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AID/SCI Program in Science and Technology Cooperation (PSTC)
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Project: BLOCK STRUCTURE OF THE LITHOSPHERE AND ITS ROLE IN THE GENESIS AND DISTRIBUTION OF METALLIC ORE DEPOSITS

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Second Semiannual Report

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(c) U.S.Geological Survey component.

The Second Semiannual Report, presented with this letter, gives results of the American University component of the project from the second 6-month period: February 16,1986 - August 16, 1986

The report consists of three parts A,B,C, listed and characterized on the next pages.

October 9, 1986

Respectfully submitted:

Dr.Jan Kutina
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BLOCK STRUCTURE OF THE LITHOSPHERE AND ITS ROLE IN THE GENESIS AND DISTRIBUTION OF METALLIC ORE DEPOSITS

A two-year project funded by the U.S.Agency for International Development. Grant # PDC-5542-G-SS-5073-00

Second Semiannual Report
of the American University component
of the project

Presented: October 9, 1986

Contents and a brief summary

Part A

J.Kutina: Criteria indicating a block structure of the upper mantle and its role in metallogeny

Full text of a paper presented at the 7th symposium of the International Association on the Genesis of Ore Deposits (IAGOD) in Luleå, Sweden, August 19,1986. The paper is supposed to be published in the Proceedings of the symposium in Stuttgart, West Germany. An abstract of the paper, printed in Terra Cognita, is attached.

The author examined deep-seated controls of mineralization within a broad belt following the 40°N Parallel and found significant regularities repeating at different places around the globe. The 40°N latitude extends across North America as well as through the Mediterranean which is part of the Tethyan-Eurasian Metallogenic Belt.

Concentration of metals occurring near intersections of major deep-seated structural boundaries of a N-S trend and an E-W trend is of a special importance for Morocco which adjoins the Mediterranean on its southern side. This pattern of regularity, tested in Morocco, is described in Part B of the present report.

Part B

J.Kutina: Intersections of the South Atlas fault with block boundaries defined in the isostatic anomaly map and the magnetic map. Metallogenic implications

This is a preliminary version of a paper which is being prepared for publication.

Metallogenic role of deep-seated north-south trending structural boundaries, distinguished in the isostatic anomaly map, is tested at their intersections with the South Atlas fault which extends across the entire territory of Morocco, starting near Agadir at the Atlantic coast. Using a magnetic map by A.Demnati, the author defined one of these intersections in an area SW of Marrakech and demonstrated its role in the concentration of metals (fig.4 in Part B of the report). The respective area is recommended as an important target for mineral exploration.

Part C

J.Kutina: Mineral reconnaissance in the Foum Zguid area, Saharan part of the Anti-Atlas, Morocco

A region in the Saharan part of the Anti-Atlas, located between Foum Zguid and the Algerian border, is defined as northern part of a major structural intersection. The first reconnaissance of this area, conducted in June 1986 by J.Kutina and A.Bennani has revealed a zone of alteration in the Ikalloula range, located at the contact between basic intrusives and calcareous sediments, partly serpentinized and mineralized. The emission spectrographic analysis of a representative sample of the zone of alteration has revealed high con-

centration of manganese with a simultaneous presence of minor elements (chromium, nickel, cobalt and boron), similar to the association of minor elements in the serpentinites from the cobalt district of Bou Azzer, described by M.Leblanc. An electron microprobe analysis of a sulfide disseminated in the sample with serpentinization from the Ikalloula range, made by K.Fredriksson and J.Nelen in the Smithsonian Institution, gave 38.6% Ni, 19.3% Fe, 4.8% Co and 33.9% S, with minor amounts of some rock-forming elements.

Trace amounts of nickel, cobalt and boron were also found in samples of a major shear zone in argillitic rocks, developed in the central parts of an anticline structure.

The above localities require further study, but the observations indicate that the respective places deserve special attention as possible targets for nickel and cobalt.

PART A

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

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Abstract. The analysis of geological and geophysical data suggests that the E-W trending structural boundaries and fracture zones, distinguished in the western, central and eastern United States by Kutina in 1969, 1980, 1983b, . Heyl in 1972 and 1983, and Kutina and Norton in 1978, reflect a pattern of very old structural boundaries, originated in the Precambrian basement. Movements of lithospheric blocks, proceeding along these boundaries, have caused their upward propagation and had an impact on the evolution of the crust. As a consequence of block movements, these dislocations can be traced across boundaries of modern stress provinces of the United States compiled by Zoback and Zoback in 1980.

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

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* Submitted for publication in Proceedings, 7th IAGOD Symposium, Lulea, Sweden, August 1986.

boundaries of other trends, especially N-S ones, 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 from Central Asia.

Introduction

The progress made in geophysics during the last decade, especially by introducing a new technique of filtering and color computer plotting of gravity data, has revealed major heterogeneities in the deeper parts of the crust and in the mantle. I want to refer, in particular, to the residual and regional Bouguer gravity anomaly maps of the United States by Hildenbrand and others (1982), prepared with a 250-km and a 1,000-km wavelength filters, to the new isostatic residual gravity map of the United States, prepared by a computer color-plotter by Simpson and others (1986), and to the modelling and mapping of the mantle by Woodhouse and Dziewonski (1984) and Dziewonski (1984), using the seismic P velocities and revealing major heterogeneities even in the lower 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. This analysis can further extend the comprehensive treatment of this topic recently presented by Shcheglov and Govorov (1985).

In my present contribution 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 and others (1969, based on previous studies by Herrin and Taggert, modified). Kutina (1980) observed, that the contours of the apparent P_n velocities show significant curvature at a latitude close to 40°N, indicating a major east-west boundary in the uppermost mantle, extending from California across Nevada and Utah as east as the Rocky Mountain Front in Colorado (marked by a dotted line in fig.1). 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 interruptions of magnetic anomalies at corresponding latitudes. The residual Bouguer gravity map with cutoff wavelengths of 250 km (Hildenbrand and others, 1982) reflects an E-W trending structural boundary in the crust, extending at the same latitude (close to 40°N) and correlating with the upper mantle boundary shown in the contours of P_n velocities (Kutina 1983b). Additional evidence, supporting the presence of a major structural break at a latitude close to 40°N is found on more detailed scales. These data, with references, are summarizied in Kutina (1980, 1986) and Kutina and 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 and others (1968)

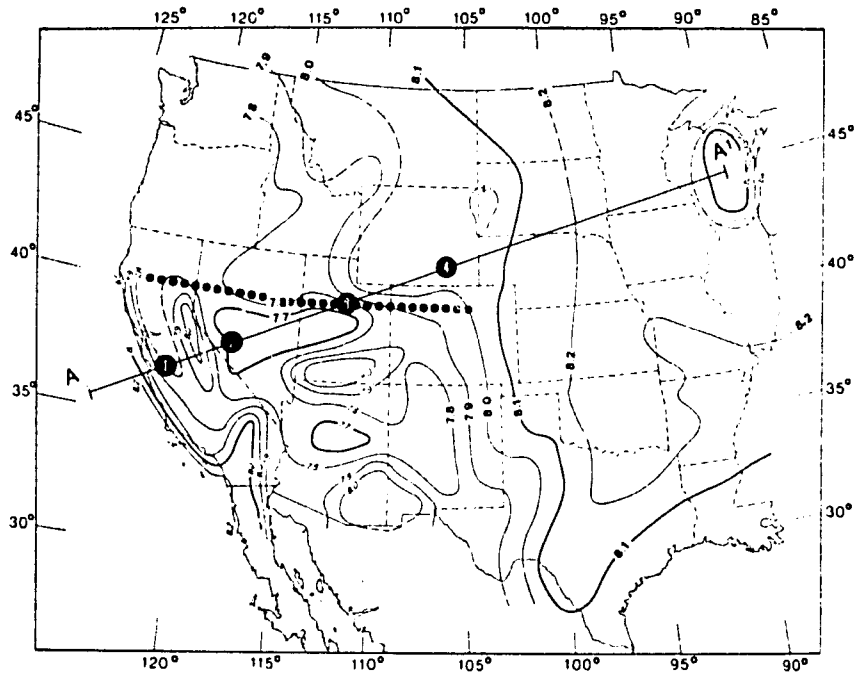

Fig.1. Apparent P_n velocities contour map of a part of the United States (from Archambeau and others 1969). The east-trending boundary (dotted line) indicated in by the contours is from Kutina, 1980, and is interpreted as a structural boundary in the uppermost mantle. Line A-A' shows position of a vertical profile reproduced in fig.2.

