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THE GEOLOGY OF THE TIMNA VALLEY WITH EMPHASIS ON COPPER AND MANGANESE MINERALIZATION — UPDATING AND CORRELATION WITH THE EASTERN MARGINS OF THE DEAD SEA RIFT

by

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תקציר

בקעת תמנע זוהתה לעיתים עם מכרות המלך שלמה, אך עיקר כריית הנחושת בה נעשתה בתקופות היסטוריות אחרות. הגיאולוגיה של האיזור נלמדה ביסודיות מאז שנת 1947. מאז הקמת מדינת ישראל בוצעו בבקעת תמנע וסביבותיה סקרים ומחקרים רבים בעיקר בהקשר לפעילות מכרות הנחושת. בשנות ה-80 בעקבות גילוי מינרליזציה של אורניום באיזור החל המחקר באיזור להתרחב. הדו״ח הנוכחי הוא עבודה קומפילטיבית בעיקרה המסכמת את הסטרטיגרפיה (עם דגש לתצורות מגיל קמבריום) והטקטוניקה של בקעת תמנע עם דגש למינרליזציות הנחושת בתצורות השונות והשואתן ליחידות מקבילות במזרח בקעת הערבה.

תצורות עמודי שלמה, תמנע ושחורת, מגיל קמבריום תחתון עד תיכון, רבודות ביחסי onlap על תבליט הסלעים המגמטיים מהפריקמבריום העליון. אבני החול הקוורץ-ארניטיות והפצלים (תצורות: אמיר, עברונה וסמר), ששויכו לחבורת כורנוב, הורבדו על גבי משטח ארוסיבי המציין גידוע של כ-2,500 מטר של סדימנטים פליאוזואיים. בתמנע הגידוע מגיע כנראה עד לפרט התחתון של תצורת שחורת.

המבנה של בקעת תמנע מאופיין בגוש מורם במרכז (מעין דום), כגלעין, המוקף מצפון, ממערב ומדרום ע״י גושים סטרוקטוראליים מעט נמוכים יותר, ובמזרח ע״י גושים ירודים ממערכת בקע ים המלח.

סלעי המקור למינרליזציות הנחושת והמנגן באיזור הם הדולומיטים של תצורת תמנע. בתהליכים אפיגנטיים, קנוזואיים, תמיסות הידרותרמליות בטמפרטורה נמוכה פעלו לאורך ובשולי שברי הבקע וגרמו להעשרה הסופית של מרבצי הנחושת ומנגן המתארחים בתצורת תמנע. יתכן והמגמטיזם של הקרתיקון התחתון בצפון בקעת תמנע תרם גם הוא לתהליכי המסה, נדידה והעשרה של נחושת ומנגן בתצורת תמנע ובאבני החול מגיל קרתיקון תחתון.

ABSTRACT

The Timna Valley, the area of the ancient king Solomon mines, has been geologically studied since 1947, mainly during the operation of the Timna Copper Mines. The present report includes the stratigraphy (with emphasis on the Cambrian units) and the structure of the Timna Valley with emphasis on the copper mineralization and its correlative occurrences in the eastern Arava Valley

The Timna Fm., together with the Amudei Shelomo Fm., onlap a paleo-relief of the Precambrian crystalline rocks. The Timna Formation is conformably overlain by the continental, fluviatile middle Cambrian(?) Shehoret Formation. The Mesozoic clastic sequence of the Kurnub Group was deposited on a regional erosive unconformity, which truncated about 2,500m of Late Paleozoic sedimentary sequence.

Structurally the Timna Valley has a high elevated internal magmatic core, cut on its eastern side by the Dead Sea rift.

The dolomites of the Timna Formation are the main source-rocks for copper and manganese mineralization in the area. Epigenetic, hydrothermal activity that occurred mainly along faults and lineaments of the Late Cenozoic Dead Sea rift, caused the final major enrichment of these metals. It is possible that Lower Cretaceous magmatic activity in the northern Timna Valley also contributed to the metallic remobilization and enrichement process.

PHYSIOGRAPHY

The Timna Valley, is an erosional horse-shoe shaped or half a "Makhtesh", bounded by steep cliffs on all sides except on the east, where it is open toward the southern Arava Valley. This valley is around 10x9km; its core is a topographical and structural high of Precambrian igneous rocks (magmatic massif, Har Timna, 5x3km) which is elongated in an E-W direction (Fig. 1).

The magmatic massif is surrounded by gently outward dipping (3-10 degrees) Lower Paleozoic to Upper Cretaceous sedimentary rocks. The lower parts of the cliffs, which are up to 470m high, are built by the sandstones of the Lower Cretaceous Kurnub Group, and the upper parts, by the limestones and dolostones of the Upper Cretaceous Judea Group.

The Timna area is drained by seven eastward-running ephemeral streams: N. Nimra, N. Raham and N. Gadna, which drain the southern parts, including Har Hahklil (409m in elevation); N. Nehushtan, which drains the southern parts of Har Timna (448m); N. Timna, which drains the northern parts of Har Timna and the southern Har Mikhrot area; N. Mangan and N. Sasgon which drain the northern parts of the valley including the northern Har Mikhrot (334m) and Har Sasgon (297m) areas.

PREVIOUS WORK

The geological mapping of the southern Negev, including the Timna Valley, was done by Shaw (1947), Bentor and Vroman (1955), Bartov (1967), Garfunkel (1970), and Segev and Beyth (1983, 1986). Additional detailed mapping of mining regions within the Timna Valley was carried out by the geologists of the Timna Copper Mines. Detailed structural mapping was done by Mart and Horowitz (1981). The magmatic core of Har Timna was mapped and studied by Zlatkine and Wurzburger (1957) and Beyth (1987b), and dated by Halpern and Tristan (1981), Bielski and Kolodny (1981), Bielski (1982) and Kroner and Beyth (1990). The stratigraphic units used in the mapping were mainly based on Bartura (1966), Weissbrod (1969a,b; 1981) and Segev (1984, 1986a). The lithostratigraphy of the classic Paleozoic sequence ("Nubian Sandstones") was studied by Weissbrod (1981), that of the Cambrian marine sequence by Segev (1986a), and Segev and Sass (1989). On the basis of paleontological studies of the latter sequence: a. trilobites (Parnes, 1971), and b. brachiopods (Cooper, 1976), a Lower Cambrian age was determined for this marine sequence.

Studies concerning the copper and manganese ores were made by Bentor (1952, 1956), Sturm (1953), McLoad (1959), Milton (1966), Wurzburger (1967, 1970), Magaritz (1969), Bartura and Wurzburger (1974), Bar-Matthews (1986, 1987), Segev (1986a,b) and Beyth (1987a). Copper mineralization in the Kurnub Group was studied by Keidar (1984).

Assuming a sinistral movement along the Dead Sea Rift (Freund, 1965) and that Feinan is the eastern continuation of the Timna Valley (Garfunkel, 1981, and Fig. 2), the works carried out on the eastern side of the rift also have

