METALLOGENY AND THE NEW GLOBAL TECTONICS

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ABSTRACT.— The economic implications of the new global tectonics are reviewed according to plate anatomy. The uprises, stable platforms, downflows, and median zones exhibit particular features in ore genesis. Intercontinental metallogenic provinces, and intersection of transform fault trajectories with local structures as ore controls are discussed. Possible applications to Turkey are considered.

HISTORICAL INTRODUCTION

Thomas Crook in presenting a history of the theory of ore deposits (1933) argued for a dominant role of exogenic processes (from without) in contrast with endogenic processes (from within). The argument is reminiscent of the current controversy over the meteoritic impact versus volcanic origin of the craters of the moon. Crook found that so many theories of origin of ores had been put forward that it was almost impossible to advance any new general theory.

American, and to a large extent worldwide, thinking on the subject of ore genesis is still strongly influenced by Waldemar Lindgren's classical genetic approach—the classification of ores according to the geological processes by which they were formed. In this classification the quantitative importance of magmatic and hydrothermal ore deposits is recognized.

The pendulum is now swinging farther to the endogenic side and global or plate tectonics provides a mechanism which was hitherto lacking. This does not mean that the time-proven concepts of magmatic segregation and injection, pneumatolysis, hydrothermal and meteoric solutions in veins and replacements, weathering, sedimentation and metamorphism, etc. in ore concentration are being thrown overboard; rather, a new unifying casual principle is emerging in the philosophy of ore search.

The new rationale appears at a time when the well-recognized spatial association of metallic ores with intrusives, as in the Western United States, is being explained as structural rather than genetic (Noble, 1970) and with the metals probably coming from the mantle, in the upper part of which there was a primitive heterogeneous distribution of metals.

That the subject of plate tectonics and ore deposits is a lively one is evidenced by the topic discussed at the March, 1971 meeting of the American Institute of Mining, Metallurgical, and Petroleum Engineers: «Regional Tectonics—How Has it Helped in the Search for Ore?»

We shall continue to employ conventional ore guides and targets—physiographic, mineralogic, stratigraphic-lithologic, and structural, etc.—for indispensable local clues, but large-scale mineral resource investigators such as United Nations, governmental Geological Surveys, and other exploration organization may be expected to apply to some degree the synoptic approach which plate tectonics provides. Whether the new thinking will prove more satisfying to the mind than profitable to the purse remains to be determined. Potentially the concept may prove as useful to the economic geologist as it has to the seismologist in explaining the geometry of the phenomena with which each is concerned.

THE NEW GLOBAL TECTONICS

The crust of the earth (lithosphere) is believed to be made up of a dozen or more plates that are growing at ocean ridges by addition of new material from the mantle, moving independently, colliding, and descending into the mantle where they are remelted. The plates are as much as 150 km thick. They comprise both continents and oceanic crust and they serve as conveyor belts for both. (Dewey & Bird, 1970; Walker, 1970; and Guild, 1971). They are the surface expression of convection cells within the earth. How mineral deposits fit into this picture is tentatively summarized by Guild in Table 1.

The Alpine orogenic period which began about 200 million years ago serves as a model. It includes events from the Triassic onward and is now in terminal cordilleran form. The Alpine drifts eradicated much of the preceding platforms and uprises but events similar to those of the Alpine period may have characterized all ten orogenic periods since 3500 million years ago (Walker, 1971).

The different environments of Alpine mantle cells to which mineralization can be related are as follows (Walker, 1971) (Fig. 1) :

- Uprise
  - a. in oceanic crustal environment
  - b. in oceanic crustal environment with sediment infilling
- Stable platform
  - c. over-ridden by continental crust
  - d. oceanic crust
  - e. continental crust
- Downflow
  - f. in oceanic crust (island arc)
  - g. in continental crust (geosyncline-cordillera)
- Median (between downflows) «Zwischengebirge»
  - h. in oceanic crust (inland sea)
  - i. in continental crust (interior plateau)

Walker's treatment is followed here, with supplemental information from other sources.

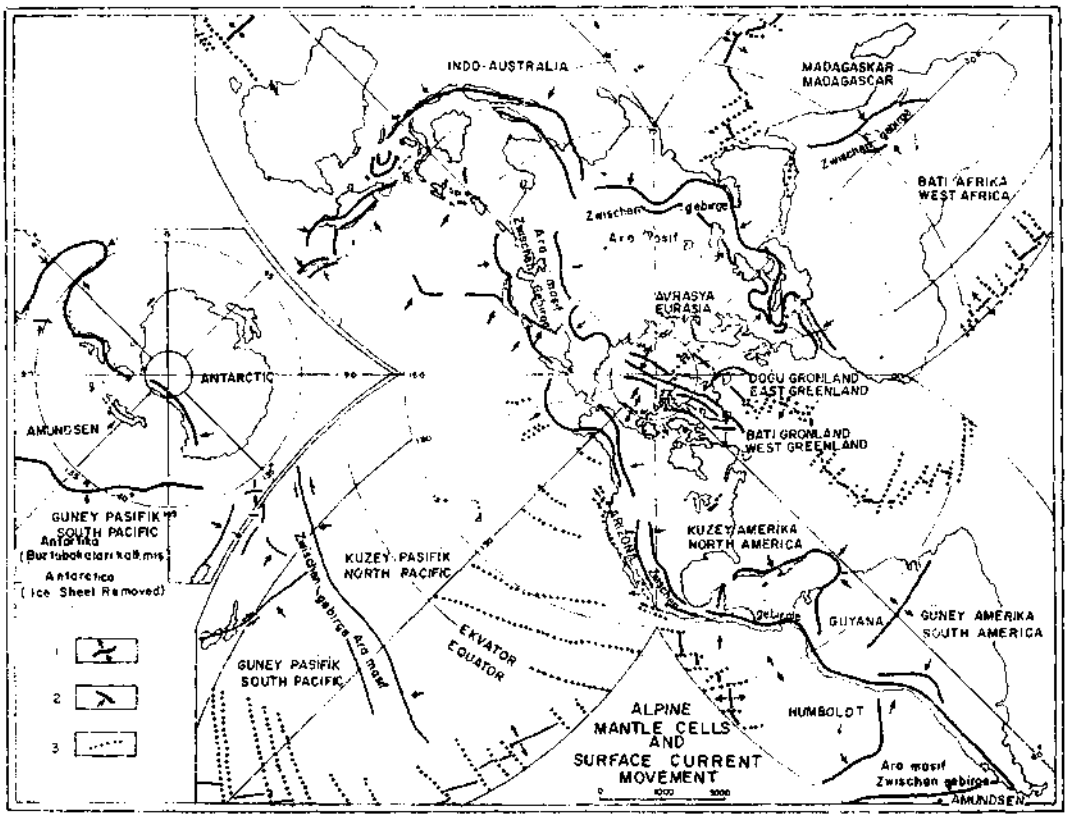

Fig. 1 - Alpine mantle cells and surface current movement (from Walker, 1971).
1 - Uprise; 2 - Downflow; 3 - Transform fault. (Names refer to mantle cells.)