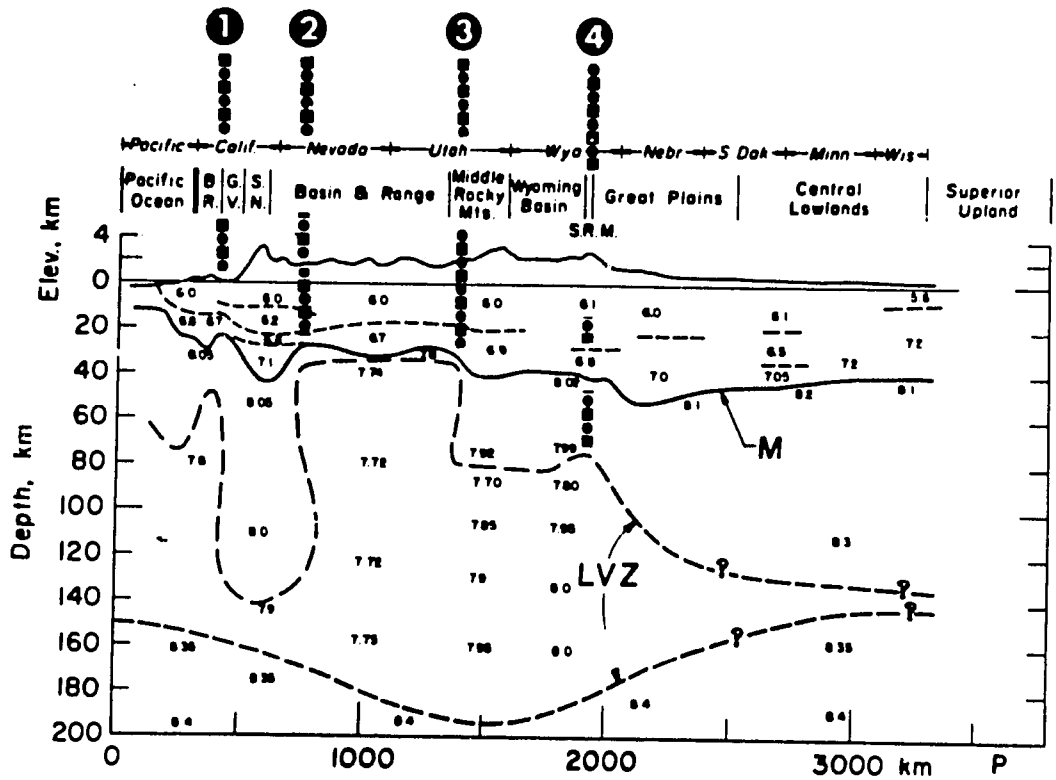

Figure 2. A vertical profile across the crust and upper mantle of the western United States (Archambeau and others, 1968). The upper boundary of the low velocity zone (LVZ) shows remarkable near-vertical steps (Nos.1-4), interpreted by Kutina (1980) as boundaries reflecting a block structure of the upper mantle.

~~fied 1983)~~ and shown in fig.2. The upper boundary of the low velocity zone (LVZ), distinguished in the upper mantle by Archambeau and others, 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 map with cutoff wavelengths of 1,000 km (Hildenbrand and others, 1982) provides information about the mass distribution beneath the above area hosting the ore deposits of the Salt Lake City area: The ore cluster occurs along the edge of a major field of gravity highs, correlating with a thinning of the crust shown in a map by Smith (1978). It means that the ore cluster originated along the eastern edge of an upper mantle updoming (Kutina and Hildenbrand, 1986).

Fig.3 shows the E-trending boundary recognized in the upper mantle and crust as extending near the 40°N latitude, as well as other significant east-west trending structural boundaries, superimposed on a map of the modern stress provinces of the United States compiled by Zoback and Zoback (1980). The E-trending lineaments of the central United States are after Heyl (1972, 1983), while those in the eastern United States come from Kutina and Norton (1978) and Kutina (1981) and are based on interpretation of the mosaic structure of large basins and uplifts. Figure 4, after Archambeau (1983, unpubl.,provided for this

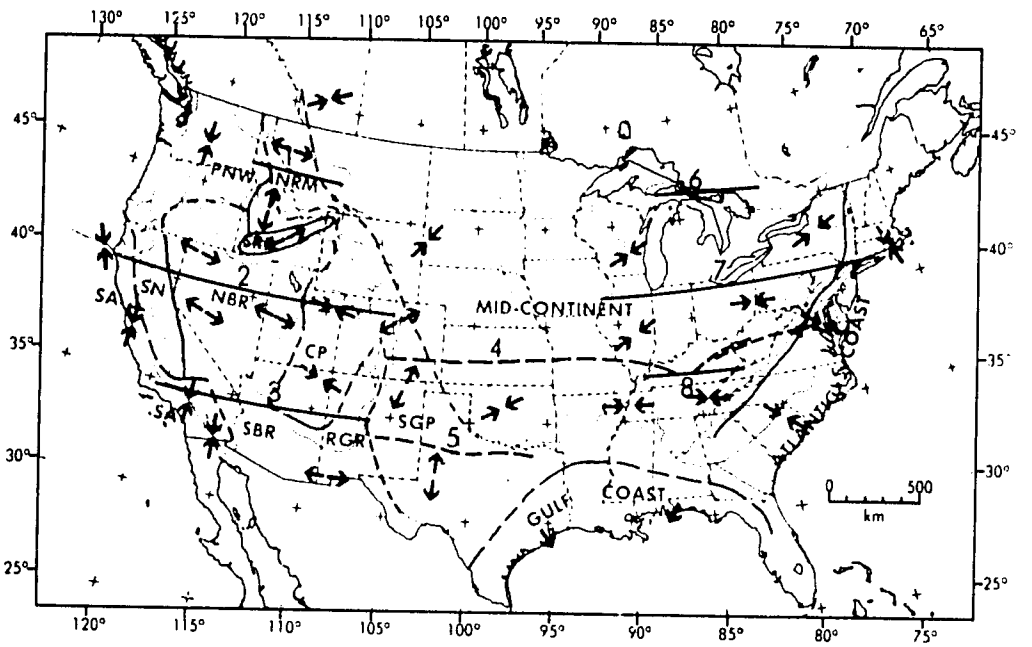

Figure 3. The modern stress field provinces of the conterminous United States, with arrows showing the principal horizontal stress orientation (primarily Quaternary in the western United States and Tertiary and younger in the East) after Zoback and Zoback, 1980 (shown in greay). The major east-west lineaments (Nos.1-3 from Kutina, 1983b, with references; Nos.4 and 5 after Heyl, 1972, 1983, and Nos.6-8 after Kutina and 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 upward through the crust.

Note for the Publisher: These two illustrations (3A and 3B) show separately the two kinds of data which are combined together in fig.3, with data from 3A 70% screened in order to appear grey in the print. If the printer cannot guarantee the distinguishing of the grey and the black color as shown in the original of fig.3, please use separate figures 3A and 3B instead. An alternative caption is attached.