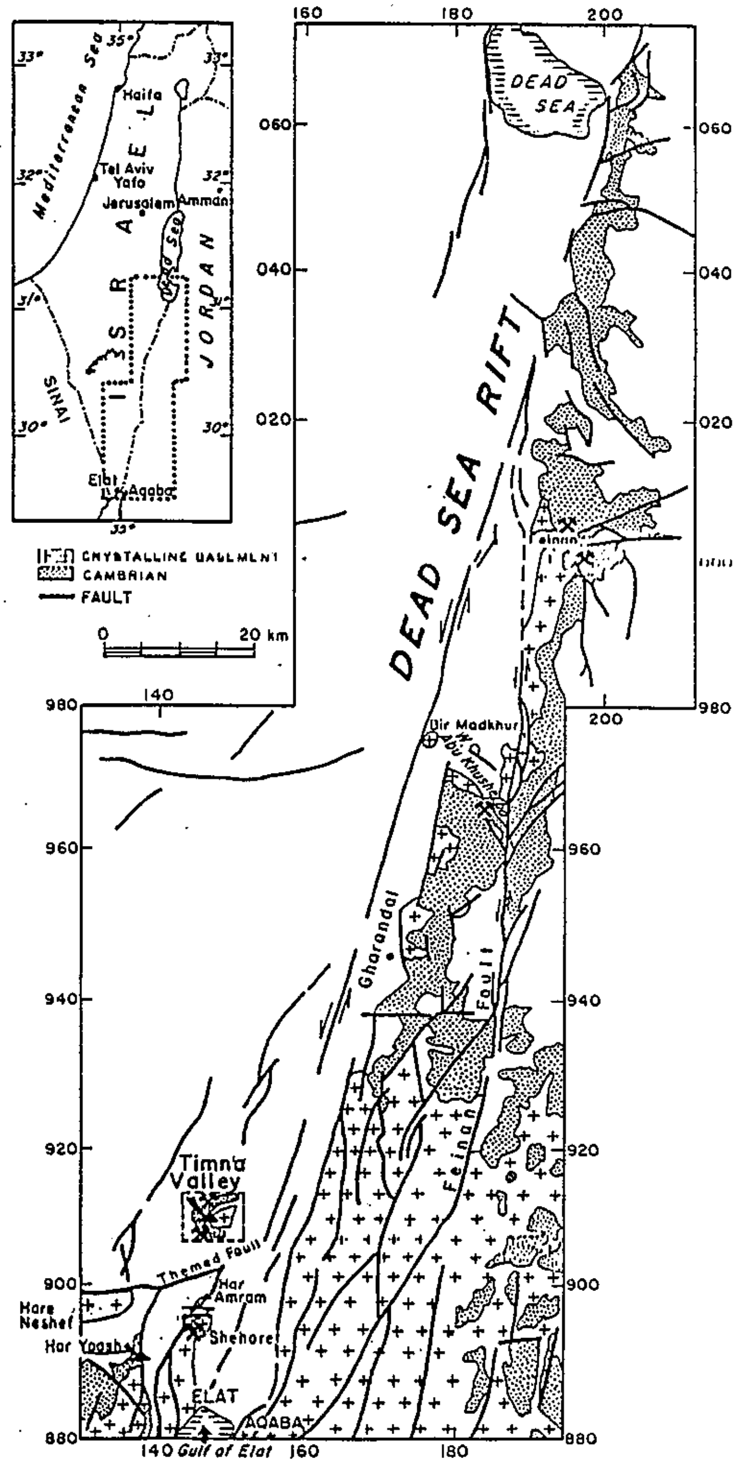


Fig. 1. Location map and main fault pattern of the southern Dead Sea Rift

important bearing for the present study.

Bender (1965, 1974) mapped the eastern margins of the Dead Sea Rift, including the copper mines of Feinan-Wadi Dana; Manganese mineralization in these areas was studied by Boom (1969); Basta and Sunna (1971, 1972), Bigot (1982) and Heitkemper (1988) studied the copper and manganese mineralizations in the same areas.

Geochemical investigations were carried out in the Timna Valley by Ayalon et al. (1985), Segev (1986a), Beyth et al. (1988), and on the Jordanian side, by Burgath et al. (1984).

For further information on previous work, see the Geological Research Bibliography of the Arava and Elat region (Bartov and Arad, 1989).

STRATIGRAPHY

Precambrian Basement

The magmatic rocks in the Timna area are in the northern margin of the Arabo-Nubian Massif (Bentor, 1961, 1985). A wide range of shallow intrusives and dikes ultramafic rocks to alkali granites constitute the Har Timna magmatic complex. This complex was studied by Zlatkine and Wurzburger (1957); Beyth (1987b) and Shpitzer et al. (1989; Fig. 3).

Detailed mapping and petrographic studies (Shpitzer et al., 1989) of a critical section in the northern part of the Har Timna complex enable classifying the intrusive rocks into three main groups: a) basic/ultrabasic (pyroxene-hornblende-olivine-peridotites and pyroxene- hornblende-olivine- norites); b) intermediate (diorites, monzo-diorites, monzonites, quartz monzo-diorite); and c) acidic (porphyritic calc- alkaline granites, perthitic alkali granites and albite-orthoclase alkali granites).

The contacts between the basic/ultrabasic rocks and the intermediate rocks are gradual, whereas those between these two groups and the acidic rocks are sometimes sharp and sometimes gradual. The contacts between rocks in the intermediate group are always gradual, with the exception of a quartz monzo-diorite body, which is located in the south of the area studied. This intrusion cuts all the other plutonic rock-types including the dikes of acidic composition.

Dikes can be classified into four main types: a) acidic (alkali rhyolites); b) basic to intermediate (dolerite to andesite), c) composite dikes, and d)doleritic dikes. The above-mentioned quartz-monzo-diorite intrusion is younger than the N-striking acidic dikes, but older than the NE-striking basic to intermediate ones.

Field relations between the various groups of rocks define their evolutionary history as follows: 1. Calc-alkaline granite; 2.basic/ultrabasic and intermediate; 3. alkali granite; 4. N–striking dikes; 5. quartz monzo-diorite; 6. NE–striking dikes; 7. Doleritic dike.

Electron microprobe analyses of olivines, biotites and amphiboles from the various groups of rocks (Shpitzer et al., 1989) yield significant variations in Mg/Fe ratios. As the rocks become more acidic the Mg/Fe ratios of the major iron and magnesium-bearing phases decrease. This corresponds to the calc-alkaline AFM trend shown by whole-rock chemical analyses (Beyth, 1987b).

Ore minerals show a transformation from chromite in the basic/ultrabasic group to magnetite in the acidic rocks. Clinopyroxenes in peridotites have a high Cr_2O_3 content of 0.70%, which is generally considered as indicating a mantle source. The mineral chemistry data and field relations support a genetic model of calc-alkaline differentiation of the basic/ultrabasic-intermediate-calc-alkaline groups.

Uplift and peneplanation during the Lower Cambrian marked the end of the evolution of the crystalline basement.

Yam Suf Group

Introduction

The exposed Lower Paleozoic (mainly Cambrian) sedimentary sequence, the Yam Suf Group in southern Israel, which reaches a maximal thickness of 220m (Fig.3) represents an accumulation of mainly clastic platform sediments (Weissbrod, 1969, 1981).

Weissbrod (1981) suggested a few criteria to differentiate the various clastic units of the Paleozoic-Mesozoic sequence in southern Israel and the adjacent countries. The most important of the mineralogical criteria are the amount of feldspars and the heavy mineral assemblages.

The Lower Paleozoic sequences in the Timna Valley are composed of arkosic and subarkosic sandstones and characterized by tourmaline, zircon, rutile, apatite and barite.

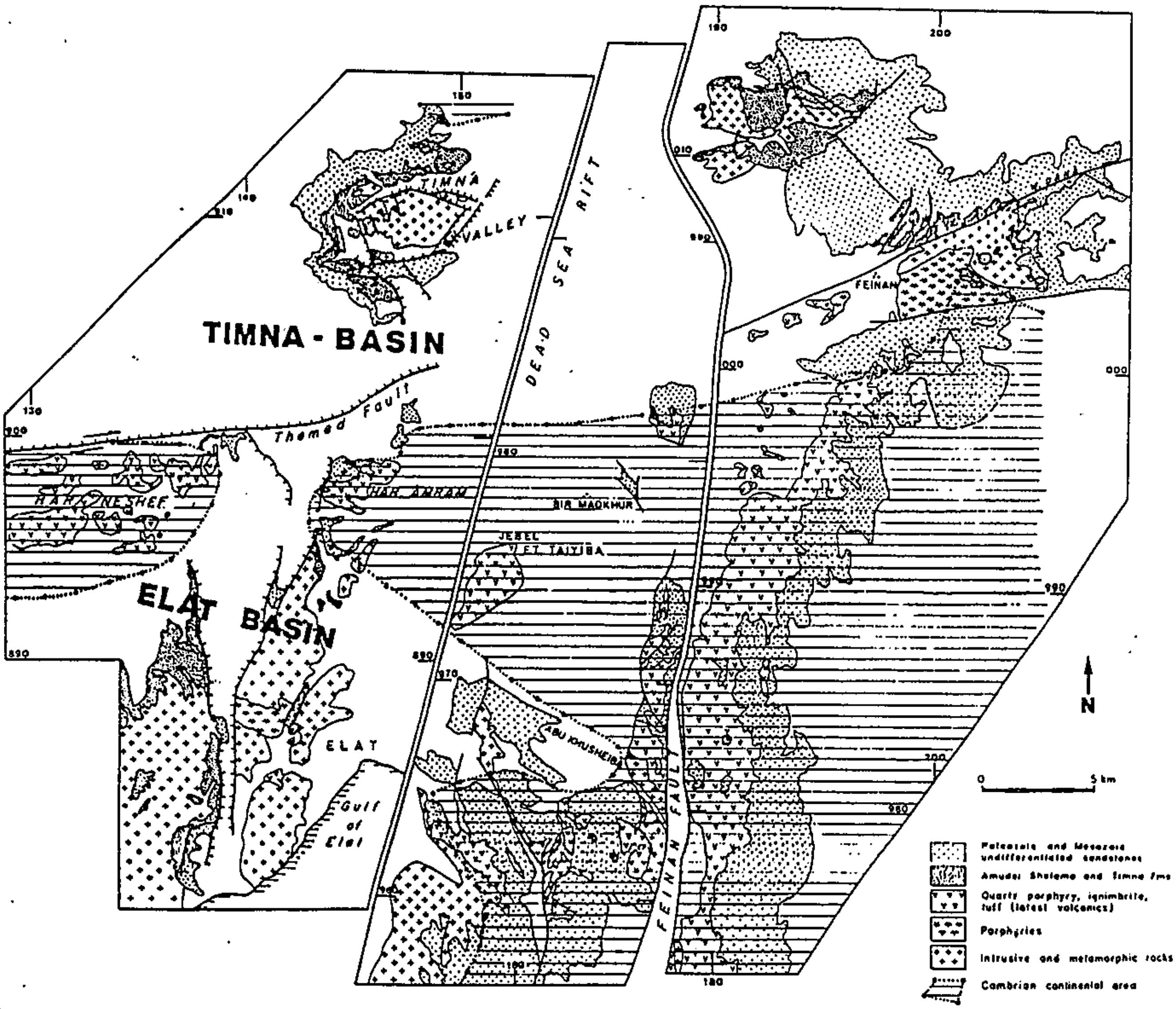


Fig. 2. Paleogeography of the marine Cambrian after reverse structural reconstruction of about 100km left-lateral strike slip

Amudei Shelomo Formation. The Amudei Shelomo Formation was studied in the Timna Valley by Karcz and Key (1966) and Karcz et al. (1971). This formation is composed of fine-grained to grit size, rounded and poorly sorted, brown red and gray subarkose, with lenses or beds of quartzitic pebble-conglomerate.