Note : Two directions of movement are common, as for the West African cell; eastward from the mid-Atlantic rise to the African rifts, northward from the rise at Bouvet Island (not shown) to the Mediterranean.

MINERAL DEPOSITS ASSOCIATED WITH SPREADING CENTERS, UPRISES, MID-OCEAN RIDGES, ZONES OF CRUSTAL SEPARATION OR RIFTS

Rift valleys now assume a special interest from the point of view of genesis of mineral deposits. Some of the rifts are sites of active mineralization.

Barsukov *et al.* (1970) note that evidence is accumulating on the importance of abyssal fractures and so-called «through» shatter zones in hydrothermal ore deposition, especially in parts of platforms activated by block tectonics and marked by andesite-basalt magmatism. They cite:

1) the ore-bearing brines in depressions in the Red Sea;

2) the discovery in 1969 of ultrabasic rocks in the mid-Atlantic ridge rift with a zone of fumaroles evacuating substantial, amounts of ore elements from depth during periods of tectonic activation;

3) the detection of very noticeable sorption of a number of ore elements in ash material during eruption of andesite-basalt lavas, and

4) the considerable concentration in volcanogenic-sedimentary Fe-Mn nodules of certain ore elements;

all indicating the role of earth mantle degassing of ore matter transported over weakened zones of the crust, including some metals not hitherto regarded as peculiar to basic magmatism. These Russian authors emphasize the role of abyssal processes of mantle fusion and degassing in the formation of hydrothermal ore deposits and urge that we define more exactly our ideas on the source of ore materials.

The hot brines and Recent iron deposits discovered in the Red Sea in 1965 are described by Miller (1966). They 'occur in an isolated submarine pool more than 2000 m deep. Iron oxide which would be economic on land occurs on the bottom and sides of two hot brine pools. Also present are heavy metals in important quantities, valued at $ 2 billion according to some estimates. The deposits are believed to be due to discharge of deep thermal waters of unknown but probably magmatic origin; they are connected with the tectonic origin of the Red Sea which is commonly regarded as a graben or rift.

Seismic, gravity, magnetic, and heat-flow studies of the Red Sea led Jean-Guy Schilling (1969) and other workers to postulate that this area is a locus of ocean-floor spreadings. «The axial trough may be analogous to the central part of a mid-ocean ridge, and the associated submarine basalts similar to those extruded on a mid-ocean ridge.» Schilling found that the abundance patterns of rare earths of submarine tholeiitic basalts from the axial trough supported this view.

On the East Pacific Rise, Bostrom and Peterson (1966) found heat-flow anomalies with enrichment of Fe, Mn, Cr, Pb, Ni, Ba, and Sr. According to J. Tuzo Wilson (1971) the East Pacific Rise may be projected into the Western United States through Arizona and Utah. In this connection (although the exact relationship is not clear at present) the Salton Sea, California, hot brines, containing abnormal amounts of Cu, Ag, K, Li, Sb, Pb, As, B, Be, Li, Ga, etc., may represent diluted magmatic waters from underlying igneous rocks related to either subduction or rise.

In discussing Irish and Arabian geofractures possibly related to rifts, Russell and Burgess (1969) observe that the nature of the geofractures will be determined by the interaction of positive pore pressures and the strength parameters of the rocks. It is possible, they believe, that in rift areas high positive pore pressures may be developed due to mantle degassing.

Since the mantle is tapped passively by uprises, rather than violently as in downflows, Walker (1971) holds that less variety of metallic mineralization and of host rocks is to be expected in spreading centers.

MINERAL DEPOSITS OF THE STABLE PLATFORMS

As pointed out by Bilibin (1967), the main difference between the magmatism of mobile belts and that of the' platforms is the minor role or even absence of granitic rocks in the platforms. One of the magmatic complexes of the platforms is the «trap formation» which includes both extrusives and intrusives which are less differentiated than those of .the early stages of evolution in mobile belts. Endogenic mineralization of these trap complexes includes magnetite deposits and segregations of copper-nickel sulphides. Lopoliths include the Bushveld platinum-nickel complex of South Africa and the Sudbuiy nickel eruptive of Ontario, Canada. Alkaline rocks are represented by the bodies of nepheline syenite (Arkansas), and alkaline peridotite (kimberlite, Africa). Also related to alkaline rocks are contact metasomatic magnetite deposits, sometimes with small amounts of copper, scheelite, and molybdenite, and hydrothermal deposits of lead and zinc, gold, and molybdenum. The metallogeny of platform regions mostly resembles that of the early stages in the evolution of mobile belts, although the structural elements are so different.

In general the exogenic deposits of the stable platforms are two-fold : on the continental crust are the Mississippian type lead-zinc-barite-witherite-fluorite deposits, potash, and other evaporites. On the oceanic crust are nodular deposits such as manganese with potentially important copper, nickel, and cobalt. All are inter-orogenic in origin (Walker, 1971).

MINERAL DEPOSITS OF THE SUBDUCTION ZONES, CONSUMING OR DESCENDING PLATES OR DOWNFLOW ZONES

The prime source of mineral deposits is the interaction of the downflowing crust and the upper mantle (Walker, 1971).

«The partial melting under high load pressures and shear stresses of oceanic crust in the descending plate provides a likely source of calc-alkaline magma erupted on island arcs as andesite and dacite. Probably involved is partial melting of quartz-eclogite (transformed lower, «dry» basaltic oceanic crust) and a refractory residue of dense eclogite, and of amphibolite (transformed upper, «wet» oceanic crust) also with residual eclogite. Blueschist (glaucophane, lawsonite, aragonite, jadeite assemblage) metamorphism occurs beneath and behind the trench in a region of high pressure and low geothermal gradient.» (Dewey and Bird, 1970.)

«As the oceanic plate descends beneath the continental rise to depths greater than 100 km, submarine volcanics are erupted behind the volcanic front. As the heat flux generated by the rise of basaltic and calc-alkaline magmas increases, an embryonic erogenic welt rises above an expanding dome, the core of which is occupied by rising gabbroic and granodioritic magmas. Post-kinematic granites are later emplaced at high levels in the erogenic belt, below a block-faulted terrain of basaltic and calc-alkaline volcanoes.» *(ibid.)*

According to these authors, the African plate is at present being consumed in a trench system south of the Aegean arc and a collision of North Africa with Greece and Turkey is impending and inevitable. «The Alpine fold belt, between the Ionian trench and the European shield-platform, is a complex maze of ophiolite-flysch-blueschist sutures representing the sites of old trenches. The massifs between these sutures were probably microcontinents and island arcs accumulated by collisions on the northern margin of Tethys.»