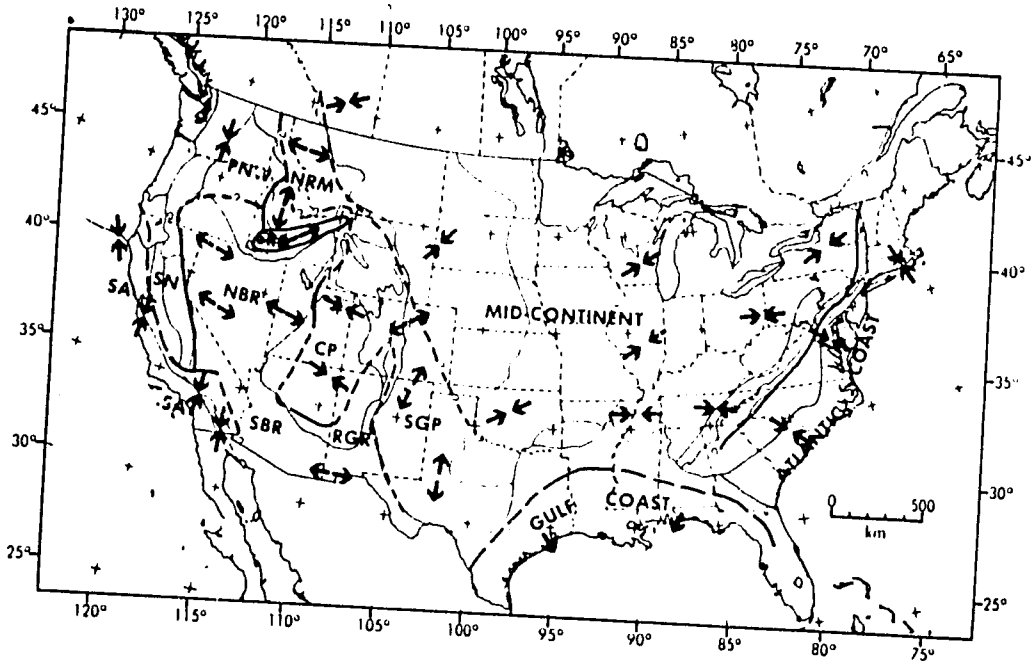

Fig. 3A

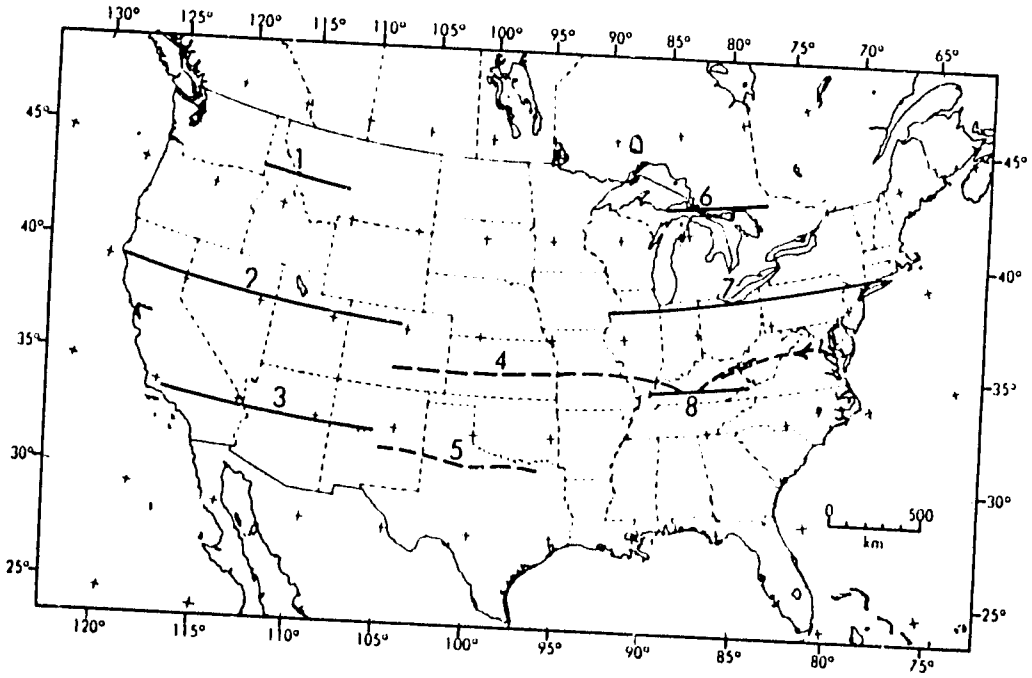

Fig. 3B

An alternative caption to fig.3 to be used if fig.3A and 3B are chosen instead of fig.3 in which the two kind of data are combined.

Figure 3A. 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 and Zoback (1980), redrafted to another geographic base map.

Figure 3B. The major east-west lineaments of the conterminous United States (Nos.1-3 from Kutina, 1983b, with references; Nos.4 and 5 after Heyl, 1972, 1983, and Nos.6-8 after Kutina and 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 upward through the crust.

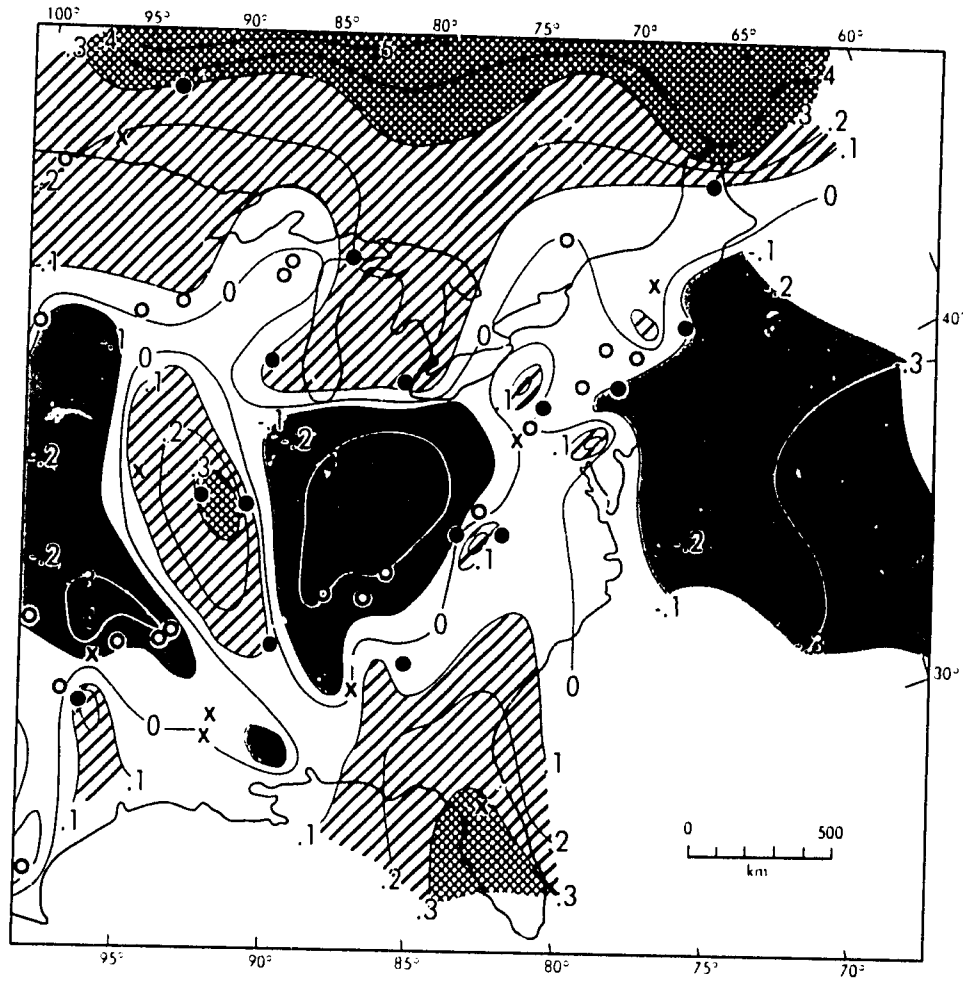

Figure 4. Variations of relative body wave magnitudes in the eastern United States (after C.B.Archambeau, 1983, unpubl., based on data in Butler, 1983). The contours give strong support to the east-trending structural boundary distinguished by Kutina and Norton (1978) along the southern tips of Lake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

paper), shows variations of relative body wave magnitudes in part of the United States, based on data in Butler, 1983, contoured by Archambeau. This illustration gives strong support to the east-west trending structural boundary distinguished by Kutina and Norton (1978) along the southern tips of Lake Michigan and Lake Erie, and shown as lineament No.7 in fig.3. The joint plot of the major E-trending lineaments of the United States, presented in fig.3, shows that they extend across the boundaries of the modern stress provinces.

The spacing of the east-trending structural boundaries, shown in fig.3, correlates with the spacing of the east-west fracture zones of the East Pacific floor and the spacing of the transform faults at the crest of the Mid-Atlantic Ridge (Kutina and Norton,1978; Kutina 1985). This correlation indicates that the east-west trending structural boundaries and fracture zones of both the continental and oceanic areas are propagated upwards from the upper mantle levels, reflecting an old fracture pattern which originated in the early history of our planet under a quite uniform stress distribution.

Comparison with China

The upper part of fig.5, reproduced from a model of block structure of the western United States (Kutina, 1983b), shows two major structural blocks (C and D) enclosed between two E-W trending structural boundaries marked 2 and 3 in fig.3. The size of these blocks is about 530 x 600 km. The north-south 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

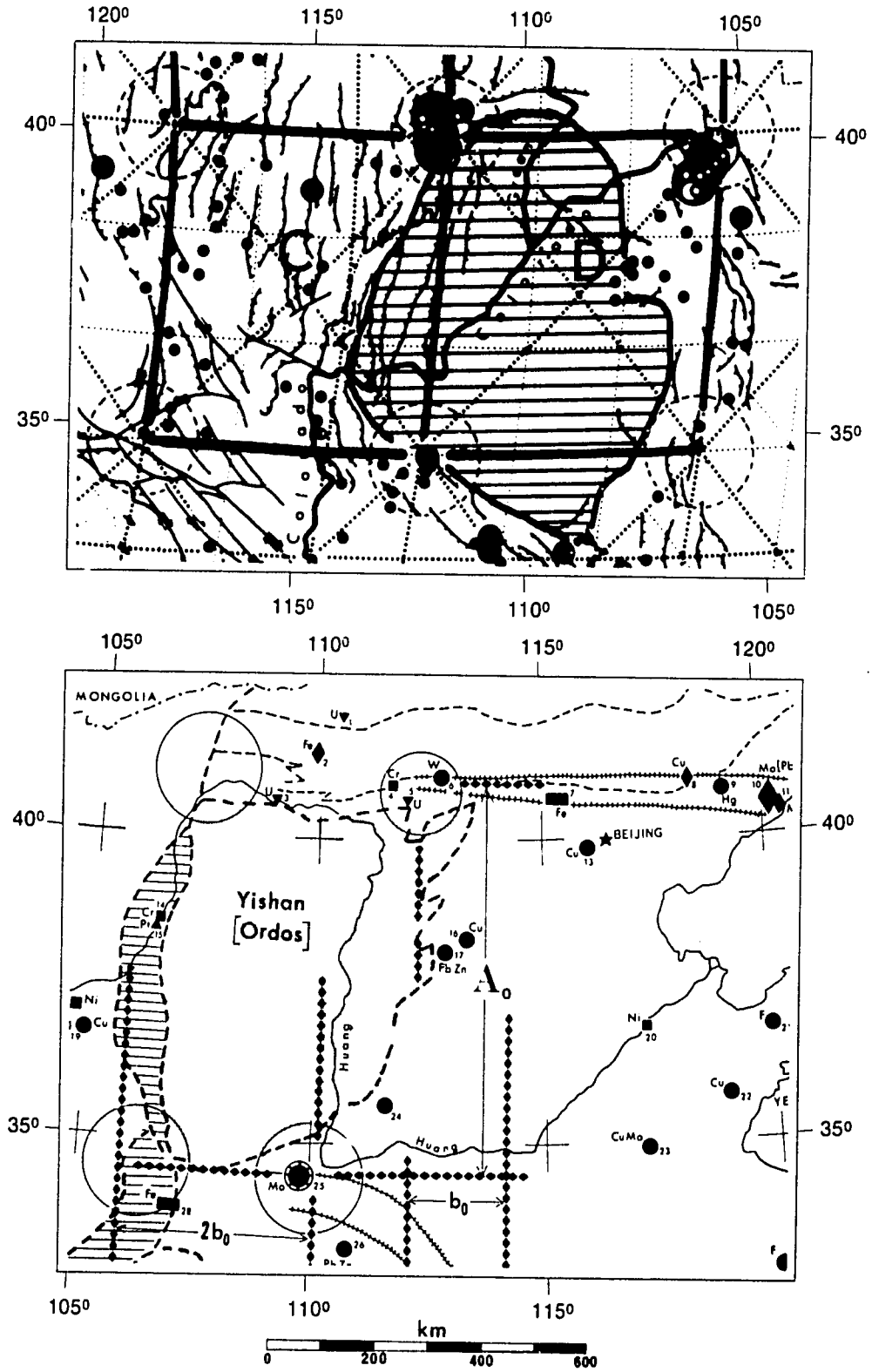

Figure 5. Similarity in the spacing of major E-W trending structural boundaries between the western United States (upper illustration) and northern China (lower illustration), with major ore deposits near the corners of structural blocks. Based on Kutina, 1983b, with references. Explanation in the text.