Often the crystalline basement is overlain by a base conglomerate, and close to the Amudei Shelomo Pillars (coord. 145500/908700) angular granitic boulders, of up to 2m in diameter, were described by Karcz and Key (1966). In places, mainly close to the lower contact, a bed of dark red, brown micaceous silts (paleosols?) about 1m thick was found. The subarkosic sandstones are composed of quartz grains (up to 90%), feldspar, mainly microcline (up to 15%), lithic fragments, (up to 10%) and heavy minerals. Large to medium scale trough and planar cross stratification, from 5–250cm thick and 0.2–10.0cm wide, are common.

The sands and conglomerates of this formation were deposited in a fluviatile environment, on a widespread erosional unconformity (usually peneplaned), with a relief of up to 90m deep in the Timna area. These overlie the Precambrian basement with main directions of paleo-channels running E–W and NW–SE. The upper contact is regular.

The age of the Amudei Shelomo Formation is constrained by the Rb-Sr age of 525–535 Ma (Early Cambrian) of the alkaline volcanic rocks, which terminated the Precambrian magmatism (Segev, 1987), and the biostratigraphical Upper Georgian (late Lower Cambrian; Parnes, 1971) age for the overlying marine Timna Formation.

Timna Formation

Introduction

Since the Timna Formation was found to have the greatest potential for metallic mineralizations, especially Cu and Mn, its rock units are dealt with in detail.

The deposition of this formation marks the first Phanerozoic marine transgression in the Middle East. It was described in southern Israel by Bentor (1952), Picard (1953), Nevo (1954), Bartura and Zemel (1956), Bartura (1966), Weissbrod (1969a,b), Garfunkel (1970), Segev (1984, 1986a) and Segev and Sass (1989).

The formation crops out on both sides of the Dead Sea Rift Valley: in southern Israel (Fig. 1) in the vicinity of Timna Valley, Har Amram and Elat continuing to southeastern Sinai; on the Jordanian side from Feinan to the northern Dead Sea (Blanckenhorn, 1914; King, 1923; Picard, 1943; Bender, 1974; Bigot, 1982).

The Timna Formation was subdivided by Segev (1984), on the basis of the newer geological mapping (Segev and Beyth, 1983) and a better understanding of the field relationships. The previous subdivision and the various nomenclatures are presented in Table 1.

Hakhlil Member

The Hakhlil Member is the lowest member and is composed of four sub-units (from bottom to top):

A. Base conglomerate (0–3.75m thick) — pink to brown polymictic conglomerate with poorly sorted, angular rhyolitic fragments, which are up to 20cm in diameter, and well rounded, well sorted quartzitic pebbles up to 5cm in diameter.

B. Laminar sandstone (1.7–5m) — well laminated red sandstone, fine-grained to grit. The cement is mainly carbonatic in the western areas of the Timna Valley.

C. Carbonatic unit (1.2–8.5m) — alternating beds of fine-grained sandstone to grit, cemented by dolomite and calcite, and sandy dolomites. These beds exhibit cross-stratified internal structures, ripple marks, crawl marks, mud cracks and pseudomorphic structures after halite crystals. The carbonate layers are interbedded with red, purple and green siltstones and shales, in places with manganese oxides.

D. Silty shaly unit (3–6m) — varicolored shales and silts containing thin beds and lenses of limestone and dolomite, forming a soft morphology, which serve as a good marker for the upper Hakhlil Member contact.

The lower boundary of the Hakhlil Member, where it directly overlies (onlap relationships) the crystalline basement, is an angular unconformity (Har Timna, western Timna Valley). The boundary with Amudei Shelomo Formation is conformable. The upper boundary with the Sasgon Member is also conformable.

Sasgon Member

The Sasgon Member, which constitutes the upper part of the Timna Formation, displays three lithofacies (Segev, 1984): the lower dolomitic (previously Nimra Member) and sandy (previously "Zebra" or Nehushtan Member) lithofacies, which occupy lateral stratigraphic positions, whereas the third, known as the shaly lithofacies (previously Mikhrot Member), overlies the two lower ones (Figs. 4a and b).

In a few sites in the eastern Timna Valley the lower part of the Sasgon Member is composed of a sandstone and grit bed with a few well-rounded quartzitic pebbles. It is found east of Har Mikhrot, south of open pit "P" and west of Har Hakhlil. The maximal thickness of this bed is 7.5m, and it wedges out westward within a short distance.

a) Dolomitic Lithofacies:

This unit in the Timna Valley consists of well-bedded sandy dolomites and dolomitic sandstones; its maximum thickness is 28m. Sedimentary structures of laminar stromatolites, cross-stratification, ripple marks and fossil remnants are very common in the study area, indicating shallow water and marine environment of deposition (Segev, 1986a, Segev and Sass, 1989).

The acid soluble phase of the sandy dolomites has a relatively high metal content (Table 2). Most of the dolomites have an average copper content of about 0.06%. Higher values, averaging 0.68%, are found in copper-rich dolomitic beds commonly showing stromatolitic structures and containing fine detrital components.

The manganese content of the dolomites situated within the dolomite crystals is significantly high (1.7–2.8%). Slightly high zinc (~140ppm) and uranium values also characterize most of these rocks. The uranium content in the common sandy dolomites highly fluctuates, ranging from 0.8ppm to 10.6ppm; the average value is about 2ppm. The above-mentioned copper-rich horizons contain significantly high uranium contents, ranging from 5 to 31ppm U in the whole horizon.

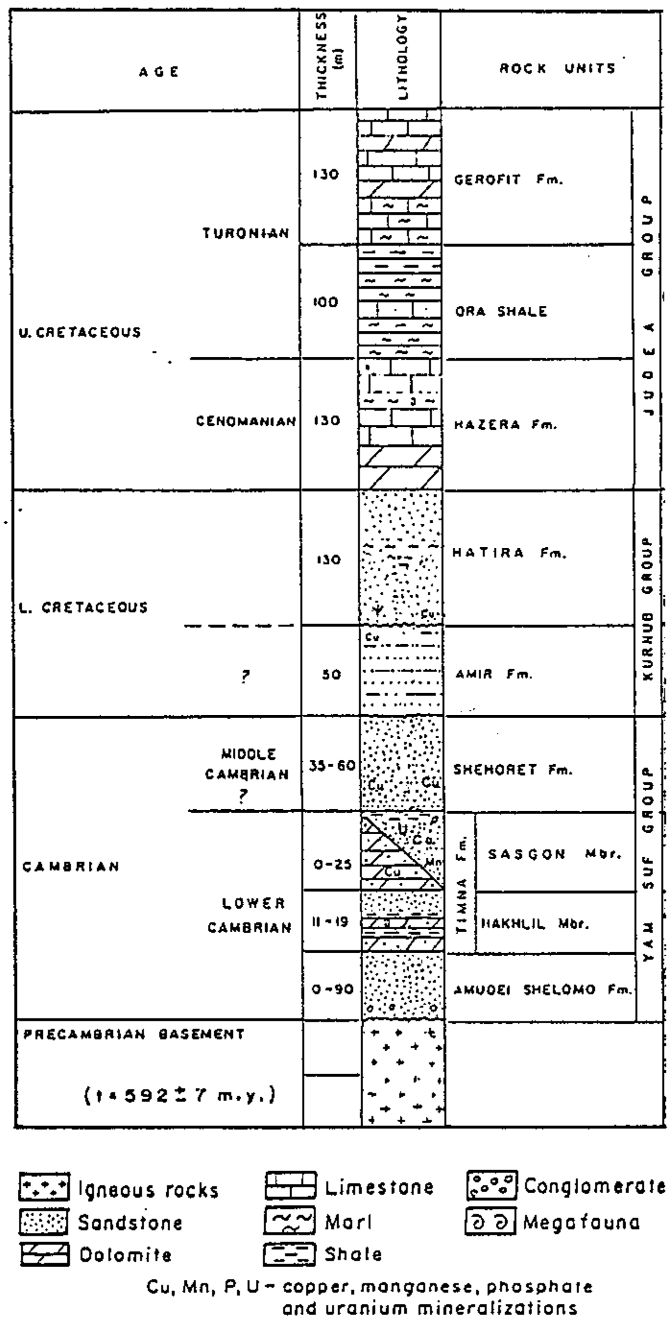


Fig. 3. Columnar section of Timna Valley

Table 1.
Comparison of nomenclatures proposed by various authors for the stratigraphy for the Lower Cambrian in Timna Valley