Of particular interest are the porphyry copper-molybdenum deposits. These are characteristic of mantle downflow areas:

a) in the continental crust environment, e.g., American cordillera, and

b) in the oceanic crustal environment as in the Phillippines, Solomons, and Puerto Rico.

In general there are no significant differences in mineralization in the oceanic and continental environments, except that layered basic intrusives seem to require a continental platform (Walker, 1971).

Following Walker and Bilibin (1968), it appears that each orogenic episode had a growth pattern of early, syntectonic, and late tectonic events. In the early stage, the outer belts of the downflow system contain flysch deposits of the sedimentary arcs with the following mineral deposits:

1) mercury;

2) the ophiolite type, with magmatic deposits of chromite and osmium, and iridium, asbestos, and lateritic nickel;

3) the gabbroic type with associated magmatic deposits of titano-magnetite and platinum and palladium;

4) the plagiogranite-syenitic type producing skarn deposits of iron and copper, and

5) the volcanic submarine spilite-keratophyre type, giving rise to pyrite-chalcopyrite ore deposits as well as ferric iron and manganese ores.

The inner volcanic belt next develops, with andesite volcanism and syntectonic granite.

Here belong the Kenoran copper-lead-zinc deposits of the Canadian Shield, probably the Alpine silver-lead-zinc belt of Mexico, and largely the tin-tungsten, lithium-beryllium, and tantalum-columbium deposits.

The most important late-tectonic products are quartz monzonite porphyries with copper-molybdenum.

MINERAL DEPOSITS OF THE ZWISCHENGEBIRGE OR MEDIAN ZONE BETWEEN DOWNFLOWS

This mass usually appears as a high platform when it forms on continental crust, e.g., the Anatolian Plateau. Other examples are the interior Plateau of British Columbia, the Colorado Plateau, and the Andean Altiplano in the American cordillera. Tibet is the best example in the Tethyan zone, and Lake Victoria basin in the African rift system. Mineral deposits include the porphyry copper-molybdenum of Highland Valley, British Columbia, and tin in Bolivia.

«When the Zwischengebirge forms in an oceanic crustal environment it is between island arcs, as in the Scotia Sea, or arcs and continents, as in the Caribbean and Seas of Okhotsk, China, and Japan, or between continents that have not met, as the western Mediterranean, -Black Sea and south Caspian Sea. In this oceanic environment no significant mineral deposits are described.» (Walker, 1971).

INTERCONTINENTAL METALLOGENIC PROVINCES

A consequence and confirmation of plate tectonics and more specially continental drift is the matched separation of parts of metallogenic provinces which were originally contiguous.

In a debate about the earth (Wilson & Beloussov, 1968) Wilson observed that from the viewpoint of petroleum exploration young strata in the heart of continents are least affected by plate tectonics. But salt domes and oil deposits of Gabon, Africa, have counterparts in Brazil, formed as the continents split apart and the ocean entered the rift opening in mid-Cretaceous time (Allard & Hurst, 1966). In relation to the occurrence of off-shore oil basins, the Gulf of Mexico was a small evaporite basin during the Jurassic; salt domes have been discovered under two miles of water. Will salt domes also be found in the Mediterranean?

In Gondwanaland the Precambrian sedimentary iron formations of Western Australia and Northeast India may once have been much closer (Dietz & Holden, 1970). The gold deposits of Kolar, Mysore, India and those of Kalgoorlie, Australia are of the same age (Crawford, 1970). Crawford believes that gem and graphite deposits such as those of Ceylon may be expected to occur in Southwestern Australia. He also notes that diamantiferous diatremes in India are closely related to carbonatites. In 1968 carbonatites were recognized in Australia where they are associated with rift networks; this will provide a clue in tracking down carbonatites in Australia, perhaps with associated niobium and other deposits characteristic of this association.

The gold deposits of Ghana occur opposite the auriferous area of Brazil. The diamond deposits of Brazil and Angola, Africa, do not observe the «color line»: the carbonado of Brazil are black, and kimberlite pipes are absent in that country.

Reconstructing the continents around the Atlantic Ocean before continental drift, Schuiling (1967) found that tin belts extend unbroken from one continent to another. The fit of Brazilian and West African deposits is most striking. The source of the tin and its associated elements must be in the crust since the ages of tin mineralization vary within the belts.

In the Irish base metal area Russell (1969) hypothesizes that vertical fissures came up from the upper mantle and deposited lead-zinc ores in Carboniferous limestones at intersections with east-west and northeast-southwest faults of Caledonian trend. The fissures he relates to continental drift which he assumes may be begun in Devonian time, although geophysicists favor a Jurassic, Cretaceous, or even early Tertiary time. Russell refers to somewhat similar deposits in the Maritime Provinces of Canada associated with east-west faults that may have been caused by splitting apart of Africa from eastern Canada. He assigns a role to convective pore water in the convection cell system dissolving lead, zinc, copper and barium ions and precipitating them at rock intersections or, in favorable conditions, on the sea floor.

In a hypothetical example of continental drift in relation to the occurrence of mineral deposits of a type found on oceanic islands, one might apply the evidence advanced by Wilson (1965) on progressive age of islands with distance from spreading centers to the search for matching phosphate and bauxite occurrences on either side of mid-ocean ridges.

A note of caution is sounded by Petrascheck (1968) on wholesale acceptance of separation of metallogenic belts by continental drift. He notes that some areas do not show satisfactory coincidences in time and space or even missing links. For example, the picture is comparatively convincing when Africa is reunited with South America: the gold provinces of Guiana correspond of those of the Ivory Coast and Gold Coast both rich in placers derived from quartz veins in Algonkian schists. The southwestern African and the southern Brazilian goldfields also show relationships. The Brazilian tin-tungsten province and that of Nigeria and Congo north to the Sahara form a belt 5000 km long. Minor metals such as niobium, tantalum, and beryllium occur in corresponding places in the two continents. However, the Gondwandian ore provinces are less clear in other southern continents. Ignoring ice-covered Antarctica, a possible junction to a belt might exist between the Hercynian tin-tungsten province of Western Australia and Argentina in early Mesozoic positions of these land masses. The Laurasian Shields show no analogies of characteristic Canadian types of deposits in Fennoscandia and vice versa, and Greenland provides no connecting link. Caledonian and Hercynian ore provinces of Europe have Appalachian counter-parts but the covered shield of central North America and the Siberian platforms do not exhibit striking similarities.