C and D is essentially based on the north-south trending Intermountain Seismic Belt (shown, for instance, in Smith, 1978) and, partly, on the Wasatch Fault System. The N-S boundary 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 is marked by horizontal ruling. The cluster of ore deposits in the NW-corner of block D is the group of major 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 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 1983b).

The magnetic and gravity lineament maps of China (Jiang Mei and 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.3.

Example from Central Asia , USSR

The studies of ore-controlling lineaments of Asia, conducted by Favorskaya and Tomson (1974) and Favorskaya and others (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 north-south. One of the most important N-S structures, defined by Favorskaya and Tomson (op.cit.), extends through Siberia and correlates with the longitude of the Chagos Ridge in the Indian Ocean floor. The intersection of this global-scale lineament with the Tethys belt is characterized by an intensive magmatic activity and by major concentration of metals in a particular area of Kazakhstan and Uzbekistan. The new free-air gravity anomaly map of the world (Bowin and others,1982) shows a major zone of negative gravity anomalies in the respective area of Central Asia. The shapes of the anomalies reflect E-W and N-S trends, giving support to the observations by Favorskaya and Tomson.

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 and others,1982) as a belt of gravity highs, with local interruptions indicating the course of transverse lineaments or structural boundaries. Southern extension of the structure controlling the Ural Mts. is not shown in Bowin's et al. map, due to a lack of gravity data. The question is: Does the north-south 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 sediments and sands of the Karakum desert. Figure 6, which I have prepared, covers this vast region and consists of three kind of data:

(1) A scheme of the most important faults of the Turan platform, adopted from Peive and others (1977). The major faults which extend N-S, re-

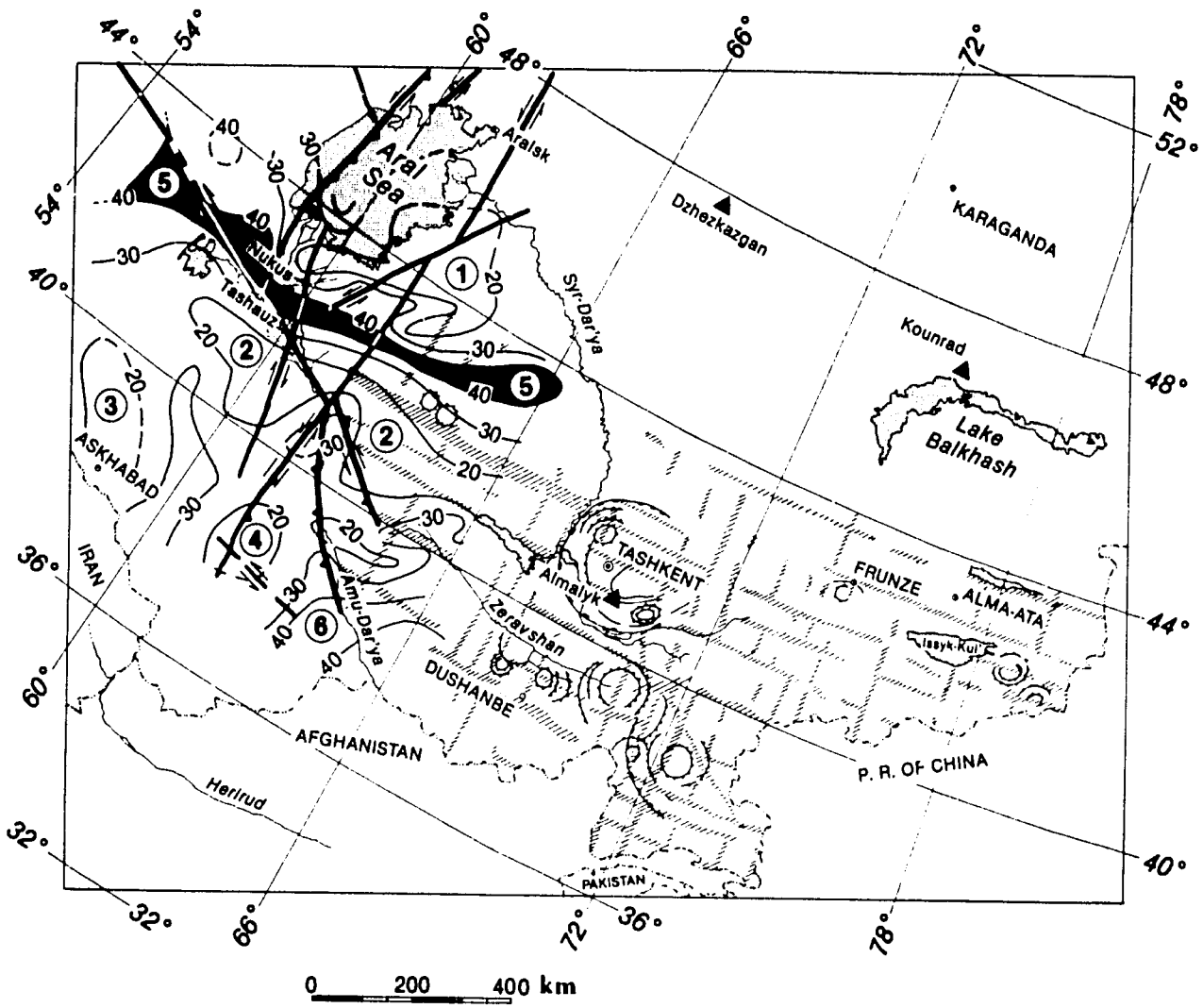

Figure 6. A major east-west belt, marked in black in the pattern of the Curie point isotherms (Khaimov and others, 1985), extends transversely to the N-S faults (heavy lines, after Peive and others, 1977) which reflect a southern extension of the structure controlling the Ural Mountains.

The pattern of deep-seated zones of fracturing of an E-W and N-S trend (marked by oblique ruling) and the circular structures are after Sapozhnikova and Volchanskaya (in Favorskaya and others,1985), simplified.

Compiled by Jan Kutina (this paper). Explanation in the text.

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 and others (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 and others, 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 and others, 1985). These data, giving the depth at which rocks are losing their magnetic properties, reveal a prominent east-west trend within the latitudes of 40°-43°N. As emphasized by Khaimov et al.,the zones Nos.1, 2, 3, and 4, enclosed by 20-km depth isotherm contours, represent relatively "warmed" zones, and zones Nos. 5 and 6, enclosed by 40-km depth isotherm contours, reflect relatively "cold" zones. It means that rocks of the latter zones (Nos.5 and 6)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 between towns Nukus and Tashaus) extends parallel to the interruptions of gravity highs in the N-S trending structure of the Ural Mountains as reflected in the global gravity map (Bowin and others,1982). Thus, it is possible that this zone (No5 in fig.6) represents a boundary between two other segments of the structure which controls the Ural Mountains and extends southward through the crystalline basement of the region located south of the Aral Sea.

The east-west 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 zone No.5 with the major N-S faults deserve special attention as possible targets where some 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 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 located 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 and Byramjee, 1974; Favorskaya, 1974; and others). Most recently, Maneeva and Tauhmi (1986) concluded that the meridional boundary between the Tunisian Atlas and the Eastern Platform (shown, for instance, in Vassilef and Popov, 1977), is a suture lineament separating two megablocks, and is of metallogenic importance.

As observed by Favorskaya (1977), some of the meridional lineaments in the Tethyan-Eurasian Belt are not easily recognizable in the surface geology and morphology, and have to be proved by geophysical methods. In the United States, especially in its western part, the N-S lineaments

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are usually better expressed than the east-west ones. The recognition of the latitudinal boundaries usually requires a geophsyical study (Kutina, 1983b). However, in both the regions, North America and Eurasia with the adjoining parts of Africa, the intersections of the deep-seated latitudinal boundaries with the transversal lineaments played an important role in metallogeny. The identification of these intersections, both in the Tethyan-Eurasian belt which extends for over 10,000 km (Jankovic, 1985) and along the east-trending deep-seated boundaries crossing North America may lead to derivation of new target areas with a potential for the discovery of new deposits of metals. The success of this work depends, in particular, on setting each of the area of study in the context of a much broader region, and on selection of the proper geophysical technique. For instance, the isostatic residual anomaly maps by Van den Bosch (1971, 1981) helped the author of this paper to define two N-S trending deep-seated structural boundaries in Morocco, which extend transversely to the Atlas and Anti-Atlas Mountains. The metallogenic role of these boundaries is now being studied (Bensaid and others, 1985).