Bartura 1966		Garfunkel 1970		Weissbrod 1981		Segev (1984)	
STAGE	ROCK UNIT	STAGE	ROCK UNIT	STAGE	ROCK UNIT	STAGE	ROCK UNIT
LOWER CAMBRIAN	Mikhrot Fm.	LOWER CAMBRIAN	Timna Fm.: Ore Mbr.	LOWER CAMBRIAN	Timna Fm.: Mikhrot Mbr.	LOWER CAMBRIAN	Timna Fm.: Sasgon Mbr.
LOWER CAMBRIAN	Nehushtan Fm.	LOWER CAMBRIAN	Timna Fm.: Nimra Mbr.	LOWER CAMBRIAN	Timna Fm.: Nehushtan Mbr.	LOWER CAMBRIAN	Timna Fm.: Sasgon Mbr.
LOWER CAMBRIAN	Nimra Fm.	LOWER CAMBRIAN	Timna Fm.: Nimra Mbr.	LOWER CAMBRIAN	Timna Fm.: Nimra mbr.	LOWER CAMBRIAN	Timna Fm.: Sasgon Mbr.
LOWER CAMBRIAN	Hakhlil Fm.	LOWER CAMBRIAN	Timna Fm.: Hakhlil Mbr.	LOWER CAMBRIAN	Timna Fm.: Hakhlil Mbr.	LOWER CAMBRIAN	Timna Fm.: Hakhlil Mbr.
LOWER CAMBRIAN	Amudei Shelomo Sandstone	LOWER CAMBRIAN	Timna Fm.: Amudei Shelomo Mbr.	LOWER CAMBRIAN	Amudei Shelomo Sandstone	LOWER CAMBRIAN	Amudei Shelomo Fm.

Table 2. Concentration of metalliferous elements in the Sasgon Member, Timna Formation (mean values)

	number of samples	Cu (%)	Mn (%)	Fe (%)	Pb (ppm)	Zn (ppm)	U (ppm)
Dolomitic lithofacies							
Sandy Dolomites	56	0.06	1.20	0.38	63	143	2
Cu-rich Dolomites(1)	15	0.68	1.04	0.32	14	53	10
Sandy Lithofacies							
Sandstones(2)	48	1.03	2.83	0.79	5100	190	14
" (3)	29	0.12	3.56	0.57	7900	260	6

(1) Copper-rich dolomitic beds.
(2) Samples from open pits and outcrops.
(3) Samples from outcrops only.

b) Sandy Lithofacies:

The sandy lithofacies (manganese-rich sandstones) is made up of fine- grained to gritty subarkoses, cemented by manganese oxides, clay minerals and often by authigenic fluorapatite. Although it may attain a maximum thickness of 21m it is generally 5-7m thick.

This lithofacies displays a wide range of secondary structures, such as steeply inclined strata, deformed and contorted lamination, collapse structures, poorly sorted breccias and intraformational faults (Segev, 1986a; Segev and Sass, 1989).

The metal content in the acid soluble fraction of these rocks (Table 2) is usually higher than that of the dolomitic lithofacies. Copper, in the form of silicates, carbonates and phosphates, constitutes an average content of 0.12%. Rocks with a higher Cu content (up to 1.5%) (Bartura and Wurzburger, 1974; Segev and Sass, 1990) are found in both the sandy and shaly lithofacies, and until recently, were considered worth mining.

The average manganese content in these sandstones is 2.83%, forming manganese oxides, mainly hollandite, cryptomelane, pyrolusite and coronadite (Bar-Matthews, 1986, 1987).

The main uranium accumulations in the sandy lithofacies are associated with the fluorapatite cement forming discordant veinlets and non-continuous lenses varying in size from a few centimeters to several tens of meters. The P_2O_5 content in these phosphate-rich sandstones varies from several percent to >30% in phosphorite concretions. The common P content within the copper ores, as defined by Barsky (1978), is 0.34–0.43%.

c) Shaly Lithofacies:

The shaly lithofacies, overlying both the dolomitic and the sandy lithofacies, has a uniform thickness of 1.5–2m, and consists of clays, siltstones and fine-grained subarkoses. These rocks are usually light green, red or brown, but in places they are black and mottled due to manganese mineralization. The shales are often contorted and the base of the overlying Shehoret Formation is brecciated.

In places, cryptocrystalline fluorapatite (micritic phosphorite; Bar- Matthews, 1986) forms small (tens of centimeters long and up to 15cm thick) lenses in one or two horizons in the shaly lithofacies commonly containing 400–750ppm U, and in one lense (probably of secondary origin) up to 4000ppm U (Segev and Beyth, 1983). Similar phosphate-rich shales were found in the Feinan region, SW Jordan (Heitkemper, 1988), indicating wide distribution of this phenomenon, and perhaps, a sedimentary origin of this feature.

Summary

Based on detailed facies analysis, sedimentologicalo, petrographical and geochemical studies, Segev (1986a) and Segev and Sass (1989) concluded that these lateral transitions between the dolomitic and the sandy lithofacies are not depositional. They suggested that the sandy lithofacies is the in-situ insoluble residue (secondary product) of the sandy dolomites, and was formed by epigenetic dissolution (karstification) of the carbonate (dolomitic) fraction caused by circulating, heated-up acidic groundwater ascending through faults and joints.

The retention of the original manganese, copper, zinc and uranium (which were already enriched in the original dolostones), as part of the insoluble residue, together with the sand grains was an additional consequence of this dissolution process. The resulting enrichment of these elements was modified by local redistribution and formation of cements, nodules and irregular veins.

The composition and the sedimentological features of the Cambrian marine, including the Hakhlil and Sasgon members, in the study area represent shallow water and intertidal marine environments in restricted marginal basins.

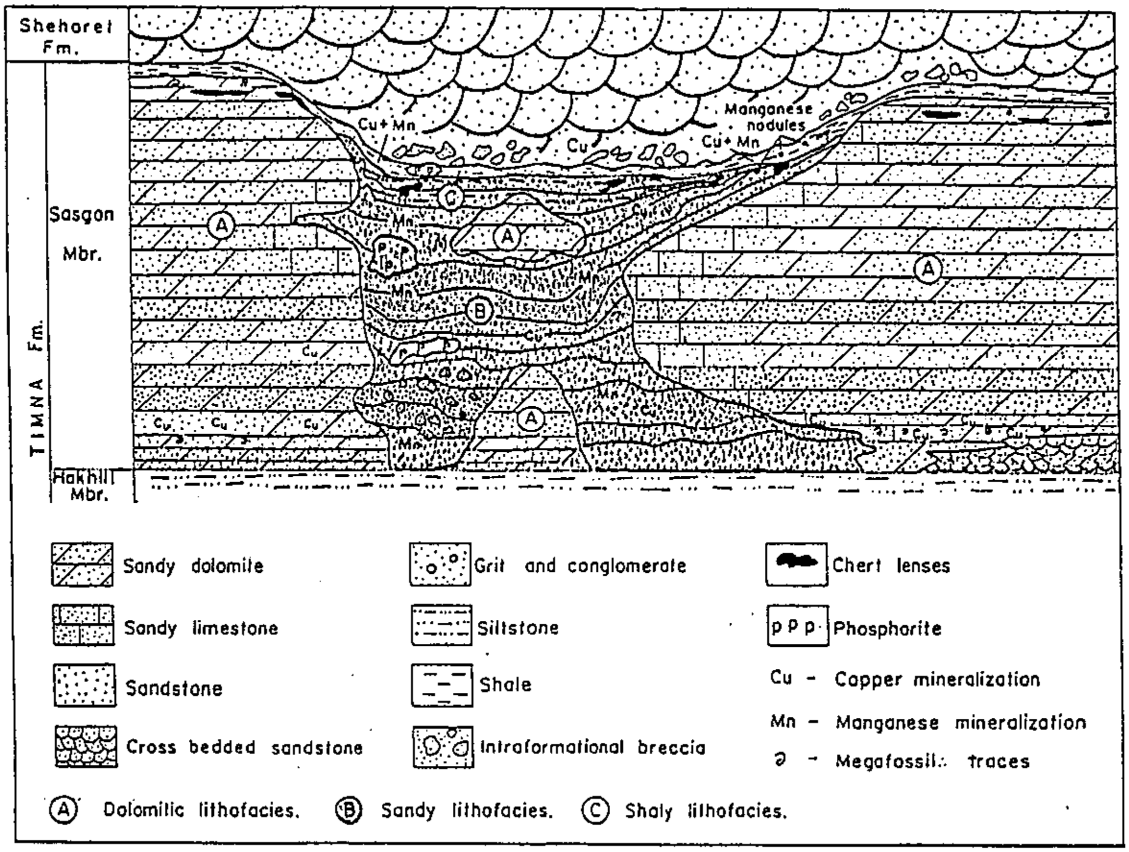
The Timna Formation, together with the Amudei Shelomo Formation, onlap the paleo-relief of the Precambrian crystalline rocks. As a result, the Timna Formation decreases in thickness from 45m in the western Timna Valley to zero in the northern part and toward the south, in Har Amram, approximately 7km south of the Timna Valley.