The great circumpacific orogenic and metallogenic belt with abundant deposits of copper (including porphyry copper), lead, zinc, and antimony is associated with the tungsten, tin and gold deposits of the Precambrian. The Tethys belt is similar petrographically and metallogenetically to the Pacific belt, with the addition of ultramafics and chromite deposits such as those of Southeast Europe, Turkey, Iran and Indonesia. Petrascheck does not consider this belt as an orogenetic result of an anticlockwise rotation of Laurasia versus Gondwana of about 50 degrees, for which large transcurrent faults in the Mediterranean, e.g., the North Anatolian fault, are cited as arguments for still active rotation. «Some features, e.g., the Hercynian Mauretanides or the facies of the Upper Cretaceous are not in agreement with an opposite position of Northwest Africa and Asia Minor—nor are old metallogenic provinces to be fitted together by this 'Operation Tethys Twist.'» He cites the Tertiary base metal mineralization of coastal Spain and North Africa, which he ascribes to the submerged sialic block in the Western Mediterranean, as proof that the relative position of the two continents has not changed since the Miocene. However, extensive shearing movements in Tethys with repeated intrusions and extrusions (ophiolites) of ultrabasic magmas with chromite ores in Paleozoic, Mesozoic, and Eocene times, Petrascheck believes, are probably the result of «deep plowing» into the substratum. Later and partly contemporaneous are many deposits of various metals related to intermediate and acid magmas. He contends that the chalcophile base metals exhalated by submarine diabasic, porphyritic, and even more acidic volcanoes came from the crust; the siderophile metals such as chromium, platinum, and nickel have their origin in the mantle. «The progressive hybridization during geosynclinal subsidence and subsequent orogenesis produced the andesites and granodiorites, associated with chalcophile and granitophile elements. The initial basic magma of the substratum has figured as a kind of collector for the chalcophile metals.» He suggests also that the stratiform deposits of the ancient platforms may have been formed by a diffusion of the primary volatiles of the basaltic substratum, which have leached and deposited metals from the crust («transduction» of Rittmann). This metal diffusion was perhaps more active during periods when the continents did not move. In short, the origin of the metals was, in Petrascheck's view, in the wandering crust and not in the mantle below.

TRANSFORM FAULT TRAJECTORIES AND MINERAL DEPOSITS

Transform faults, usually normal to mid-ocean ridges, are among the major structural features of the earth. They are rotated clockwise with respect to the trend of ridges in the northern hemisphere and counterclockwise in the southern hemisphere on two-thirds of those mapped (Howell, 1970). The mechanism of their formation is not clear. Howell invokes Coriolis force as a possible explanation. It seems reasonable to assume that they may have a landward trajectory although this has been questioned. [As a matter of historical interest, the author used early and sketchy reports on dislocations of the Carlsberg Ridge in the Arabian Sea to explain structural control of the course of the Indus River, West Pakistan (Snelgrove, 1967). These right-handed dislocations, the major one now known as the Owen Fracture Zone, were subsequently identified as transform faults.]

The Murray Fracture Zone is one of the principal breaks in the crust of the northeast Pacific basin. It has been traced from a point off the coast of southern California westward for over 4000 km. It loses its topographic expression on encountering the Hawaiian Arch but can be traced magnetically to its intersection with the Hawaiian Ridge (Naugler & Erickson, 1968). It is with the eastward extension of the associated Mendocino and Pioneer big fracture zones that Kutina (1969) has erected a bold new hypothesis of structural control of hydrothermal ore deposits of the Western United States. Quoting his abstract: «Empirical plotting of four sets of equidistantly spaced shear stress trajectories, based on regularities in distribution of actual faults and ore veins in the continental area and on the landward prolongation of the big fracture zones in the northeastern Pacific gives rise to a prospecting net for the western United States. Preferential accumulation of big ore deposits (including such deposits as Bingham and Tintic) along landward prolongation of the main fracture zones of northeastern Pacific, in the vicinity of intersections of four systems of trajectories and along boundaries of crustal blocks suggests several possibilities for prospecting for unknown deposits in the Cordilleran part of the United States.»

APPLICATIONS TO TURKEY

Turkey, as part of the Tethys mobile belt of Alpine folding, is a downflow zone of continental crust. It is bordered on the north and south by east-west trending mountainous areas which are separated by a median plateau containing the Kırşehir and Menderes stable massifs. It is bounded on the north by the Black Sea oceanic crustal segment which separates it from the Russian platform; on the southeast by the Arabian platform; on the southwest by the Mediterranean oceanic segment which separates it from the African platform; and on the west by the Aegean plates (Fig. 2 and 4).

The Turkish situation is complicated by «Operation Tethys Twist» (Pavoni, 1961 a, *b),* in which Gondwanaland, of which Arabia and Africa are parts, is moving westward along the North Anatolian fault with respect to Eurasia. An additional and recent tectonic element is the separation of Arabia and Africa at

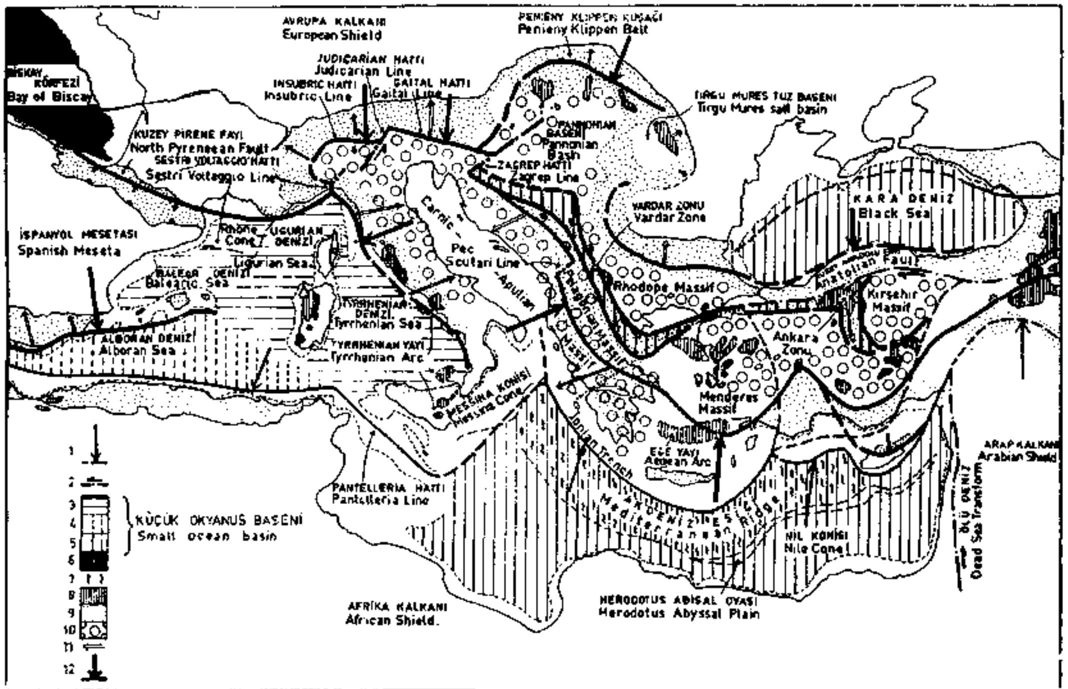

Fig. 2 - Outline of the structure of the Alpine fold belt and the Mediterranean
(from Dewey & Bird, 1970).