Conclusions

The deep-seated structures which control the distribution of some major ore clusters in the United States, China and Central Asia show remarkable similaraties. All the three areas reveal a block structure with major E-W trending structural boundaries within the same latitudes. The spacing between the E-W structural boundaries in the western and eastern United States and in China is very similar and correlates with the spacings 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-W trending boundaries and fracture zones originated in the mantle under a uniform stress distribution that prevailed at the time of their origin. The author assumes that these E-W trending fracture zones are very old, Precambrian, rejuvenated during later geological history and propagated upward through the crust. The forces causing the E-W 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 (1963a,b), Štovičková (1966, 1973) 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-W 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

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diamonds, bauxite, fluorite, and minerals of niobium, beryllium, titanium, vanadium-clays, silver-lead-zinc, gold, barium, thorium, and rare earths. One Mississippi Valley-type district, the Illinois-western Kentucky district, alone shows a relationship to Hicks Dome, a very large, mostly unbreached cryptovolcano and its central breccia. This relationship is shown by zonation of minerals, some trace elements, and lead isotopes. This breccia body is very large and contains beryllium, niobium, fluorine, thorium, rare-earth elements, and barium. The breccia probably overlies a large deep-seated felsic syenite stock. No other Mississippi Valley main districts show any certain relationship to alkalic igneous rocks, but spatial relationships between the intrusions and these deposits are known in several other districts.

1.10
CRITERIA INDICATING A BLOCK STRUCTURE OF THE UPPER MANTLE AND ITS ROLE IN METALLOGENY

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The analysis of geological and geophysical data suggests that the E-W trending structural boundaries and fracture zones, distinguished in the western, central and eastern United States by Kutina in 1969, 1980 and 1983, Heyl in 1972 and 1983, and Kutina and Norton in 1978, reflect a pattern of very old structural boundaries, originated in the Precambrian basement. Movements of lithospheric blocks, proceeding along these boundaries, have caused their upward propagation and had an impact on the evolution of the crust. As a consequence of block movements, these dislocations can be traced across the boundaries of modern stress provinces of the United States, compiled by Zoback and Zoback in 1980.

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, especially the N-S ones, delineate lithospheric blocks. The edges and corner areas of these blocks provided pathways favorable for the ascent of magmas and ore-forming fluids.

The author demonstrates the application of different geological and geophysical data (including the contours of P_n velocities, residual gravity maps, isostatic anomaly maps, global magnetic anomaly maps based on the POGO and MAGSAT measurements) in distinguishing the lithospheric blocks and defining areas which have potential for the discovery of large concentrations of metals. Examples are also shown from structural and metallogenic manifestations of deep-seated structural boundaries extending transversely to orogenic belts.

1.11
THE EAST TUNISIAN STRUCTURAL-METALLOGENIC ZONE: TYPE, ZONING AND TIME OF FORMATION

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Along the boundary between the Tunisian Atlas and the Eastern Platform, there extends a zone transverse to the Mediterranean metallogenic province and elongate in a meridional direction. It shows specific metallogenic features and is referred to as the "province fluoree".

The geotectonic position of this zone is controlled by a suture lineament related to deep faulting and the tectonic mobility beween two megablocks which suffered differential vertical movements of different direction. Its formational affinity is governed by the sedimentary Mesozoic formations of terrigenous-carbonate and carbonate type, among which the limestone-clay and reef formations are of particular importance. Small amounts of tuffogenic Miocene deposits are related to the uppermost parts of the section. A basement of clay-evaporitic Triassic rocks is a characteristic feature of the zone. This plastic saliniferous series favours intensive polycyclic halokinesis. It models the main structural plan of the zone–from consedimentational swells and cryptodiapirs to asymmetric horst anticlines, flexures and thrusting with considerable horizontal transport to the ESE.

The mineral deposits are related to regions of stable uplift, to curvings of the fault structures in plan, rock series with unconformities, paleokarst and specific physico-chemical properties. The morphology of ore mineralizations is variable but stratiform ore bodies predominate.

Typical ore formations in the zone are barite-lead-zinc-carbonate and fluorite-polymetallic deposits with respective transitional types. Accompanying formations are the upper-sulphosalt and mercury formations.

The main mineral parageneses show a normal centripetal zoning with respect to the N-S axis of the zone. In its northern part, this zoning is bilateral in plan while, in the southern part, it is unilateral and asymmetric. This tendency indicates the probable area of most active ore generation and the influence of satelite-detected lineaments as conduits of the ore-bearing solutions.

Lead-isotopic studies shed light on the age and source of ore mineralizations. The thorogenic age of the lead is 32–35 Ma which relates mineralization to epigenetic stratiform deposits developed in areas of tectonic activity. The data on the uranogenic model age and the lead isotope ratio show that the lead was generated most probably in the upper part of the crust. The ore mineralizations resulted from Late Alpine remobilization, and are related to relatively low-temperature (c. 200°C) mineralized solutions in different favourable stratigraphic horizons.

1.12
REGIONAL PROSPECTING BASED ON A PLATE TECTONIC MODEL IN THE PRECAMBRIAN EGLAB MASSIF, SOUTHWESTERN ALGERIA

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The Eglab massif, comprising the northeastern part of the West African craton (eastern part of Reguibat Shield), is mainly composed of Lower Proterozoic calc-alkaline plutonic and volcanic rocks dated at 1850–2080 m.y. and formed during the Eburnean Orogeny. They comprise about 70% of the area, the remainder being older, probably Archaean volcano-sedimentary rocks folded and metamorphosed under greenschist to amphibolite facies conditions.

Precambrian granites are of I- and S-type and are characterized by increased potassium content from west to east. The whole massif is deeply eroded, peneplained and covered with relatively thick desert soil unfavorable for formation of geochemical soil anomalies. Mineralization occurrences are very poor and, if any of economic value are present, they would be deep-seated below the weathered zone.

In order to define zones promising for future prospecting, a

PART B

Intersections of the South Atlas fault with block boundaries defined in the isostatic anomaly map and the magnetic map. Metallogenic implications *

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Abstract

Metallogenic role of intersections of the South Atlas fault in Morocco with N-S trending block boundaries defined in the isostatic anomaly map and the magnetic map is described. An example from the Marrakech sheet is presented and a target area for mineral exploration defined. The discussion is set in the context of a pattern of regularity observed on a global scale.

Structural and metallogenic background

The South Atlas fault or fault zone is an important structural boundary which, as a whole, trends ENE, extending from the city of Agadir on the Atlantic coast across the entire territory of Morocco (fig.2). A possible continuation of the South Atlas fault on the opposite side of the Atlantic was suggested, and movements on the fault since the Hercynian time reported (Manspeizer and others, 1978, with references).

The South Atlas fault bounds the High Atlas Mountains on its south-

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* Part B of the Second semiannual report of 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. Presented September 30, 1986.

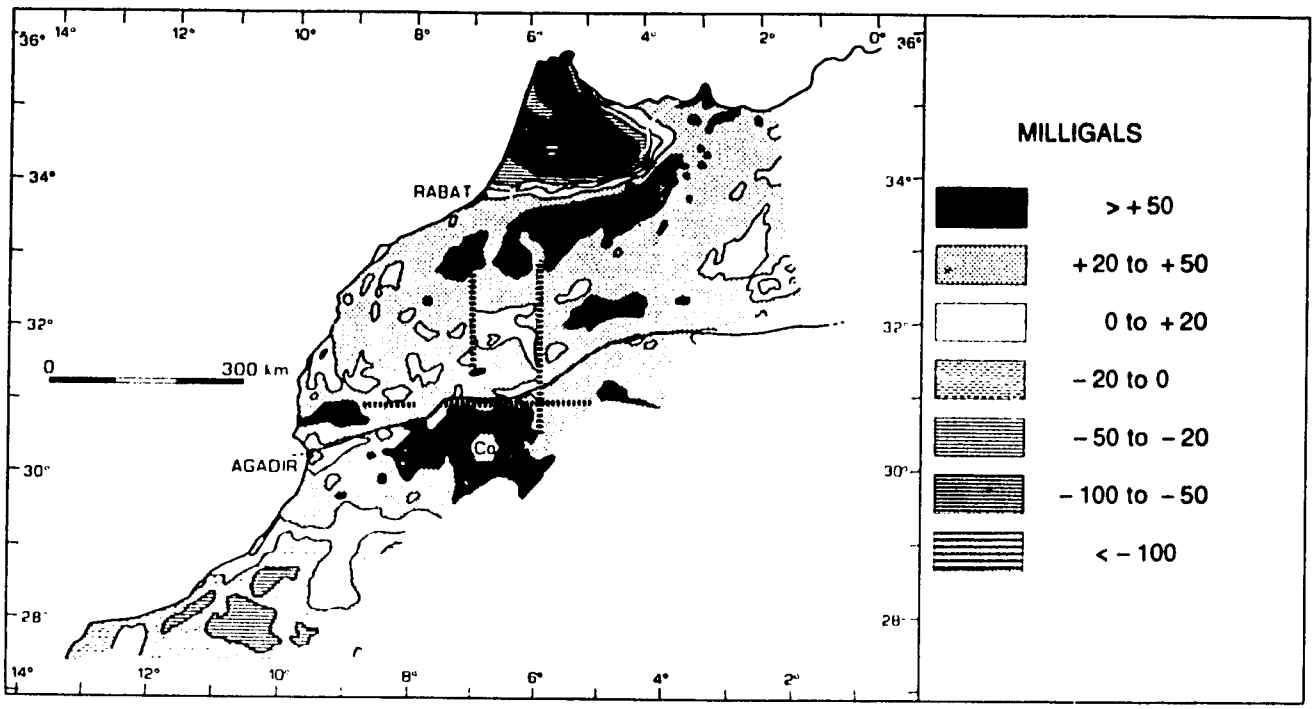

Fig.2

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.3) are structural boundaries distinguished by Jan Kutina. The South Atlas fault, extending east-north-easterly from Agadir, is introduced from Saadi's (1982) map. Reproduced from Bensaid and others, 1985.