The Timna Formation is conformably overlain by the continental, fluviatile, Middle Cambrian(?), lower Shehoret Formation (Weissbrod, 1969a,b).

Shehoret Formation

In southern Israel and Sinai the Shehoret Formation was divided into three members (Weissbrod, 1969a,b; 1981), according to color and sedimentological criteria (from top to bottom): Variegated Member, White Member, Multicolored Member ("Cassata").

a.



b.

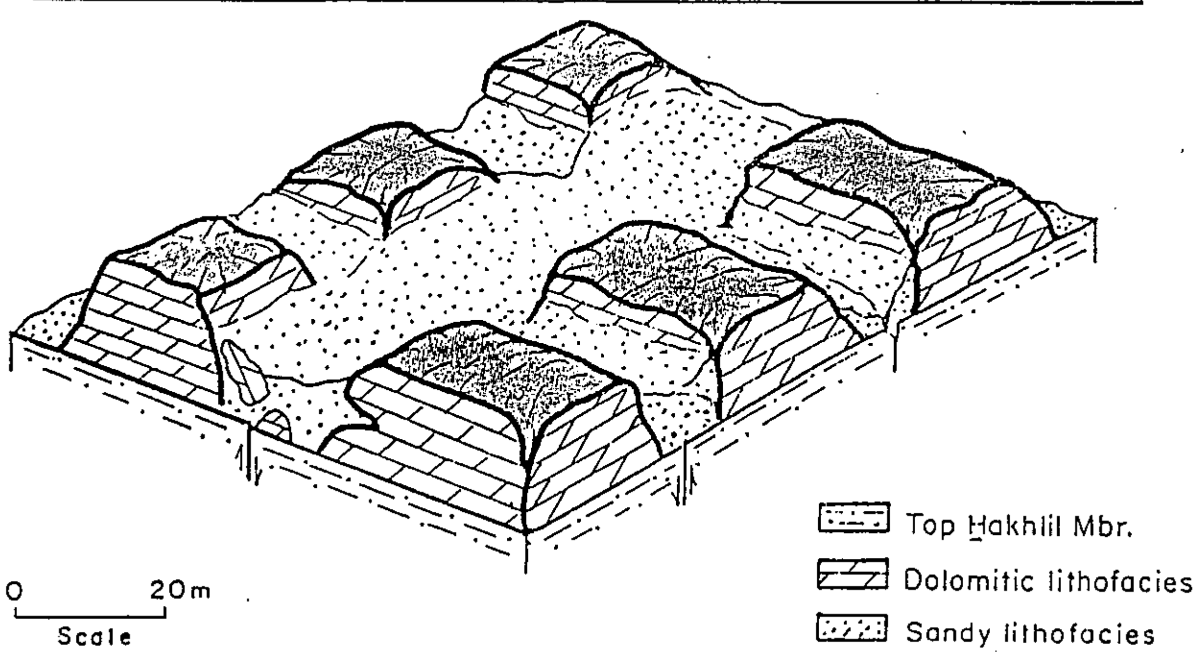


Fig. 4. Schematic diagram showing: a) lithofacies relations in the Sasgon Member. b) Field relations

The formation forms steep, reddish cliffs above the brown to black, massive or soft Timna Formation. Only in the Timna Valley is the lower Multicolored Member found.

The Multicolored Member is composed of alternating ledges of yellowish fine to coarse-grained subarkose, grit and pebble, with beds of reddish brown silt and clay. The White Member, which crops out south of Har Amram, is composed almost entirely of fine-grained arkose. The sandy beds of the Variegated Member are cross-bedded while the silty-clay beds are horizontally laminated.

The rocks of the upper and the lower members of the Shehoret Formation were deposited in a fluviatile environment, whereas those of the middle member were probably deposited in a marine environment (Weissbrod, 1981).

In the Timna Valley the lower contact of the Shehoret Formation with the shaly lithofacies of the Sasgon Member is conformable, and is typified by contortion of the shales and brecciation of the sandstones. In places with high basement relief (northern Timna Valley and Har Amram) the Multicolored Member directly overlies the Precambrian basement (onlap relations).

The upper contact with the Amir Formation is an erosional regional unconformity (Weissbrod, 1981) and could not always be exactly identified during the mapping of the Timna area.

In the Timna Valley the thickkness of the Shehoret Formation ranges from 35m in the southern part to 25m in the northern part. Its age, as indicated by regional correlation, is Middle Cambrian(?) (Weissbrod, 1981).

Kurnub Group

Introduction

The Mesozoic clastic sequence in the Timna area, the Kurnub Group, about 200m thick, was deposited on a regional erosive unconformity, which truncated about 2,500m of an Ordovician to Lower Cretaceous sedimentary sequence (Weissbrod, 1981; Weissbrod and Gvirtzman, 1988). These clastic sequences (probably of Lower Cretaceous), are composed of quartz arenites, with the most stable transparent heavy minerals.

Amir Formation

The Amir Formation is mainly composed of white friable, very fine-grained sandstones, subrounded to subangular, and moderately well sorted (Fig 5). Coarse grains and granules of quartz are randomly distributed. The formation commonly has a kaolinitic matrix and is cemented by amorphous silica. The formation is thinly bedded and laminated, with cross-bedding and recumbent cross-bedding and ripple marks. Thin layers of variegated micaceous siltstone appear mainly in the middle part of the formation (Weissbrod, 1981). The lower and upper contacts of the Amir Formation are unconformable. The formation overlies the Shehoret Formation and is overlain by the Avrona Formation. The lower boundary is generally regular and in places in the Timna area it cannot be easily distinguished from the Shehoret Formation without close examination, whereas the upper boundary is clearly defined (Weissbrod, 1969a). The formation is devoid of fossils and its age is uncertain. Due to its stratigraphic position it is assumed (Weissbrod, 1970; Weissbrod and Sneh, 1990) to be of Lower Cretaceous age. Steinitz, Bartov and Eyal (1992) suggested that the Amir Fm. in W. Zalaqa, Sinai, is older than Circa 270Ma.

The Amir Formation in the Timna Valley forms white yellowish cliffs with a dark brown patina overlying the reddish cliffs of the Shehoret Formation. It reaches a thickness around 37m at coord. 1427/9096.

Avrona Formation

The names Avrona and Samar formations were suggested by Weissbrodetal. (1992).

The Avrona Formation consists mainly of gray, white and yellowish quartzose sandstones, which are medium to fine-grained, subrounded to rounded, and moderately to poorly sorted (Fig.5). The sandstones, which are thickly bedded, are commonly cross-bedded, and contain abundant thin layers of grit and quartzite pebbles. Scattered pebbles, granules and coarse grains occur equally. Gray or violet siltstone layers appear mainly in the upper part of the unit, whereas in its lower part, a copper mineralization zone is evident (Weissbrod, 1970). This type of mineralization was the main source of ores for the ancient copper exploitation (see below).

The Avrona Formation is poorly cemented by calcite. It is characterized by grayish weathered crust, and by rounded cliffs, often with arches. This formation unconformably overlies the Amir Formation; the unconformity is manifested in a lithological change and an irregular surface, and in places includes a basal conglomerate. The upper contact is also unconformable, whereas the Avrona white sandstones grade to the variegated siltstones and sandstones of the Samar Formation. The boundary is generally regular, but in places such as in the Timna area, volcanoclastic sediments (termed "Crazy Wall" Barak Fm. by Bartura, 1956) cut across this formation as well as the Amir and Shehoret formations.

The formation is about 60m at coord. 1427/9096. It has been assigned to the Lower Cretaceous on the basis of regional stratigraphic considerations (Weissbrod, 1970, 1981; Weissbrod and Sneh, 1990).

Samar Formation (see Avrona Fm.)

The Samar Formation is mainly composed of violet, brown and whitish, fine-grained sandstones which alternate with variegated siltstone layers that appear mainly in the lower part of the formation (Weissbrod, 1992). It ranges in thickness from 80m(?) to about 150m, at coord. 1428/9092. The lower boundary, as noted above, is unconformable and the upper contact with the overlying Cenomanian marine carbonates also seems to be unconformable, but this may also be due to facies changes. The age of the formation is presumed to be Lower Cretaceous, but its uppermost part may be Lower Cenomanian.

Barak Formation ("Crazy Wall" "Kir Meshuga")

A special feature, mainly within the Avrona Formation with continuations down to the Lower Cambrian Timna Formation was described and was mapped (Segev and Beyth, 1983) in a few places at the northern edge of the Timna Valley (coords. 1471/9135; 1460/9130; 1488/9134 and 1496/9131).

This clastic sequence consists of local brecciated materials, basaltic fragments, all poorly sorted and notably angular. The following vertical succession is distinguished (Weissbrod et al., 1989, Fig. 6).

Unit 1 — A coarse, polymict breccia of local sandstones, granites and dolomites, together with fragmented basalts. All components are highly angular. Sandstone blocks are the largest component, reaching 1.5m in diameter. The finer fractions are dominated by weathered basalt. Overall color of this unit is reddish, and it is up to 13m thick.

Unit 2 — A somewhat finer breccia (fragments up to 10cm), dominated by weathered basaltic clasts of alkaline composition, but with original texture and mineralogy strongly obliterated by alteration. Overall color is green to black; maximum thickness is 20m.