1 - Consuming plate margin (arrow on plate being consumed indicates slip direction); *2 - Transform plate margin; 3 - Oligocene - Miocene; 4 - ? age; 5 - Pre-Mesozoic; 6 - Atlantic oceanic crust; 7 - Deformation of sediment; 8 - Neogene volcanics; 9 - Intense Mesozoic-Tertiary deformation; 10 - Tethyan microcontinents; 11 - Structural polarity; 12 - Mesozoic-Tertiary consuming plate margin* (arrow on plate consumed).

the Afar Triangle, a tri-junction of the Gulf of Aden, Red Sea, and African rifts (Tazieff, 1970). The northeasterly movement of Arabia associated with the spreading of the Red Sea may have occurred along the sinistral Levant fault (Gulf of Aqaba) (Burgess, 1969).

The Benioff zone of deep-focus earthquakes which marks plate margins lies in the southern Aegean (Ergin, 1966) but is not as well defined as the one along the western coast of the United States. Cyprus appears to be the site of an underthrust of the African crust as Africa approached Eurasia, heaving up the ultrabasic and related rocks of the mantle (Holmes, 1965, fig. 805). From an analysis of seismicity of the Mediterranean basin, Caputo, Panza, and Postpischl (1970) concluded that the African plate is wedged under the Euro-Asiatic plate with a slope of approximately 35 degrees in the Aegean region, the inflection point being around Nicaria, an island about 120 km southwest of İzmir. The two plates are in relative compression along the contact. (Elsewhere in the world where there is relative compression between two plates, the contact is characterized by volcanic activity, with magmas typical of island arcs, along a line parallel to the contact, and deep-focus earthquakes are found well back of the trench.) Another point of view in the underthrust versus overthrust controversy is expressed by Coleman (1971) who finds that «Focal mechanisms of recent intermediate depth earthquakes in the eastern Mediterranean region suggest overthrusting of the

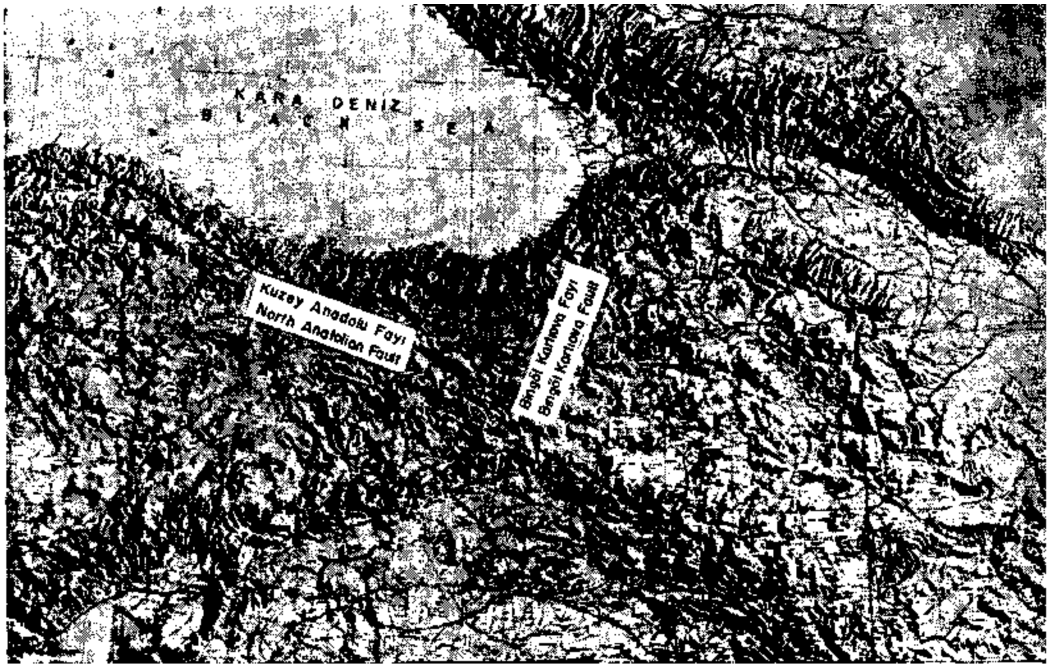

Fig. 3 - Pseudo-radar imagery of Eastern Turkey.

Illumination from northeast. North Anatolian fault terminates at Bingöl - Karlıova fault and may be offset by the latter. Bingöl - Karlıova fault and its extensions may mark margin of Turkish tectonic plate and/or may represent stress trajectory of Gulf of Aqaba - Levant fault - Dead Sea - Lebanon structure. Raised plastic relief map by U.S. Army Map Service, sheet NJ 35, series 1301 P, 1 : 1,000,000. (Photograph courtesy of Mineral Research and Exploration Institute.)

Aegean Sea plates onto the Mediterranean Sea floor.» On the Turkish mainland such southward overthrusting is most pronounced in the southeasterly tectonic unit—the Border Folds (Gümüş, 1970).

Before plate tectonics came into vogue, Mouratov (1960) showed the border of the Russian platform on the northern shore of the Black Sea to be marked by an abyssal fault immediately north of the Crimea. The distribution of foci of earthquakes in the Crimea reveals a concentrated zone dipping steeply under the southern shore of the Crimea. «Thus one can mark the location of a fault zone separating the Crimea from the Black Sea basin; these faults have the character of steep reverse faults, which are still active.» (Beloussov, 1962, Fig. 1.)

That the three earthquake zones of Turkey (North Anatolia, the Aegean, and the northeast-southwest zone at the east) outline a large plate is suggested by Ambraseys' map (Fig. 6).

The well-known authority on Turkish geology, Brinkmann (1969) observed that the oldest sediments in Tethys formed on the borders. He raised the question as to whether Turkey corresponded to a mid-ocean trench between Eurasia on the north and Afro-Arabia to the south. This suggestion, however, is contrary to the idea of petrographic simplicity of ocean-floor spreading centers.

In their outline of the structure of the Alpine fold belt and the Mediterranean, Dewey and Bird (1970) depict the south shore of the Black Sea as a pre-

Mesozoic consuming plate margin and the north Anatolian fault as a transform plate margin with westward movement on the south; Kırşehir and Menderes massifs and the Ankara Zone are shown Tethyan microcontinents. The African plate with overlying oceanic crust is represented as plunging northward beneath the Turkish continental crust in the Mediterranean just south of Turkey, and the Black Sea oceanic crust perhaps subducting northward also (Fig. 2).

