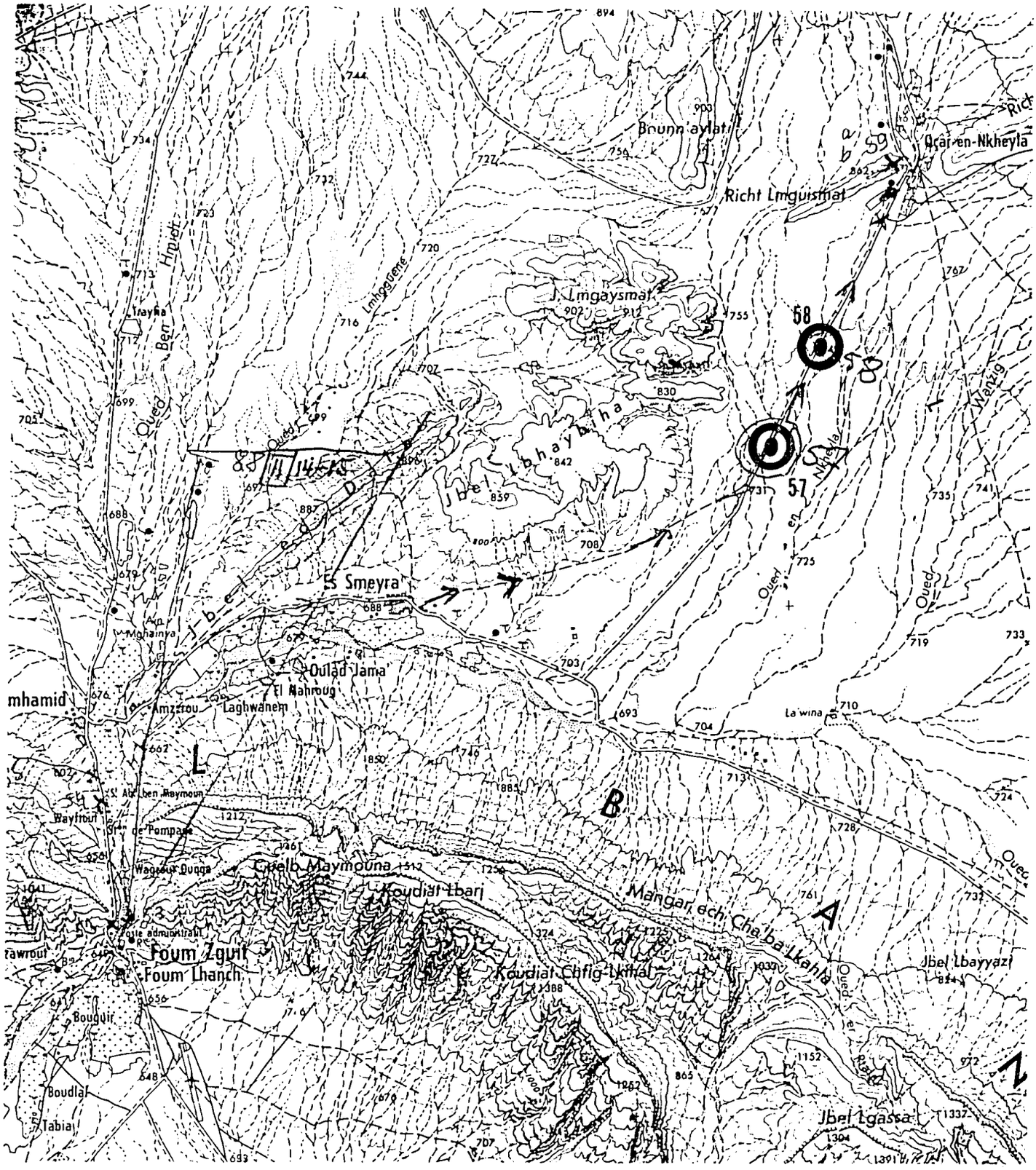

Figure 3. Secondary localities of serpentinized ultrabasic rocks (Nos.57 and 58) in the flats between Es Smeyra and Ocar-en-Nkheyla, northeast of Foum Zguid, Saharan part of the Anti-Atlas, Morocco. Explanation in the text.