Unit 3 — A non-stratified, poorly sorted arenite with granule- to gravel-size clasts of weathered basalt, diminishing upward. Unit color changes from greenish to yellow. It reaches up to 20m in thickness.

Unit 4 — Fine-grained sediments, dolostone and chert up to 2m thick overlain by paleosol.

This feature was suggested, firstly, to be a fossil river (Bartura, pers. comm., 1980) cutting through the Avrona and the Amir formations. In a reappraisal of the "Crazy Wall" Weissbrod et al.(1989) suggested an Early Cretaceous volcanoclastic event. The volcanoclastic nature of the sediments, together with the geometry of the depression it fills — unique in this entire section — suggests a fossil explosion pipe with possible linear offshoots, refilled with its own ejecta which underwent some transport and weathering.

Beyth and Segev (1983) found these volcanoclastic rocks in close genetic association with the basaltic plug (east of Har Mikhrot), which was dated by the K-Ar method and yielded Lower Cretaceous dates of 107Ò2 and 99Ò2Ma. Volcanism of this age is well known in a great number of localities in Israel.

Judea Group

Introduction

The Judea Group in the Timna area includes the Upper Cretaceous Cenomanian Hazera Formation, the Turonian Ora and Gerofit formations and the Zihor Formation mainly from the Coniacian.

This group, which comprises thick platform carbonatic sediments, builds up the upper part of the escarpments

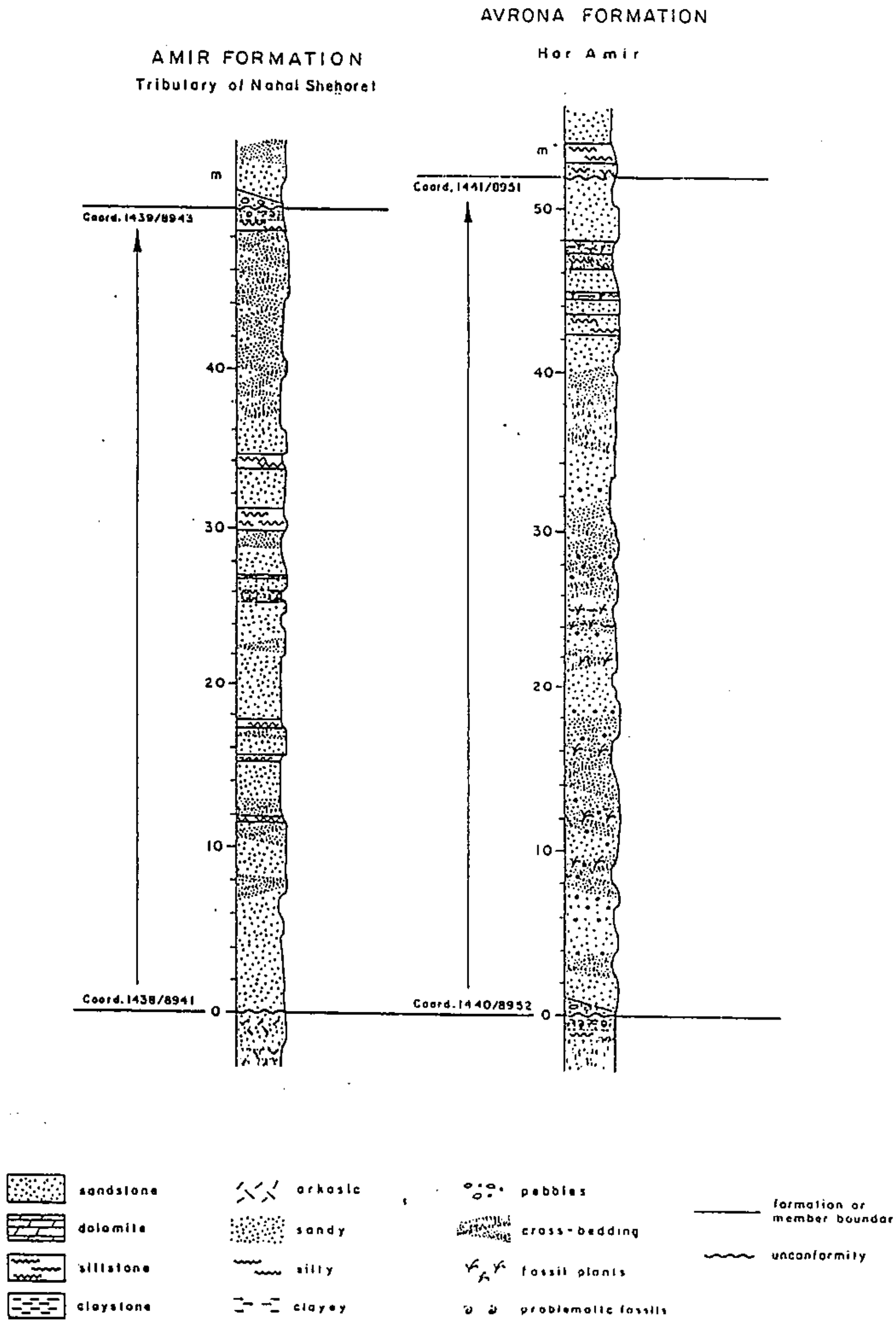


Fig. 5. Columnar section of the Amir and Avrona formations (from Weissbrod 1970)

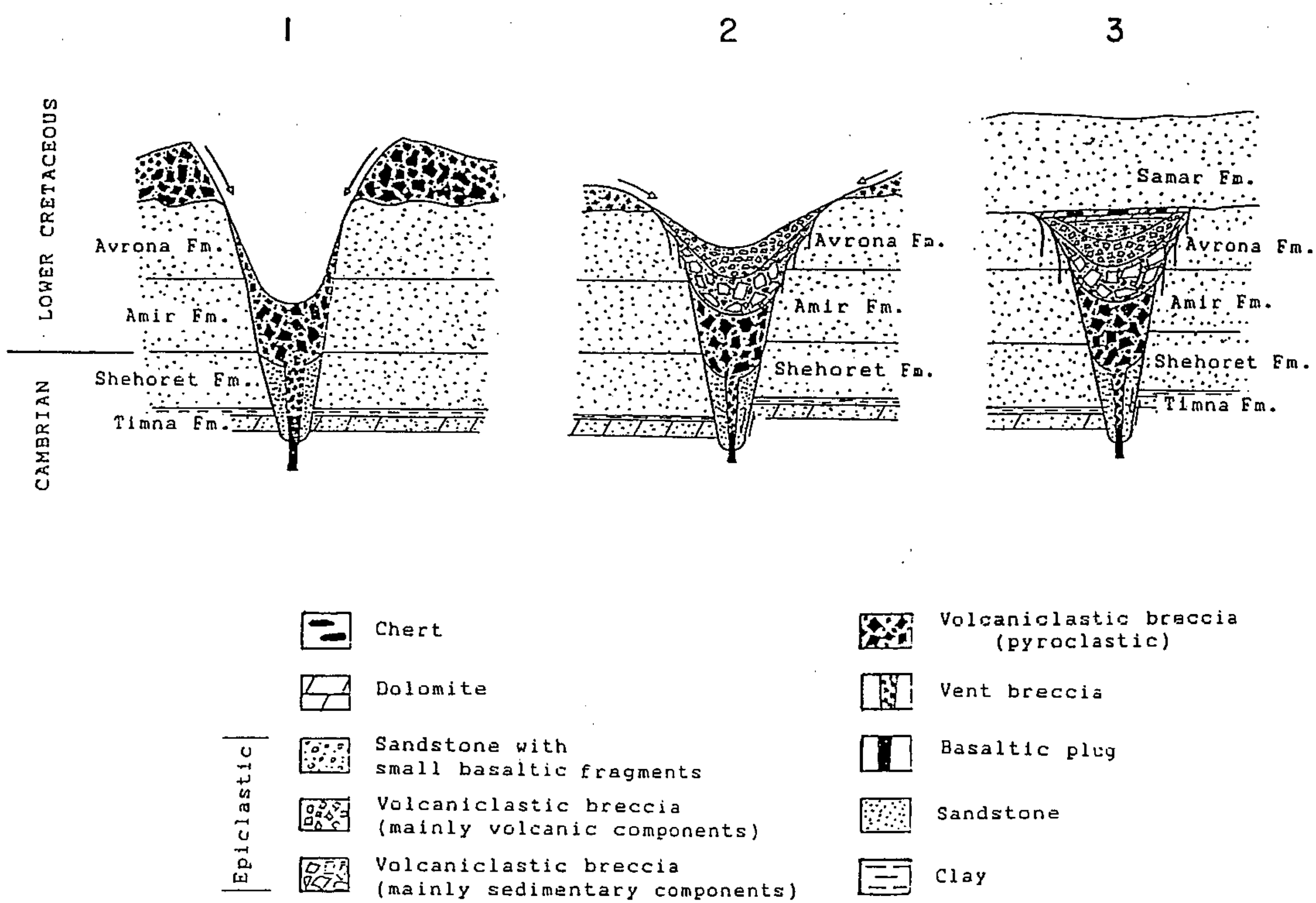


Fig. 6. Stages in the development of the volcano-sedimentary feature of the Barak Formation ("the Crazy Wall"), Timna Valley (from Weissbrod et al., 1989)

surrounding the Timna Valley.