The illustration is included here to show changes in the course of the South Atlas fault and their relation to a deeper structure of Morocco, discussed in the text.

ern side, separating it from the Anti-Atlas domain - a belt between the High Atlas on the north and the African Platform on the south. The parts of Morocco located north of the South Atlas fault were invaded, in the Mesozoic, by marine transgression of the Tethys Ocean. The course of the High Atlas and the Middle Atlas Mountains indicate two main pathways of the marine transgression (fig.1).

From a metallogenic point of view the domain of the Atlas Mountains of Morocco belongs to the Tethyan-Eurasian Metallogenic Belt, defined by Jankovic (1985, 1986) as extending from the western Mediterranean, (north Africa and southern Spain) via Alps, Carpatho-Balcan, Lesser Caucasus and Iran into Burma and southern Indonesia, for a total distance of over 10,000 km. The belt was formed during the Mesozoic and post-Mesozoic times in the area of the former Tethys Ocean along the southern margin of the European plate, flanked on the south by the Afro-Arabian and Indian plates (Jankovic, op.cit.).

The belt contains major concentrations of metals, occurring in different geological environments (including rifting, subduction, and other). Among the various types of deposits are magmatic, volcano-sedimentary, ophiolite-bound deposits, porphyry-type, hydrothermal vein-type deposits and other. Similarly as in other metallogenic belts, many ore deposits of the Tethyan-Eurasian belt occur in clusters, separated by segments without significant concentrations of metals. It was shown that such separations of clusters of endogenic ore deposits are, in both the shield and orogenic areas, commonly related to a pattern of deep-seated structural boundaries which delineate lithospheric blocks (Kutina 1976, 1983, and other).

Most recently, the author studied deep-seated controls of mineralization within a broad belt along the 40°N Parallel which extends, on the

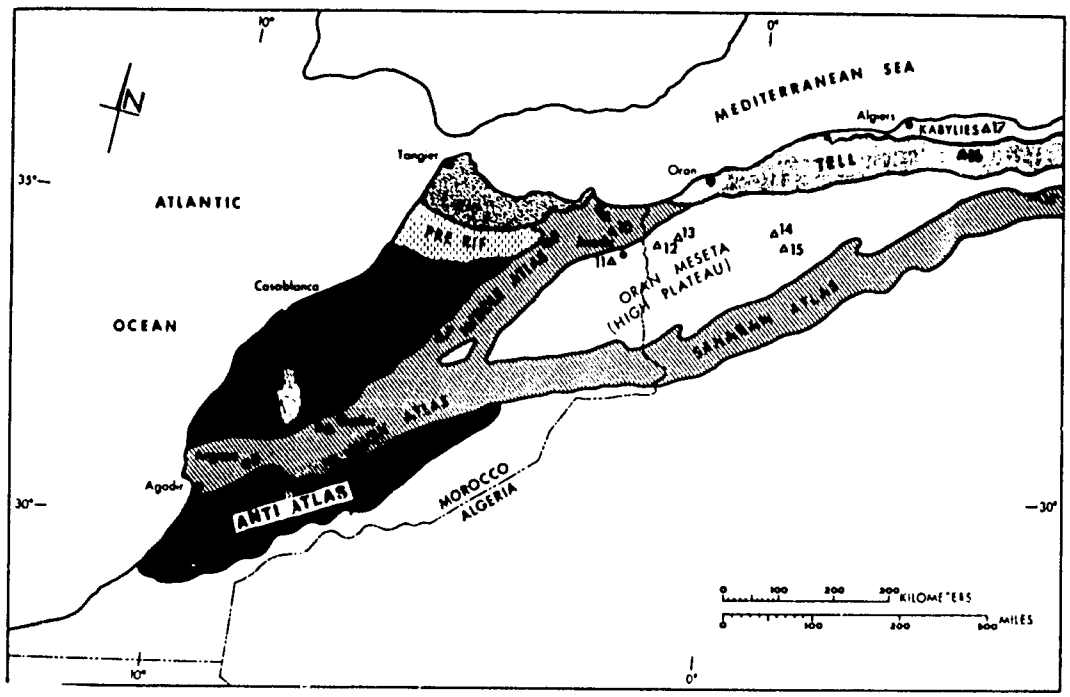

Fig.1. A scheme of the main structural provinces of northwest Africa. After Manspeizer and others (1978).

Note: This illustration will be modified and re-drafted before publication.

western side of the Atlantic basin, across the North American plate and, on the eastern side through the Tethyan-Eurasian belt (Kutina 1986 *). The study revealed significant similarities around the globe, which are of equal importance for Morocco, a territory adjoining the Mediterranean. Among the observations coming out from the global study are: A set of east-trending fracture zones occurs within the belt following the 40°N Parallel. These fracture zones extend across boundaries of modern stress provinces, reflecting a pattern of old structural boundaries originated in the upper mantle under a quite uniform stress distribution. These east-trending boundaries intersect with structural boundaries of other trends, especially the north-south ones, delineating major lithospheric blocks. The movements along boundaries of these blocks have caused their upward propagation through the crust. The same boundaries provided pathways for the ascent of heat, magmas, and ore-forming fluids, so that major concentration of metals could take place preferentially near corners of lithospheric blocks and near intersections of orogenic belts with deep-seated lineaments extending transversely to the belts.

The presence of deep-seated structural boundaries in Morocco was noted by several authors. According to Michard (1976) a dominant role belongs to the NE-SW and E-W directions in the basement. Saadi (1980) and Saadi and Mahmood (1984) have distinguished four sets of structural lineaments, whose general trends are E-W, N-S, NE-SW and NW-SE. Bensaid and Mahmood (1986) recorded two main lineament sets on satellite images of Middle Morocco (the NE-SW and the NW-SE sets). The authors noted

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* A full text of the paper is included as Part A of the present Report.

that the NW-SE set is prominent in older Precambrian and Paleozoic terrains, while the NE-SW set is observed both in the old terrains, as well as in the younger chains and considered the NE-SW lineaments as a reactivated fracture set.

The Moroccan territory provides an opportunity to study deep-seated structural boundaries extending transversely to the High Atlas, the Middle Atlas and the South Atlas fault and to investigate possible role of these intersections in the concentration of metals.

On the scale of the entire Tethyan-Eurasian Metallogenic Belt, the role of such intersections has already been described: Favorskaya and Tomson (1974), Favorskaya (1977),and Favorskaya and others (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 north-south (giving examples, in particular, from Central Asia and the Caucasus). According to Burollet and Byramjee (1986) and others, several N-S trending fracture zones traverse the Mediterranean and the adjoining parts of Europe and Africa. On the African side, the meridional boundary between the Tunisian Atlas and the Eastern Platform has been recently defined as a suture lineament separating two megablocks and was found of metallogenic importance (Maneeva and Tauhmi, 1986).

North of the Moroccan territory Kutina (1971) recognized a major NNW-trending structural boundary limiting the Precambrian of the Iberian penninsula on its western side (the 'Galicia Lineament') and proposed several parallel lineaments in Spain. Favorskaya, Tomson et al. (1974) suggested that the Galicia Lineament belongs to one of two broad structural zones of a N-S trend, extending from Europe into Africa and controlling the distribution of ore clusters.

The task of the present paper is to examine, in the context of the above observations, the presence and metallogenic role of structural boundaries extending transversely to the South Atlas fault in Morocco.