Carte du Maroc 1:100,000, Feuille NH-29-XVIII (sheet Foum Zguit [Zguid]), published by the Direction de la conservation fonciere et des travaux topographique, Division de la carte, Rabat, 1968.

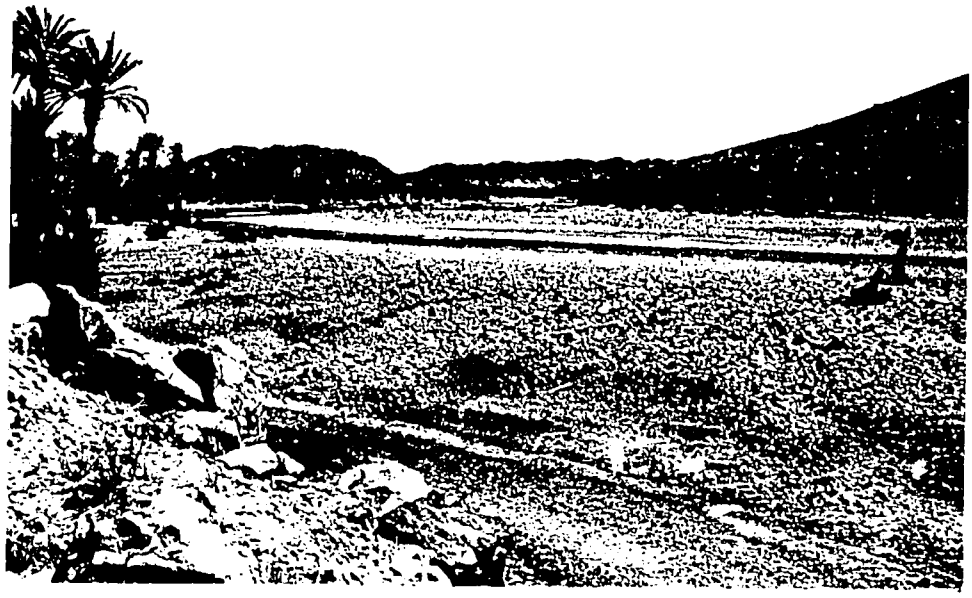

Figure 4. A general view of the Great Dike of Dolerite NNE of Foum Zguid, manifested as a NE-trending range (Jbel ed Dala). Viewed toward NNE from Lamhamid. Photo by Jan Kutina

Figure 5. The Great Dike of Dolerite (Jbel ed Dala) as seen from a close distance at Amzzrou, north of Foum Zguid. Photo by Jan Kutina.

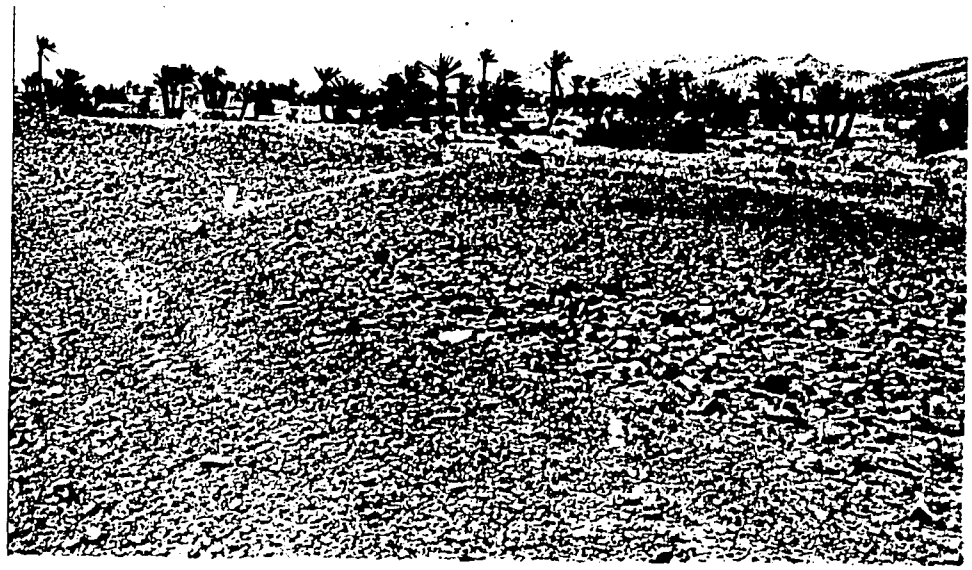

Figure 6. The secondary locality of serpentinized ultrabasic rocks in the flats between Es Smeyra and Ocar-en-Nkheyla, north-east of Foum Zguid. Photo by Jan Kutina.