It has been suggested (Wong *et al.,* 1971) that the boundaries of continental plates often may be complicated by the existence of small plates whose motion is not simply related to the motion of any of the major plates involved. Thus, the present north-south magnetic lineations of the Troodos Massif, Cyprus, may be due to rotation through approximately 90° since Mesozoic time when, as petrographical and geophysical evidence suggests, Troodos formed at the crest of an east-west-trending Tethyan mid-ocean ridge. The boundaries of the rotated block must be quite close to the present Cyprus Coast. In this connection, the East Mediterranean Ridge, extending from Apulia in Italy across the Levant Sea to the Northern Range of Cyprus (Troodos is in the Southern Range) and continuing into the Turkish mainland as the Misis Mountains is not characterized by linear magnetic anomalies typical of mid-ocean ridges, nor does it possess a central rift valley. «A postulated transcurrent fault is believed to form the western boundary of the wedge-shaped Cyprus block and to extend into Antalya Bay. This fault presumably released the stresses set up by the different rates of northward movement of the African and Arabian Plates. The relative motions between the Eurasian, African, Aegean, and Turkish plates have produced only compression and east-west lateral shear (except along the northern boundary of the Aegean plate) at least since Triassic time. This rules out the possibility of active sea-floor spreading since that period.» (Wong *et al.,* 1971).

McKenzie (1970) asserts that the northern boundary of the Turkish plate is the North Anatolian fault; this fault is continuous with the northern boundary of the Aegean plate which takes up the motion towards the west. «The southern boundary of the Turkish plate is not well defined by the seismicity... It seems to join the southern boundary of the Aegean plate south of southwest Turkey, and to run south of Cyprus into the Gulf of İskenderun to join the North Anatolian fault east of Erzincan.» (see Karlıova structure below) (Fig. 4).

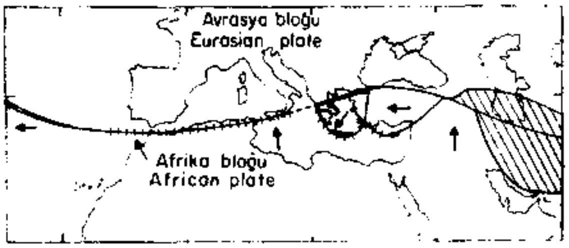

Fig. 4 - Approximate positions of plate boundaries at present active, with arrows marking the directions of motion relative to the Eurasian plate.

Boundaries creating lithosphere are shown with a double line, boundaries consuming plates with short lines at right angles to them. The cross-hatched region in Eastern Turkey and Iran is seismically active throughout. Fault plane solutions here are all overthrusts and show that the crust is being thickned all over this region. Most major shocks within the cross-hatched area occur on major active faults mapped by Wellman from aerial photographs and shown as solid lines (from McKenzie, 1970).

Any account of the tectonics of Turkey must pay special attention to its major fault structure, the North Anatolian faulty This fault, some 1300 km in length, with dextral movement since the beginning of Tertiary time of some 400 km according to Pavoni

(1961), has been compared with the San Andreas fault zone of California and the Alpine fault zone in New Zealand. There is a controversy over the actual amount of displacement on the North Anatolian fault, however. Ketin (1969) gives a figure of 800 to 1000 meters since the Quaternary or Pliocene and a few km during the latter period.

Fig. 5 - Sketch map showing relationship of North Anatolian fault (east-west) to Dead Sea fault system (from Allen, 1969).

Pavoni (19616) states that Upper Cretaceous ophiolites and «colored-melange» type rocks often occur in such fault paths; he believes that in foreland Asia such horizontal movements may indicate relative displacement between Eurasia moving eastwards and Gondwana westward. A surprising feature of the North Anatolian fault is its very abrupt eastward termination of Quaternary displacements 10 km east of Karlıova, Bingöl Province (Allen, 1969). Allen gives as a possible mechanical explanation for this termination: a southwest-trending conjugate fault which terminates at the same point, forming an eastward-pointed wedge. He believes this conjugate fault, part of which is shown on the Erzurum geological quadrangle, to continue more than 70 km southwestward. This structure is revealed strikingly by pseudoradar imagery (Snelgrove, 1970) to extend still farther toward

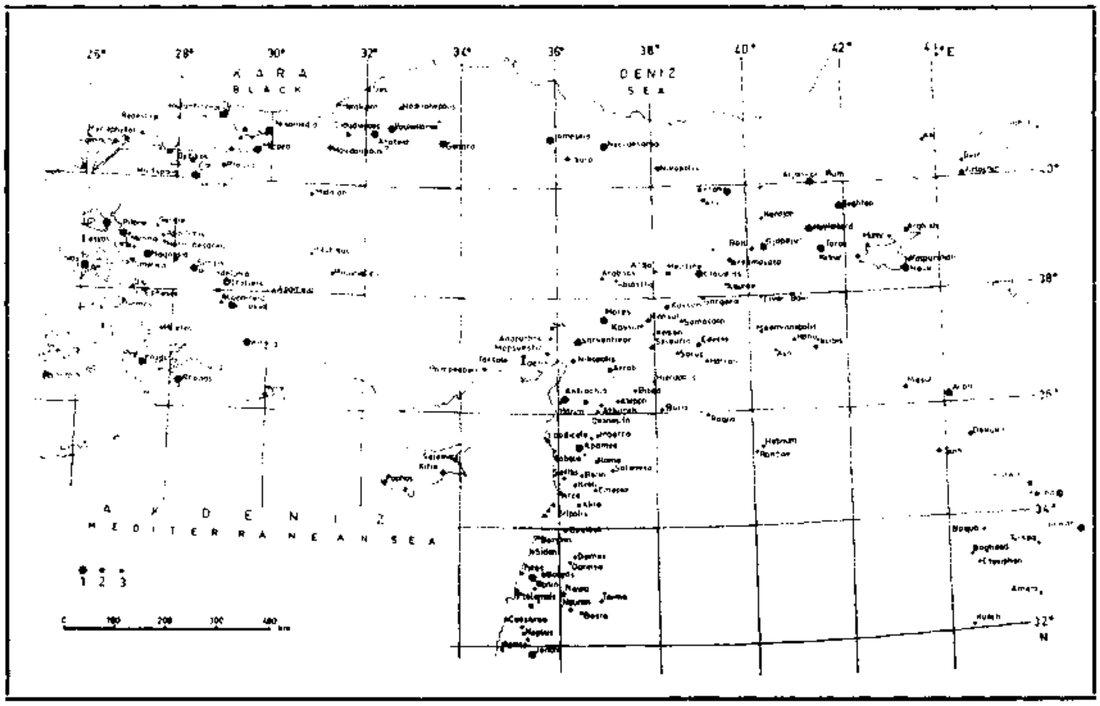

Fig. 6 - Historical earthquakes in the Middle and Near East for the period 10 - 1000 A.D. including historical faulting for the period 850 - 1070 A.D. (from Ambraseys, 1970).

the Syrian border; it possibly displaces the north Anatolian fault dextrally some 50 km and Snelgrove extrapolates it tentatively to Lebanon. The Dead Sea, and the Gulf of Aqaba on the Red Sea, although the sense is sinistral in the south (Figs. 3 and 5).