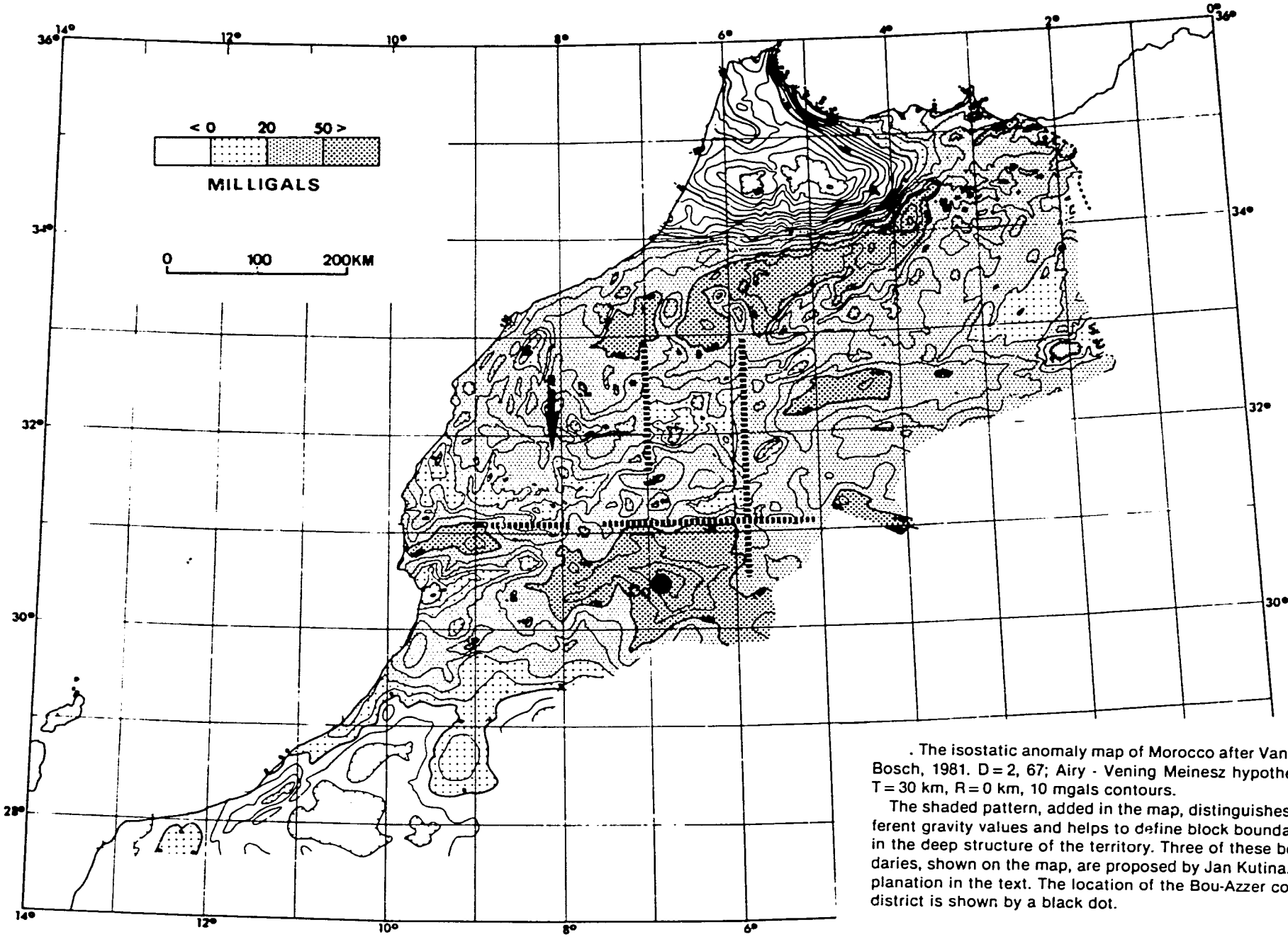
Intersections of the South Atlas fault with N-S trending structural boundaries

The isostatic anomaly map of Morocco, compiled by Van den Bosch (1971, 1981) indicates the presence of structural boundaries of different trends. Two north-south trending boundaries, distinguished in these maps by the author (in Bensaid and others, 1985) are shown in figs.2 and 3. An additional, parallel boundary is shown by an arrow in fig.2, at a longitude close to $8^{o}10'$W.

The above three N-S boundaries extend southward toward the South Atlas fault. The course of the fault, transferred from Saadi's (1982) structural map of Morocco onto a generalized isostatic map of Van den Bosch (1971) is shown in fig.2. The fault, extending from Agadir on the Atlantic coast, exhibits significant changes in its course:

1. An ENE-trending segment extending from Agadir to about $7^{o}45'$W longitude;
2. A short NE-segment between about $7^{o}45'$W and $7^{o}15'$W;
3. An east-west segment between about $7^{o}15'$W and $6^{o}15'$W;
4. A northeast-trending segment between about $6^{o}15'$W and $4^{o}30'$W;
5. A long, essentially east-trending segment, extending from about $4^{o}30'$W beyond 2°W.

Comparison of the above changes in the strike of the South Atlas fault with the gravity patterns in figs.2 and 3 indicates that the changes are related to deeper structure of Morocco. In particular, the E-W segment of the fault occurring between about $6^{o}15'$ and $7^{o}15'$W



. 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.

Fig.3.

This illustration, first reproduced in Bensaid and others (1985) is presented here to show the position of a third N-S trending structural boundary newly distinguished at a longitude close to 8°10'W (marked by an arrow) and discussed in the text. A set of N-S faults, occurring in A.Demnati's 'Magnetic Map of Morocco' (fig.4) indicates a southward extension of the above structural boundary and its intersection with the South Atlas fault.

correlates with an east-west limitation of a zone of gravity highs. While this east-west boundary in the gravity contours can be traced farther west, the South Atlas Fault deviates (between 7°15 and 7°30'W) from the E-W trend, abruptly changing its course toward southwest. A question arises: what is causing such an abrupt change in the course of the South Atlas fault?

The answer of the above question is given in fig.4 which gives the isobath contours of the crystalline basement and A.Demnati's interpretation of magnetic data, both from the excellent 'Carte magnetic du Maroc', scale 1:1,000,000, sheet Marrakech (Demnati, 1979).

The major magnetic lineament, extending from Agadir in an essentially ENE-direction, reflects the course of the South Atlas fault. Two long segments of this lineament can be distinguished :

Segment A striking about N23°E

Segment B striking about N5°E.

The boundary between these two segments is marked by three short magnetic lineaments of a N-S and a NNE-trend. A regional extension of these lineaments is indicated, in southern part of fig.4, by several magnetic lineaments of a similar strike and, in northern part of fig.4, by a north-south limitation of an anticline structure, distinguished in the basement by A.Demnati. The longitudinal position of the three north-south magnetic lineaments, shown at the boundary between segments A and B of the South Atlas fault, correlates very well with the longitude of the gravity lineament distinguished in the isostatic map at about 8°10'W (fig.3).

On the basis of the above data I am interpreting the main structural features of fig.4 as intersection of the South Atlas fault with a N-S

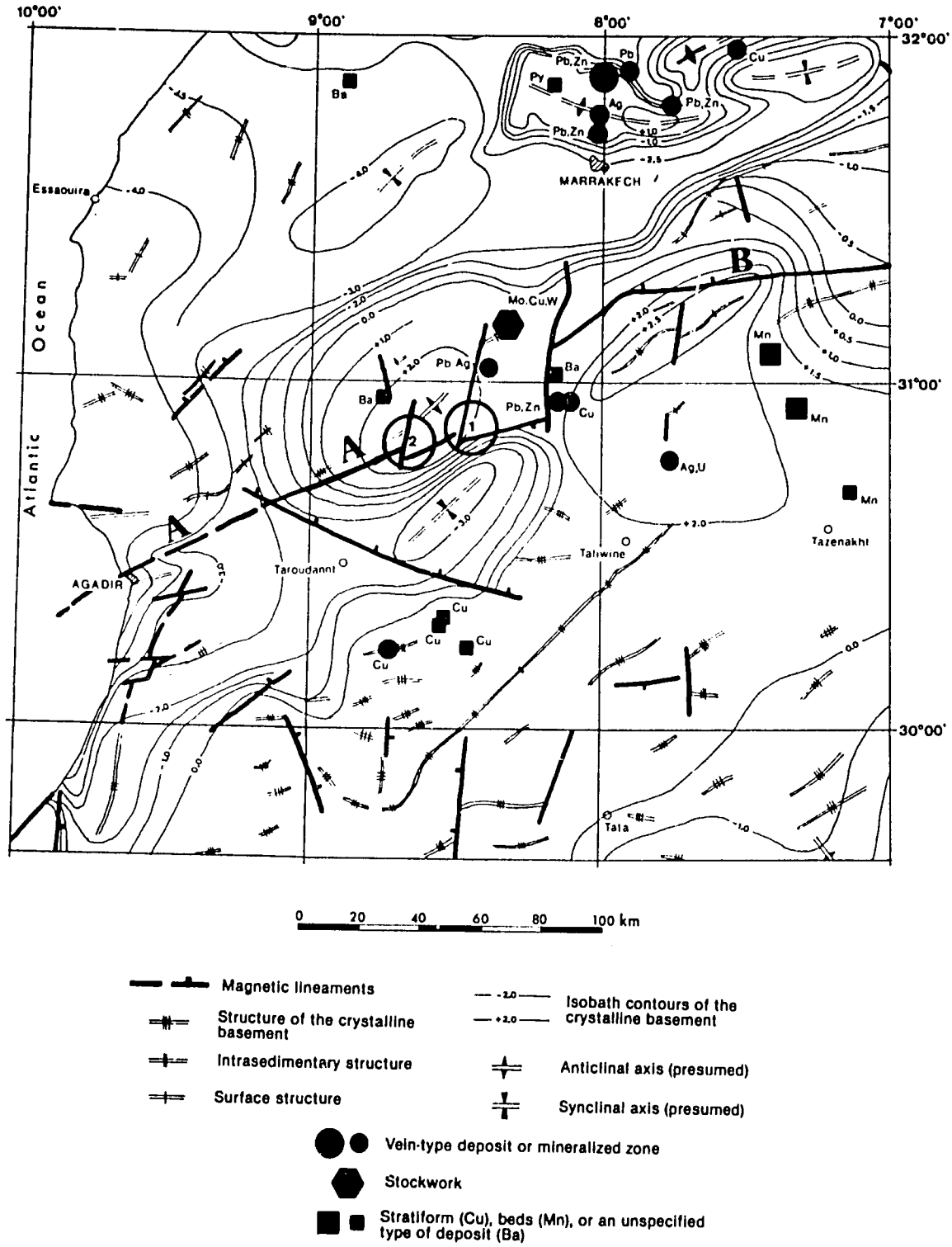
Fig.4.