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PART VIII

PERSPECTIVES FOR A FUTURE FOLLOW-UP OF THE PROJECT

by

Jan Kutina and Mohammed Bensaid

1. Basic results which provide background for a follow-up study

The project has introduced a new approach to mineral exploration in Morocco, based on the relationship of metallogenic processes to deep structure. Of particular importance was to identify structural boundaries which may extend down to the base of the lithosphere where the rocks are partially molten. These boundaries may act as conduits guiding heat, magma and also hydrothermal fluids toward the Earth's surface. Therefore, these boundaries play a crucial role in the concentration of metals. In order to reveal a pattern of such deep-seated structural boundaries, an isostatic gravity anomaly map (adopted from Van den Bosch, 1971, 1981), has been used (fig. 4 in Part IV of this Report). According to Airy's model of isostasy, it was expected (1) that lithospheric blocks of different densities would tend to be submerged to different depths in the plastic, partially molten substratum beneath the base of the lithosphere; (2) that this isostatic adjustment of structural blocks of different densities may produce observable isostatic anomalies, thus revealing the deep-seated boundaries along which vertical movements proceeded.

The isostatic anomaly map reveals a set of N-S and E-W trending gradients that may represent block boundaries (fig. 4, Part IV). The Atlas Mountains, shown on the map by heavy full lines, essentially reflect the

shape of the trough or sedimentary depression from which, later, this orogenic belt was formed. Although the orogen as a whole tends to extend northeasterly, there is a strong correlation between the changes in the course of the orogen and the pattern of the N-S and E-W structural boundaries. This correlation may indicate that the subsidence (origin of the trough or depression) was, to a considerable degree, controlled by a block structure. This relationship is best visible at the southern boundary of the High Atlas Mountains, known as the South Atlas Fault: In the eastern part of the map (fig. 4 in Part IV), within latitudes close to 32°N, the South Atlas Fault, as well as the whole orogenic belt, extend E-W, following the gravity gradients. At about longitude 4°30'W, the southern boundary of the orogen changes strike from E-W to NE-SW but, at about latitude 31°N its trend is again E-W, following the northern border of a major dense block.

Preferential concentration of metals has been found:

(1) Near intersections of deep-seated boundaries of the N-S and the E-W trend. For instance, a cluster of about 50 occurrences and deposits of Pb, Cu, Ag, Au and other metals, including the important silver deposit of Imiter occurs within an area of about 40 x 50 km near the intersection of the N-S trending boundary which extends along a longitude 6°W and the E-W trending boundary extending close to the latitude 31°N.

(2) Near the intersections of the South Atlas Fault with the N-S trending structural boundaries which extend transversely to the orogenic belt. An example is given in Figure 5 (Part IV), on the background of a magnetic map by Demnati (1979).

The N-S trending structural boundaries are reflected as morphological steps on the northern border of the High Atlas Mountains: one of them at a longitude close to 7°W and another one close to 8°W (fig. 4, Part IV).

Although these N-S boundaries do not manifest themselves continuously in the geology of the region, criteria have been found which indicate that they extend at a greater depth. An example is shown in Figure 6 (Part IV of this Report), where the NE-axis of the Hamsailikh Anticline turns to the north, along a longitude corresponding to the southern extension of the N-S trending boundary which is shown in the isostatic anomaly map at a longitude close to 7°W.

It has been concluded in Part IV of this Report that the major concentration of the gabbro-dolerite magmatism of the Foum Zguid region was controlled by the intersection of the above N-S trending structural boundary (distinguished at close to 7°W) and a major E-W trending boundary which extends into the Foum Zguid region from the Atlantic coastal region, following a latitude close to 29°N (apparent in the isostatic anomaly map, fig. 4 in Part IV and fig. 4 in Part II). A detailed investigation of this major structural intersection led to the discovery of a Ni-Co concentration which has been defined as a target for mineral exploration (Parts IV and VII of this Report).