On an eastern hemisphere scale the North Anatolian fault is part of a dextral system of transcurrent east-west motion which finds expression also in the Azores and the Atlas Mountains of North Africa (Ritsema, 1969). To the east, the parallelism between the Levant - Dead Sea - Lebanon structure and the Owen Fracture Zone displacing the Carlsberg Ridge in the Arabian Sea is striking, but the former is sinistral and the latter is dextral. A similar anomaly exists in West Pakistan where the movement along the Quetta line projection of the Owen Fracture Zone is sinistral whereas on the Arabian sea floor it is dextral. The Owen Fracture zone is one of half a dozen such structures in the Indian Ocean, all of which have a N 15°E trend. They are parallel to a still more extensive continental feature known as the «platinum-nickel zone» which has been traced by Thamm (1969) from eastern Africa through the Middle East and on to Northern Siberia. New discoveries in this great circle system of jointing and mineralization are pipe-like deposits of nickel in Saudi Arabia and platinum deposits in Soviet Armenia. This zone is older than the Alpine folded belt of the Middle East and is slightly deflected in trend eastward to the north of the Caucasus, perhaps due to rotation of the northern block or the southern block.

Within this structural framework metallogenesis in Turkey reflects the tectonic units present. The subject is discussed by Egeran (1946), Nahai (1958), and Gümüş (1970). Of fundamental importance is the plate tectonic relationship of these units: are they features of cordilleran-type continent/ocean collision (which is the type site of most orogen-associated endogenic mineral deposits throughout the world), or are they due to continent-continent collision in which neither plate can descend far because of buoyancy and consequently the force is dissipated by severe crushing? The continent/continent collisions do not produce igneous rocks and are notably deficient in hydrothermal ore deposits (Guild, 1971). An example of continent/continent collision is the Himalayas with a dearth of mineral deposits, quite unlike Turkey. A possible explanation is that upper-level magmatism in the Himalayas was inhibited by the thick sedimentary column.

Gümüş (1970) states that the tectonic development of Turkey took place from the north and northwest towards the south and southeast. Crystalline massifs arc present in every unit but their ages are not precisely determined. The six tectonic units recognized by Egeran (1946) and their main tectonic characteristics are:

1) Pontides. At the north. Affected by Cretaceous and Eocene tectonism. Continuation to east in Elburz Mountains of Iran and Hindu Kush Mountains of Afghanistan (CENTO, 1969).

2) Anatolides. Pre-Eocene movements dominant.

3) Median Unit. Movements during Eocene and Cretaceous, also Oligecene and Miocene.

4) Taurides. Paroxysm before Eqcene. Formed by northward movement and counterclockwise rotation of Arabia and its thrusting against Eurasia (Girdler, 1970).

5) Iranides. Extensive movements during Eocene and Upper Cretaceous. Continuation of 4 and 5 to east in Zagros Mountains of Iran (CENTO, 1969).

6) Border folds at the southeast. Movements started in Oligocene and continued up to Pleistocene. Continuation to the east in folded belt of the southwest Zagros, and the Indus Basin area of Pakistan (CENTO, 1969).

Ignoring pre-Alpine igneous activity, three groups of intrusions formed during the subsidence and folding of the Alpine geosyncline:

Ultrabasics; Cretaceous to Eocene, common in the Iranides and northern part of the median unit;

Basic and intermediate (gabbro, dolerite, basalt, diorite, andesite); Cretaceous to Eocene, in the Pontides and median unit; and

Acidic; Mesozoic - Eocene, at the margins of the median unit and the eastern Pontides.

Of post-Alpine age and closely related to cratogenic movements are Eocene basalts, Oligocene - Miocene andesites, trachytes, and rhyolites, and Quaternary basalts; these are found chiefly in the median unit near the Arabian Shield.

According to Egeran the distribution of ore bodies with respect to tectonic units shows that, with the exception of sulphur deposits, most mineralization is associated with Alpine igneous rocks where intensive tectonism has occurred. Important deposits are found in eastern Anatolia where the Pontides, Anatolides, Torides, and Iranides converge. The Anatolides, Torides, and Border Belt have no important mineralization because these units are part of the deepest portion of the Alpine geosyncline where thick sedimentation and lateral orogenic movements occurred and no intrusives are present. The most intensive mineralization is localized along the southern margins of the Pontides (copper, manganese, and lead - zinc), along the northern margins of the Iranides (chromite, lead-zinc, copper, associated with Upper Cretaceous and Eocene intrusives) and along all the margins of the median unit (with chromite, iron, zinc, lead, mercury, and stibnite).

With the above metallogenic provinces already defined and following the principle that «like breeds like» the search for new deposits within individual units is likely to be guided by conventional approaches. What use, then is plate tectonics in ore search?

It seems to the author that the most intriguing and potentially most important application of the new global tectonics in Turkey lies in exploration for porphyry copper-molybdenum deposits. Such deposits have been discovered in adjacent parts of the Tethys mobile belt—Medet in Bulgaria, Chalkidiki in Northern Greece and Sar Chesmeh in the Kerman region of Iran — and the Government of Turkey - United Nations Development Programme Project TUR-32 may have found one at Bakırçay, Merzifon Subdistrict, north of Amasya, in the Pontides tectonic unit.

If the suggestion be accepted that the three earthquake zones of Turkey outline a large tectonic plate, each of these zones presents a broad target in the search for porphyry copper-molybdenum.[2] Narrowing the target are the well recog-