The Judea Group, as indicated by the rock types and fossils, reflects a shallow marine environment. The amount of clastic, sand material increases southward, indicating proximity to the continent. In Turonian time, at the time of the deposition of the Ora Shale, the Negev was divided into a few depositional basins, some of which were evaporitic (Freund, 1962).

This part of the sedimentary sequence in the Timna Valley does not include any significant metallic mineralization, and is described first briefly here. For more detailed information see Arkin and Braun (1965) and Bartov et al. (1972), among others.

Hazera Formation

The Hazera Formation was divided (Arkin and Braun, 1965) into members: Hevyon, En Yorqe'am, Zafit and Yotvata. The En Yorqe'am is marly, whereas the others are composed mainly of limestones (Bartov et al., 1972). The Hazera Formation is up to 120m thick and forms upper parts of the Zuqe Timna cliffs. The formation is of Cenomanian age.

Ora Shale Formation

The lower part of the Ora Shale is composed of greenish marls and gypsum with a few thin interbeds of nodular limestone and gypsum. The upper part contains red shales and gypsum (Freund, 1962). It is about 100m thick and is of Lower Turonian age.

The Gerofit Formation

The lower part of the Gerofit Formation is composed of contorted shales and marls; the upper part is built of dolomite and limestone ledges whose uppermost parts consist of calcarenites, chert and fossiliferous limestone (Eckstein, 1963). The formation is 100–130m thick; its age is Upper Turonian (Lewy, 1989).

Zihor Formation

The Zihor Formation is composed of brown-yellowish marls and soft limestones, dolomites and clays with arenitic sandstones (Sakal, 1967). It is of Coniacian age (Lewy, 1975) and is known from the southern Negev and Sinai; It is 20 to 30m thick.

Mount Scopus and Avedat Groups

There are only very small sporadic outcrops of these groups in the Timna area, along N. Raham (Bartov, 1967) and, therefore, they are not described in this work.

The Dead Sea Group

Large areas of the Timna Valley are covered with undifferentiated conglomerates. The oldest are of Miocene age (Garfunkel, 1970). These conglomerates are 20m thick at the western boundary of the Arava Valley, at open pit "P", where they overlie the Varicolored Member of the Shehoret Formation, and 40m at open pit "N", where they overlie the diorite and the Timna Formation. At the western boundary of the Timna Valley around the Red Canyon (coord. 1431/9111) they reach a thickness of about 10m along ancient river valleys.

River terraces and talus and their relation to changes in the geomorphic regime at Zuqe Timna were studied in detail by Gerson and Grossman (1985), Finkelstein-Grossman (1982) and Gerson (1982).

In the Timna Valley colluvial-derived deposits (debris-flow texture) and alluvial (stratified, lenticular and well sorted) sediments in rather wide-braided flood plains, were deposited during the Pleistocene, when a mature fluvial regime prevailed. Sand was deposited with very little limestone gravel, during the period of almost no talus activity in the Late Holocene to present dry phase. During the last 4,000 to 5,000 years there were no extreme climatic fluctuations, the talus gullied and stripped away and large amounts of sand were transported and deposited in a flood plain. During the Holocene an interfluvial climate predominated and coarse to poorly sorted sediments were deposited.

Summary

The geological history of the Timna Valley is schematically summarized in Fig.8. The major events which could also have influenced the copper mineralization are: The Cambrian marine ingression; the post Devonian truncation; the lower Cretaceous magmatic event; the Miocene rifting.

STRUCTURAL GEOLOGY

Introduction

The Timna Valley is situated on the western margin of the Dead Sea Rift (a strike-slip fault with a left-lateral movement of about 100km (e.g., Freund et al., 1970; Garfunkel, 1981; Fig. 1) north of its junction with the Tamad Fault (a regional E-W fault from the Gulf of Suez to the Arava Valley).

The Tamad Fault

The Tamad Fault is the southernmost fault of an E-W transversal fault system crossing the southern Negev and central Sinai. In the Negev area the downthrow of the northern blocks is usually 0–100m. A few domal ¿P structures close to and contemporaneous with this fault were mapped by Bartov (1974). The fault forms a boundary between the southern Har Amram block and the northern Timna Valley block. The southern block and the adjacent area is intensively faulted in a N–S direction, whereas the northern block is more tabular.

The Tamad Fault is probably a dextral strike-slip fault with an estimated 2.5km lateral movement (Bartov, 1974 and Garfunkel, 1970). Close to the Arava its strike changes from E–W to ENE–WSW. They suggested that the change of the strike was due to a northward movement of the southern block during activation of the Dead Sea transform.

This fault is probably a Precambrian structure rejuvenated in the Miocene predating the Dead Sea Rift, and hence its continuation in the eastern margins of the Arava. According to Freund et al. (1970) and Garfunkel (1981) it is the Wadi Dana Fault (Fig.1).

The Dead Sea Rift

The Dead Sea Rift system is a Leaky Transform Fault, more than 1000km long, that is younger than the Tamad Fault, and which was formed by the breakup of the once continuous Arabo-African craton. It is a sinistral strike-slip fault system in which the eastern Jordanian block (Arabian Plate) moved about 100km northward (Quennel, 1959; Freund, 1965, among others).

The continental breakup was accompanied by widespread, predominantly basaltic, volcanism that began in the Oligocene, mainly 30–20Ma ago (Meneisy and Kreuzer, 1974; Coleman et al., 1977 and Steinitz et al., 1978, among others), while major rift faulting began only after 20Ma ago, i.e., in the Miocene. Garfunkel (1981) suggested that this sinistral movement took place during an initial Miocene phase (60km movement), and a younger Plio-Pleistocene phase (40km movement). Also important was extensive uplifting of the new plate margins, which is generally 1–2km along the Arava, but increases southward, reaching 3–5km close to the Red Sea and even more in the Dead Sea.

The greater part of the Dead Sea transform is marked by a conspicuous morphotectonic depression, 10–20km wide, generally delimited by normal faults, and partly filled by sediments. The present physiography was formed by the latest tectonic phase, which continues up to the present.

The Internal Structure of the Timna Valley

The recent morphotectonic shape of the Timna Valley is a half cirque with a structurally high core. Bentor (1952) described it as a "Makhtesh" with an elevated, hard, magmatic core, Har Timna.

Of the older tectonic movements the most prominent are: a) the Precambrian faults (Zlatkine and Wurzburger, 1957) and dilatational dikes which intruded the Timna Granite post 592 m.y.; b) uplift and peneplanation during the

Lower Cambrian (Garfunkel, 1980); c) vertical movements during Paleozoic and Mesozoic times, which are reflected by unconformities at the top of the Shehoret Formation and the base of the Avrona Member in the Timna Valley (Weissbrod, 1981) and probably movements associated with the magmatic activity during Lower Cretaceous age (Beyth and Segev, 1983; Weissbrod et al., 1989).

Mart and Horowitz (1981) divided the Timna Valley into six tectonic blocks (Beer Ora, Nimra, Hakhlil, Nehushtan, Mt. Timna and Milhan) and described three grabens (Nehushtan, Raham and Arava) surrounding the central block of Har Timna. Later, Segev and Beyth (1983), divided this area into the following eleven tectonic blocks (Fig. 7): 1) Raham; 2)Hakhlil; 3)Nimra; 4)Gadna; 5)"Step Faults"; 6)Har Timna: 7)Arava; 8)N. Timna Graben; 9)N. Timna; 10)Northwestern Timna; 11) Mikhrot.

This division was made along main faults that caused significant different structural levels, sometimes with significant differences in their internal fault and joint systems.

<u>*Reverse Fault System Striking in a ENE Direction*</u>

A few of the faults striking ENE and delimiting some of the tectonic blocks were identified as reverse faults: a) the southern Har Hakhlil fault (striking N65 E) was mapped as a reverse fault by Garfunkel (1970); b) in the southern "Step Fault" block a reverse fault was described by Bentor (pers. comm., 1971; and Beyth et al., 1990), whereas the eastern continuation of this fault line, the southern Har Timna fault, is completely buried under young conglomerates. Because of its location and direction, Segev and Beyth (1983) interpreted it as a reverse fault; c) part of the northwestern Har Timna fault and northern Nahal Timna fault were described as possible reverse faults (Segev and Beyth, 1983) based on their geological position, the parallel joint system within the nearby crystalline rocks, and the trend of these faults.

<u>*Fault and Joint Systems Within the Tectonic Blocks*</u>

The predominant internal fault system strikes SE to NW (315-345 degrees azimuth); most of the faults are normal, and some of the main faults delimit the tectonic blocks. Some faults at the "Step Fault" block, which is associated with small grabens, were identified as small dextral strike-slip faults.

A rose diagram of the fault directions in the Timna Valley depicts the relations between the normal fault and joint systems and the reverse faults (~90 degrees), as well as the angle between the latter systems and main direction of the Dead Sea Rift system (azimuth 15 -20 , which is about 45 degrees).