The isostatic anomaly map as shown in Figure 4 (Part IV) provides an invaluable gross picture of density distribution in the lithosphere. One feature of special interest is the large zone of gravity highs between latitudes 30 and 31°N. The cobalt district of Bou Azzer lies in the central part of this gravity zone, and the new Ni-Co target is in the southern peripheral part of this zone, located SW of Foum Zguid. As there are also other occurrences of cobalt within the same zone of gravity highs, it has been suggested in Part VII that a geochemical specialization of the upper mantle may underlie this region. In the surface geology there are, of course, rocks of different density within the zone. For instance, a detailed view of the area

near Foum Zguid (fig. 6, Part IV) shows not only gabbros and dolerites, but also sedimentary rocks of different formations, especially Devonian.

Thus, we have, on one hand, a detailed picture of the surface geology of varying density and, on the other hand, a gross picture of mass distribution on the scale of Morocco, which reveals a broad zone of high gravity values between latitudes 30 and 31°N. This zone of high gravity as seen in the isostatic anomaly map indicates that the lithosphere beneath the very heterogeneous rock complexes of the near-surface levels is composed of relatively dense rocks. The serpentinized ultrabasics of the Bou Azzer-El Gaara zone, and the gabbro-dolerite rocks of the Foum Zguid region may be related to the underlying high density rock complexes. Further steps in mineral exploration require a more detailed picture of mass distribution and of boundaries between rock units of different density in the crust and upper mantle of the region between latitudes 30° and 31°N. A similar study is needed for all of Morocco, especially a study of structural lineaments extending transversely to the High Atlas Mountains.

The above task can be achieved in a follow-up study using the residual and regional Bouguer gravity maps and related filtered anomaly maps compiled for this purpose by Hildenbrand, Kucks, Hamouda, and Bellot (1988) and reproduced at a reduced scale in Part V of this Report.

2. A brief outline for a follow-up study

Based on the review presented in the preceding section (VIII/1), we are suggesting the following topics for a follow-up research:

(a) Structural and metallogenic study of a zone of gravity highs in the Anti-Atlas

The study would focus on the zone of high gravity values as shown in the isostatic anomaly map betwen latitudes 30° and 31°N (fig. 4 in Part IV of this Report).

The residual and regional Bouguer gravity anomaly maps with different wavelength filtering, as well as other derivatives such as the first vertical derivative and the horizontal gradient map, compiled under the AID-project by Hildenbrand, Kucks, Hamouda, and Bellot (1988), will be compared with the available geological, structural and metallogenic data. The new Carte de Gîtes Minéraux du Maroc on the scale of 1:500,000 will be used, as well as additional data on mineral distribution in the files of the Geological Survey of Morocco.

Special attention will be given to the sublatitudinal and submeridional structural boundaries and fault zones extending through the zone of gravity highs of the isostatic anomaly map. These structural boundaries will be compared with the pattern of mass distribution in the filtered gravity maps of Hildenbrand et al. In particular, the zone hosting the ophiolite complex of Bou Azzer, which has been interpreted as a suture zone (Leblanc, 1983), will be compared with the gravity pattern of the filtered maps.