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

The South Atlas fault, 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 the structure of the crystalline basement. More detailed explanation is in the text.

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 by J.Kutina inside the broader area of intersection, understood as potential for concentration of metals at least as north as the Mo-Cu-W stockwork deposit near Azegour.

Compiled by Jan Kutina, September 1986.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Pb,Zn
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Py
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Pb Ag
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A
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0 20 40 60 80 100 km
Magnetic lineaments
Structure of the crystalline basement
Intrasedimentary structure
Surface structure
Isobath contours of the crystalline basement
Anticlinal axis (presumed)
Synclinal axis (presumed)
Vein-type deposit or mineralized zone
Stockwork
Stratiform (Cu), beds (Mn), or an unspecified type of deposit (Ba)

Fig.4.

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trending structural boundary reflecting block structure of the basement.

The metallogenic role of the above intersection has been examined by plotting ore deposits of the Carte Géologique du Maroc (scale 1:1,000,000, published 1985) onto the structural map of fig.4. The illustration shows that several vein-type deposits (Pb-Ag, Pb-Zn, Cu), as well as a larger Mo-Cu-W stockwork deposit and a stratiform barite deposit occur near the intersection of the South Atlas fault with fractures of the north-south set. It is possible that also the cluster of vein-type deposits occurring north of Marrakech, and the group of copper deposits or occurrences located in southern parts of fig.4 are associated with regional extension of the same N-S or NNE-trending structural lineament.

The above observations, especially the occurrence of the stockwork deposit of molybdenum, copper and tungsten near Azegour indicate that the area between segments A and B of the South Atlas fault, where the fault is intersected by a set of N-S or NNE-trending faults, can be considered as a major target for mineral exploration. The two circles numbered 1 and 2 are places where I suggest that a mineral reconnaissance of the area is started. It should be understood, however, that the whole area of intersection located between the N-S faults and adjacent to them (as north as the Mo-Cu-W deposit) deserves special attention and a detailed mineral exploration. Examination of the new 'Carte de Gîtes Minéraux' , scale 1:500,000, 1980, unpublished), provided by M.Bensaid and A.Bennani, shows that several deposits and occurrences, including Mo, Cu, Pb-Zn and Au) have already been discovered within the areas enclosed by circles No.1 and 2.

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The pattern of regularity described above suggests that concentration of metals may also occur near intersections of the South Atlas fault with the other two N-S trending boundaries distinguished in the isostatic map (figs.2 and 3). The location of the major silver deposit of Imiter (shown in fig.2 in Bensaid and others,1985) indicates that these intersections may be very promising from the viewpoint of concentration of metals. Similarly, intersections of the N-S trending structural boundaries with other NE- or E-W trending boundaries of the basement may be of metallogenic importance. One of them, interpreted in the Foum Zguid region of the Saharan part of the Anti-Atlas, is being recently studied by J.Kutina and A.Bennani. The results will be reported in a separate paper.

The observations presented in this paper resemble a pattern of regularity described from the Příbram Ore Field in Czechoslovakia (Kutina and Tělupil, 1966). In the latter case, the changes in the strike of a NE-trending regional fault zone (the "Clay Fault"), developed along steep-dipping flanks of the Příbram syncline, were found to be related to intersections with N-S trending fracture zones, very poorly expressed in the surface morphology. The classical Ag-Pb-Zn ore veins of the Příbram district, associated with swarms of diabase dikes and extending down to a depth of over 1,500 meters, occur near intersections of the NE-trending Clay Fault with fractures of a N-S trend.

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PART C

Mineral reconnaissance in the Foum Zguid area, Saharan part of the Anti-Atlas, Morocco *

Preliminary Report

By

Jan Kutina

A region of the Saharan part of Morocco, symmetrically flanked on its northern side by two long segments of Jebel Bani (one trending northeasterly and the other essentially northwesterly) and, on the south, delineated by the Oued Draa depression at the Morocco-Algerian border, is interpreted as part of a major structural intersection. This intersection, centered at approximately 29°30'N and 7°00'W, is based on criteria indicating southern extension of a major N-S trending structural boundary defined by the author in Van den Bosch's(1971) isostatic map of Morocco as extending along longitude 7°W (Bensaid and others, 1985) and on the presence of a major latitudinal boundary extending close to 29°30'N.

The northern part of the intersection, occurring on the Moroccan territory, is referred to as the 'Foum Zguid intersection' and is characterized by a great accumulation of basic intrusives, mostly referred to as dolerites.

The first stage of mineral reconnaissance of tn Foum Zguid area, carried out by J.Kutina and A.Bennani in June 1986 was focused, primarily, on criteria which may indicate possible presence of mineralization associated with basic and ultrabasic rocks, especially cobalt,

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nickel, chromium and metals of the platinum group. The field work revealed, in particular:

(1) A site with an outcropping layered-type intrusive;

(2) A zone of alteration near the contact between a basic intrusive and a calcareous sedimentary rock, which is partly serpentinized and mineralized;

(3) A zone of shearing and alteration in argillitic rocks, occuring in central parts of an anticline structure.

The emission spectrographic analysis of a sample with partial serpentinization coming from the SE-tip of the Ikalloula range, has shown in particular, a high concentration of manganese (5,000 ppm), 300 ppm of chromium, 30 ppm of nickel and 10 ppm of cobalt.

One of three samples of a sheared and altered argillitic sediment from the southeastern flanks of Jebel Amsailikh did also reveal traces of cobalt (15 ppm) and nickel (20 ppm).

Relatively high contents of manganese with simultaneous presence of cobalt, nickel and chromium are known from serpentinites of different localities, including Bou Azzer (Leblanc, 1981). It may be of interest to note that both the serpentinites from Bou Azzer and the sample with serpentinization from the Ikalloula range, as well as all three samples of the sheared argillitic rock from Jebel Amsailikh which were analyzed, contain boron. The boron contents given by Leblanc (op.cit.,p.274) in different types of serpentinites from Bou Azzer are in the range of 3 to 28 ppm. Our sample from Ikalloula gave 100 ppm of boron, and the three samples of a sheared argillitic rock from southeastern flanks of Jebel Amsailikh revealed boron contents in the range of 15 to 20 ppm.

The morphology of the Ikalloula range (topographic map, scale 1:100,000, sheet Tissint) and its position with regard to a large anticlinal structure of Ordovician to Devonian rocks (Carte Géologique des Plaines du Dra au Sud de l'Anti-Atlas Central, sheet Agadir Tissint - Oued Zemoul, scale 1:200,000, publ.1971), indicate that the range is controlled by a NE-trending fault following the southeastern flank of a major anticlinal structure.

The sample of a partly serpentinized rock which was used for spectrographic analysis has revealed, under the ore-microscope, minute grains of a sulfide in dimensions usually less than 5 microns. The electrone microprobe analysis of a grain (30 micron size) performed by K.Fredriksson and J.Nelen in the Dept.of Mineral Sciences, Smithsonian Institution, gave the following result:

	Weight %
Ni	38.6
Fe	19.3
Co	4.8
S	33.9
Total	96.6 %

The difference to 100% is partly due to minute inclusions of rock-forming components, giving about 0.9 % CaO. Also manganese has been detected in the same sample. Arsenic, if present, is below the detection limits of the electrone microprobe analysis.

No arsenides of cobalt, iron and nickel, described from Bou Azzer (Vinogradova and others, 1980) have been seen in the samples analyzed.

Preliminarily, the occurrence of serpentinization in the southeastern tip of the Ikalloula range, along with the results of spectrographic analysis and the electrone microprobe analysis indicate that the locality deserves special attention as a possible target for nickel

and cobalt. The author is conducting a mineralogical study of the samples as well as of heavy concentrate from a desintegrated rock from a nearby place, collected with A.Bennani.

Samples from other locations of the Foum Zguid area, collected in 1986, are also being studied.

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The field work in the Foum Zguid area has been done jointly with A.Bennani, Chef du la Division de la Recherche Minière, Ministère de l'Energie et des Mines, Rabat, accompanied by Mohammed Khalek, Head of the Service Regional de la Géologie in Ouarzazate. Best thanks are given to Dr.M.Bensaid, Directeur de la Géologie, and Dr.M.F.Hamouda, Director ajoint de la Géologie, Ministère de l'Energie et des Mines, Rabat, for the support they gave this study.

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