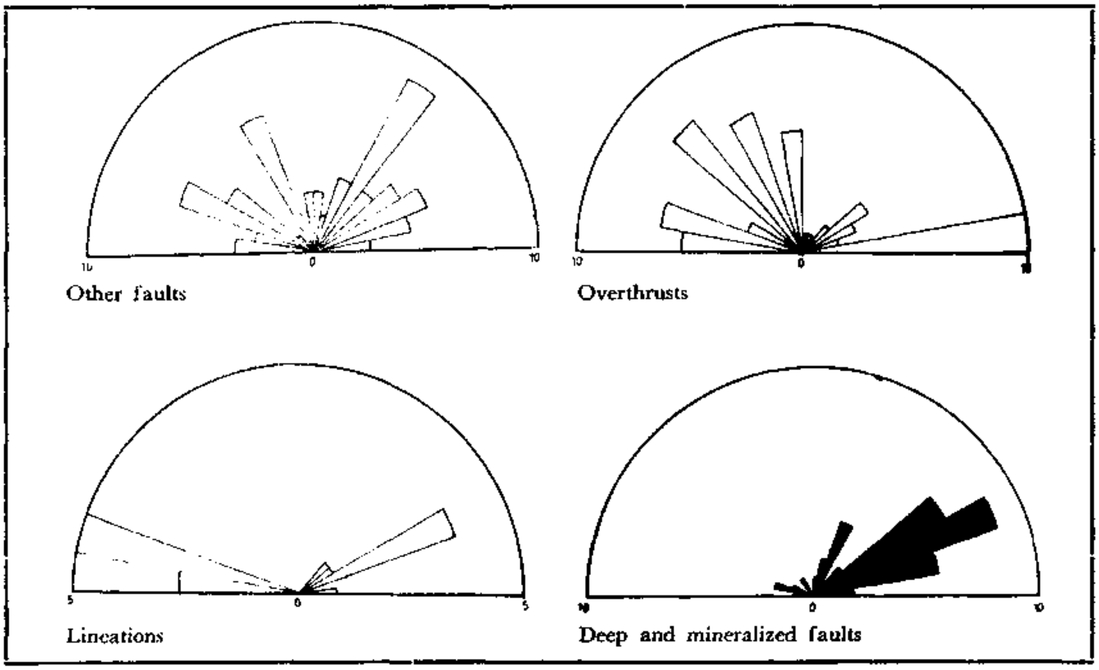

Fig. 7 - Rose diagrams of other faults, overthrusts, lineations, and deep and mineralized faults. Plotted from Altan Gümüş's map (1970) by Ender Atabey, M.E.T.U. student.

nized association of these deposits with crackled quartz monzonite stocks about 1 mile in diameter, their space relationship to lineaments and fracture patterns as in the southwestern United States (Badgley, 1962), an average age of about 60 million years, specific coaxial concentric zones of lateral and vertical alteration and mineralization, and relative concentration of cobalt, gallium, germanium, indium, nickel, silver and tin in chalcopyrite and sphalerite in mantle-tapping districts as compared with occurrences of these minerals in deposits formed by meteoric waters[3] (Lowell and Guilford, 1970; Badgley, 1962).

Recognizing the value of local controls, the advanced students in Geological Engineering at Middle East Technical University recently began a statistical analysis of Turkish epigenetic mineral deposits. For example, intersection of N-S/NW-SE and W-E/NE-SW fractures exerts a control of ore at Murgul copper area, whereas northwest fractures are preferentially mineralized and northeast ones are barren at Göynük-Çukurören, Gediz antimony area. This survey is being computerized by Mineral Research and Exploration Institute (M.T.A.). Plotting only those structures shown on Gümüş's (1970) map of Turkey, strong orientation of north seventy-five degrees east is noted for deep and mineralized faults and to a lesser extent for lineations[4] (Fig. 7).

Table - 1

Proposed relationship of some ore-deposit types to plate tectonics

Deposits formed	*Type, possible examples*
At plate margins:	Orientation of deposits, districts, and «provinces» tend to parallel margin.
Accreting:	Red Sea muds. Ancient analogs (?).
	Podiform Cr (probably carried across ocean basin before incorporation in orogen).
Transform:	Podiform Cr, Guatemala (?)
Consuming:	Chiefly of continent/ocean, also of island arc/ocean types; deposits formed at varying distances on side opposite oceanic, descending plate.
	Podiform Cr, Cuba, California, Oregon, Alaska.
	FeS-Cu-Zn (Pb) strata-bound massive sulfides, Cuba, California, Alaska, Kuroko ores, Japan.
	Mn of volcanogen type associated with marine sediments, Cuba, California, Olympic Peninsula.
	Magnetite-chalcopyrite skarn ores, Puerto Rico, Cuba, Mexico, California, British Columbia, Alaska.
	Au, Mother Lode, SE Alaska.
	Bonanza Au-Ag deposits.
	Cu (Mo) porphyries, Puerto Rico, Panama, Mexico, SW United States, British Columbia.
	Ag-Pb-Zn, Mexico, western United States and Canada.
	W, Sn, Hg, Sb.
Within plates:	Deposits tend to be equidimensional; distribution of districts and «provinces» less oriented.
In oceanic parts:	Mn (Cu, Ni, Co) nodules.
	Mn-Fe sediments in small ocean basins with abundant volcanic contributions (?)
	Evaporites in newly opened or small ocean basins.
At continental margins of Atlantic (trailing) type:	Black sands, Ti, Zr, magnetite, etc.
	Phosphorite on shelf.
In continental parts:	Mississippi Valley-type Pb-Zn-Ba-F deposits.
	Mesabi and Clinton types of iron formation.
	Evaporites; Michigan Basin, Permian Basin; salt, potash, gypsum, sulfur.
	Red bed Cu; Kupferschiefer and Katangan Cu.
	U, U-V deposits, Colorado Plateau and elsewhere.
	Ti in anorthosite.
	Carbonatite-associated deposits of Nb, V, P, Re.
	Diamonds in kimberlite.
	Stratiform Cr, Stillwater; Cr, Fe-Ti-V, Pt, Bushveld.
	Kiruna-type F, SE Missouri.

Source: Guild, Philip W., 1971, Metallogeny: A key to Exploration, Mining Engineering, Jan., p. 70.

The question arises whether major faults are themselves mineralized or whether they served as conduits for mineralizing solutions. The San Andreas fault of Western United States and the Great Glen fault of Scotland are not mineralized, but the Kirkland Lake, Ontario, Canada «break» is the locus of important gold deposits. Is the northeasterly Karlıova-Bingöl fault and its presumed southwesterly extension a plate margin or, as a transform-fault stress trajectory of the Red Sea rift, does it provide a structural guide to porphyry copper in combination with appropriate intrusives and local structures?[5] The situation is broadly analogous to that in Arabia where, as Russell and Burgess (1969) observe, «The intersections of north-northeast wrench faults with northwesterly tension fissures in the Arabian segment may be favorable sites for mineralization, depending on availability of metals and sulphur in the crust, as well as the presence of suitable host rocks.»

This is but one of the tempting dishes which plate tectonics offers to the exploration geologist in Turkey.

Added in proof:

In a discussion of «Seismotectonics of the Persian Plateau, Eastern Turkey, Caucasus, and Hindu Kush Regions,» Ali A. Nowroozi (Seismological Soc. Amer. Bull., vol. 61. no. 2, April, 1971, p. 322) shows that the Abul-Samsar fracture zone of the Caucasus extends southwest into Turkey and is delineated by a line of shallow-focus earthquakes in the vicinity of the Bingöl-Karlıova fault. This is another piece of evidence for what appears to be a throughgoing fracture zone stretching between latitudes 28°N (Gulf of Aqaba) and 43°N.

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