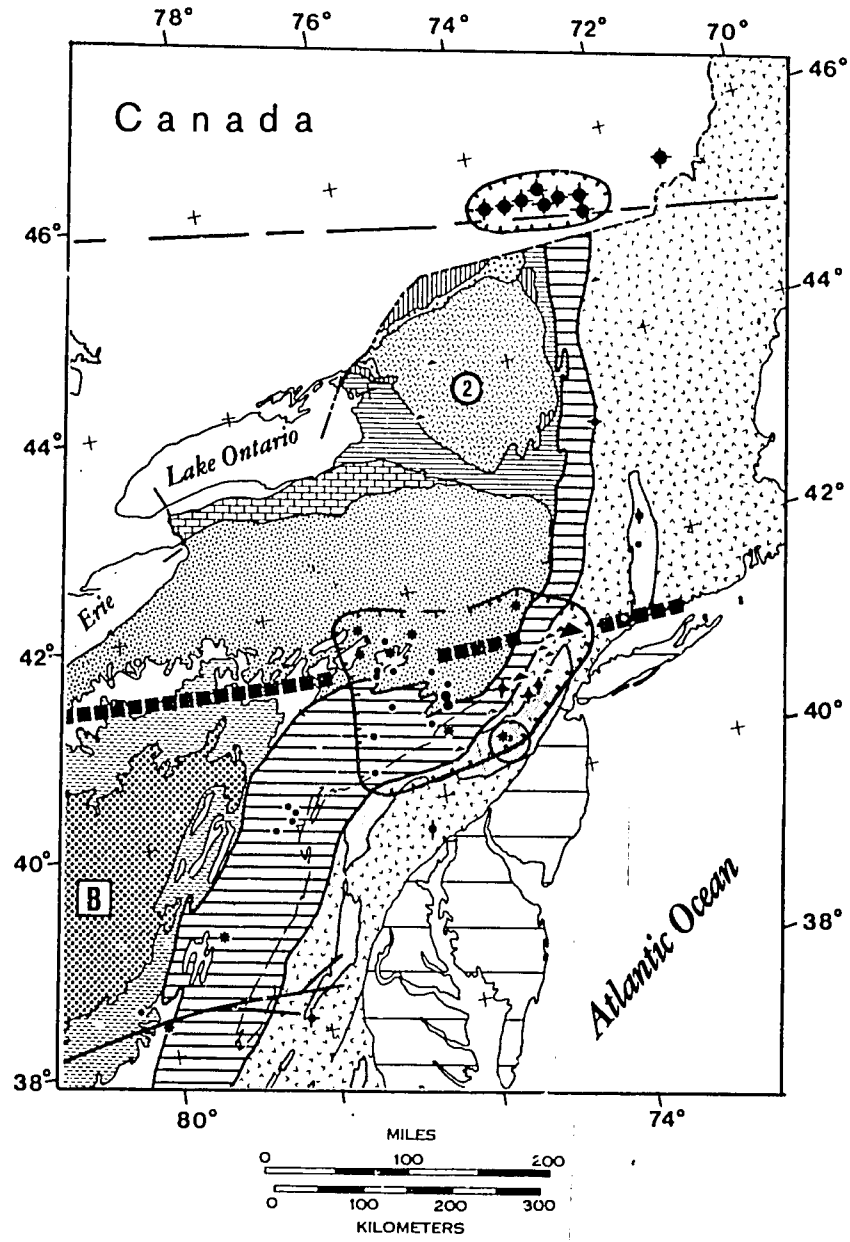
Using the filtered gravity maps and comparing them with the geology of the region, an attempt will be made to define in detail the block structure within the zone of high gravity values in the isostatic anomaly map. This pattern will then be used to evaluate the location of the new Ni-Co target SW of Foum Zguid and also the cobalt occurrence at the southern edge of the Siroua Massif. The data on mineral distribution, mineral assemblages and the rocks with which they are associated, as well as the trace elements in the deposits will be used to characterize the region which is expressed by the high gravity values in the isostatic anomaly map. A combination of the metallogenic and structural data will be used to evaluate mineral potential of the region, in particular its value for the discovery of new cobalt deposits.

(b) Metallogenic processes related to structural boundaries which extend transversely to the High Atlas Mountains

It has been noted by several investigators that the intersections of orogenic belts with deep-seated structural boundaries may guide magmatism from great depths and provide favorable conditions for concentration of metals. A few examples are given in the paper by Kutina (1988, chapter 'Global Regularity'), reproduced in Part VI of this Report. An example from the Appalachians may be useful for comparison with the High Atlas Mountains: Figure 1 shows a major curvature of the Appalachian foldbelt (marked by horizontal ruling), occurring within the latitudes 40°-42°N. This curvature occurs in places where the foldbelt is intersected by a deep-seated structural boundary of an east-west trend, extending transversely to the Appalachian orogen. In the area of this intersection, a cluster of uranium occurrences originated (fig. 1). The same area also contains concentration of other metals, especially of zinc (Kutina, 1981). Ratcliffe (1981) has described a 30-km wide belt of alkalic intrusives (the Cortland-Beemerville belt) which crosses the Appalachian foldbelt within the same latitudes as the E-trending structural boundary shown by a heavy broken line after Kutina and Norton (1978).

In Morocco, we have recognized several N-S trending structural boundaries which extend transversely to the High Atlas Mountains (fig. 4 in Part IV). The role of these boundaries in the concentration of metals has been demonstrated in Figure 5 of Part IV of this Report, but no systematic study has yet been done. The filtered gravity maps of Morocco, compiled by Hildenbrand et al. (1988) and reproduced in Part V, provide an excellent opportunity to conduct a systematic study of these interesting features. Superimposing the geology of the High Atlas Mountains on the residual gravity map with wavelengths less than 100 km provides interesting correlations:

The southern and northern boundaries of the orogenic belt coincide with gradients of pronounced negative anomalies which may be related to hydrothermal processes proceeding along the boundaries of the High Atlas Mountains and, therefore, should be tested in the next steps of mineral exploration. At the southern border of the High Atlas Mountains A. Bennani and J.Kutina have observed a major zone of hydrothermal alteration which was discovered by M.D. Lalaoui and possibly provides an example of a process contributing to the origin of gravity anomalies along the South Atlas Fault. A systematic study may provide important criteria in the search for unknown mineral deposits in Morocco. Such an investigation will be aided greatly with filtered magnetic anomaly maps. In this connection, the compilation of a uniform magnetic map of Morocco (which is planned by the Service G ologique du Maroc) is very important.



Precambrian

Cambrian (includes smaller areas of Precambrian rocks in the Ozark uplift)

Ordovician (upper parts in the uplifts by structural interpretation)

Ordovician (lower parts in the uplift by structural intepretation)

Silurian

Devonian

Mississippian

Pennsylvanian (Lower and Middle in the Illinois Basin, series P1 and P2 of King and Beikman map, 1974; series P1 in the Allegheny Basin)

Central parts of basins: Upper Pennsylvanian in the Illinois Basin (A); Middle-Upper Pennsylvanian and Permian in the Allegheny Basin (B); Pennsylvanian undifferentiated plus younger continental sediments in the Michigan Basin (C)

Triassic

Sediments of Coastal Plain, undifferentiated (Upper Cretaceous, Teriary, and Quarternary)

"Crystalline Appalachians" in the sense of P.B. King (1977, Fig. 38), including the Piedmont

"Appalachian folded belt" as defined in this paper, corresponding to "Sedimentary Appalachians" of P.B. King (1977, Fig. 38)

Figure 1. Example of metal concentration at intersections of an orogenic belt with deep-seated structural boundaries extending transversely to the orogen.

The illustration shows a cluster of uranium occurrences in eastern Pennsylvania and the adjoining parts of the states of New York and New Jersey, occurring in the area where the Appalachian foldbelt (shown by horizontal ruling) is intersected with an E-trending deep-seated structural boundary (shown by a heavy broken line).

The other cluster, shown in Canada, is a group of deposits of pyrochlore.

From Kutina (1981).

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ACKNOWLEDGEMENTS

We want to express our sincere thanks to the Office of the Science Advisor, Agency for International Development in Washington, D.C., especially Dr. M. Rechcigl and Dr. I.M. Asher, for their interest in our study and the support we have received. The original Project Proposal was submitted through the AID Mission in Rabat. We extend our best thanks, especially to Dr. Robert A. Kahn, for supporting the project.

The program for the project was prepared in 1984 in cooperation with Mr. Moussa Saadi, then-Minister of Energy and Mines of the Kingdom of Morocco, and got valuable advice from Mr. Josiah Royce, Coordinator of Mineral Activities at the U.S. Trade and Development Program. The cooperation and support by Messrs. Moussa Saadi and J. Royce are gratefully acknowledged.

The quantitative chemical analyses of rocks from the Anti-Atlas have been performed in the Branch of Geochemistry, U.S. Geological Survey. Our thanks are due to Mr. Byron Berger, Chief of th Branch, and the chemists whose names are given in Part IV of this Report.

The Service Géologique du Maroc in Rabat and the associated offices in Marrakech and Ouarzazate provided valuable help to our expeditions.

The field work in the Saharan parts of the Anti-Atlas, performed by A. Bennani and J. Kutina, has received valuable assistance from the Chief of the Administration of the Foum Zguid district and the military. We express our gratitude.