Summary

Bentor and Vroman (1955) described the Timna Valley as a domal structure, cut on its eastern side by the Dead Sea rift, with an internal magmatic core, whereas the sedimentary sequence on top of it inclined outward (5-10 degrees) radially. The dome was considered to be the product of vertical uplift. In the absence of a radial fault system, which is expected from such a domal structure, and in view of the orthogonal fault pattern at Har Timna, Mart and Freund (1977) negated the domal model. Later on, Mart and Horowitz (1981) suggested that due to the drag of the sinistral strike-slip faulting along the Dead Sea rift (as suggested by Garfunkel, 1970), the Har Timna block was displaced diagonally northward and upwards.

A model for the uplifting of the Har Timna block (Segev, 1986; Fig.7) suggested an uplifting reverse fault system normal to the main compressional stress, whose directions are similar to the Dead Sea stress field (Eyal and Reches, 1983).

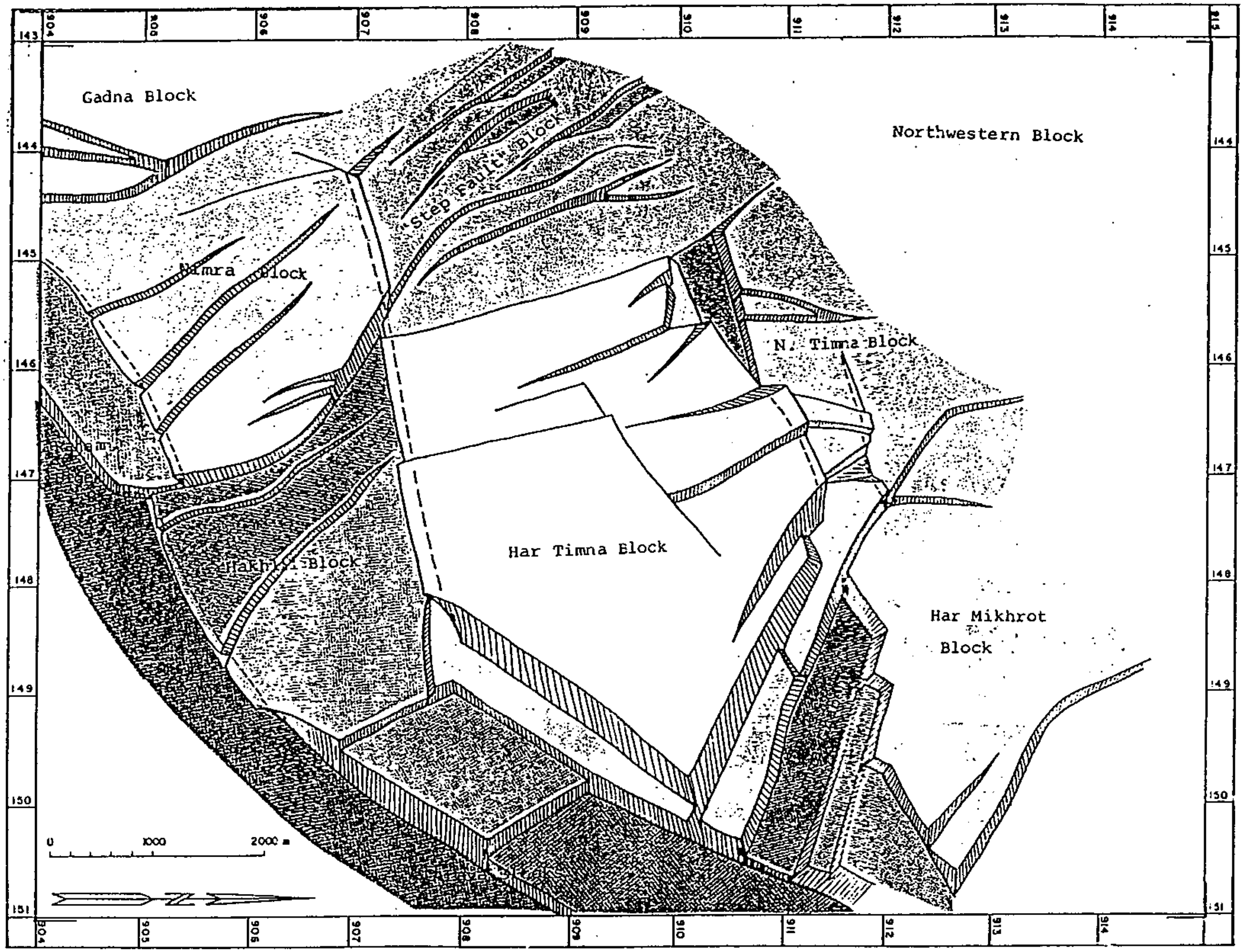


Fig. 7. Block diagram of the main faults in Timna Valley

MINERALIZATION

Introduction

Copper mineralizaton in the Timna Valley was found from the Precambrian igneous rocks through the Cambrian sediments, and up to the Lower Cretaceous sandstones. In ancient times copper was exploited mainly in the top Amir and base Avrona formations whereas the modern mining activities produced copper from the Cambrian host rocks. Copper mineralizations outside the Timna Valley were exploited in ancient times along the margins of the Dead Sea Rift (Fig.1) from Feinan in the north (Fig. 2) to the Gulf of Elat in the south. The major locations outside the Timna Valley are Feinan, W. Abu Khusheiba, Har Amram and south of W. Shehoret.

Metallic mineralizations in the crystalline basement

In the first detailed study of the Timna Massif, Zlatkine and Wurzburger (1957) reported the presence of chrysocolla ($CuSiO_3 \cdot 2H_2O$) and chalcocite (Cu_2S) in rocks very near the contact with Paleozoic sediments. They suggested that this mineralization may have originated by a percolation of copper-rich solutions which originated in the chalcocite-bearing sediments.

Wurzburger (1967, 1970) reported the presence of hypogene sulphides and oxides in rocks of the mafic "Deshe" area. The porphyritic calc-alkaline granite contains: chalcopyrite ($CuFeS_2$), digenite (Cu_5S_9), chalcocite, covellite (CuS), whereas the alkali rhyolitic dikes contain only chalcocite-covellite. Both occurrences are considered to be hydrothermal in origin, but the latter assemblage may have formed at a lower temperature. The alteration products are green minerals, mainly paratacamite ($Cu_2[OH]_3Cl$), malachite ($Cu_2[CO_3][OH]_2$) and chrysocolla. Pyrite (FeS_2) and its oxidation product hematite (Fe_2O_3) occur in alkali rhyolitic dikes. The olivine gabbro contains pyrrhotite (FeS)-pentlandite ($[Ni,Fe]_9S_8$) chalcoparite and two forms of magnetite (Fe_3O_4), chromian — early stage of non chromian — low temperature. The Ni-Fe-Cu sulphide assemblage is considered to be an early magmatic liquid sulphide segregation and relatively late sulphide crystallization.

In the eastern side of Wadi Arava, in Jordan, Burgath et al. (1984) explored the Precambrian-Early Cambrian volcanic rocks, which have an andesitic to rhyolitic composition. Copper mineralization was found in these rocks mainly in two areas: Wadi Abu Khusheiba and Wadi Abu arqa. Sulphidic copper ores (chalcopyrite-chalcocite-covellite) occur in andesitic and rhyolitic dikes and in the breccia formed at the beginning of the extrusive phase. They appear together with cuprite-tenorite-malachite and chrysocolla along flow textures of the rhyolitic dikes and along fractures in the basement close to the contact with the rhyolites. The authors assumed that the primary mineralization in these volcanic rocks are sulphidic. Although copper mineralization is common, mining of the copper does not appear to be economic (Burgath et al., 1984).

Mineralization within the Timna Formation

The Dolomitic Lithofacies. All dolostones in the Timna basin contain anomalous high copper values (averaging 0.06% Cu), whereas a few dolomitic horizons (showing stromatolitic structures), mainly at the lower part of this unit, host stratiform copper mineralization. These cupriferous dolostones ("pre- dolomitic copper horizon" according to Bentor, 1952) were found in most of the well-preserved outcrops of the dolomitic lithofacies throughout the Timna Valley (Segev, 1986a). They occur as greenish beds 13–100cm thick with a copper content ranging between 0.22% and 1.77% (0.68% on the average). The copper mineralization occurs as thin undulating laminae, less than 1mm thick, and as thin veins, similar in composition, which commonly cut across a few laminae. Paratacamite is the predominant copper mineral in these horizons with minor amounts of small dark gray copper sulphide nodules (up to 20mm long and 5mm thick). The sulphide is djurleite ($Cu_{1.85}Ag_{0.05}S$) surrounded by a greenish (oxidized) rim composed of paratacamite and malachite. Segev and Sass (1989) suggested that the initial stratiform copper mineralization in the dolostones was copper sulphide, which took place in a reducing bottom marine environment (syngenetic mineralization), that was probably due to the presence of organic matter in algal mats. The paratacamite and malachite represent a later diagenetic process of oxidation, which resulted in a local, small-scale redistribution into secondary minerals.

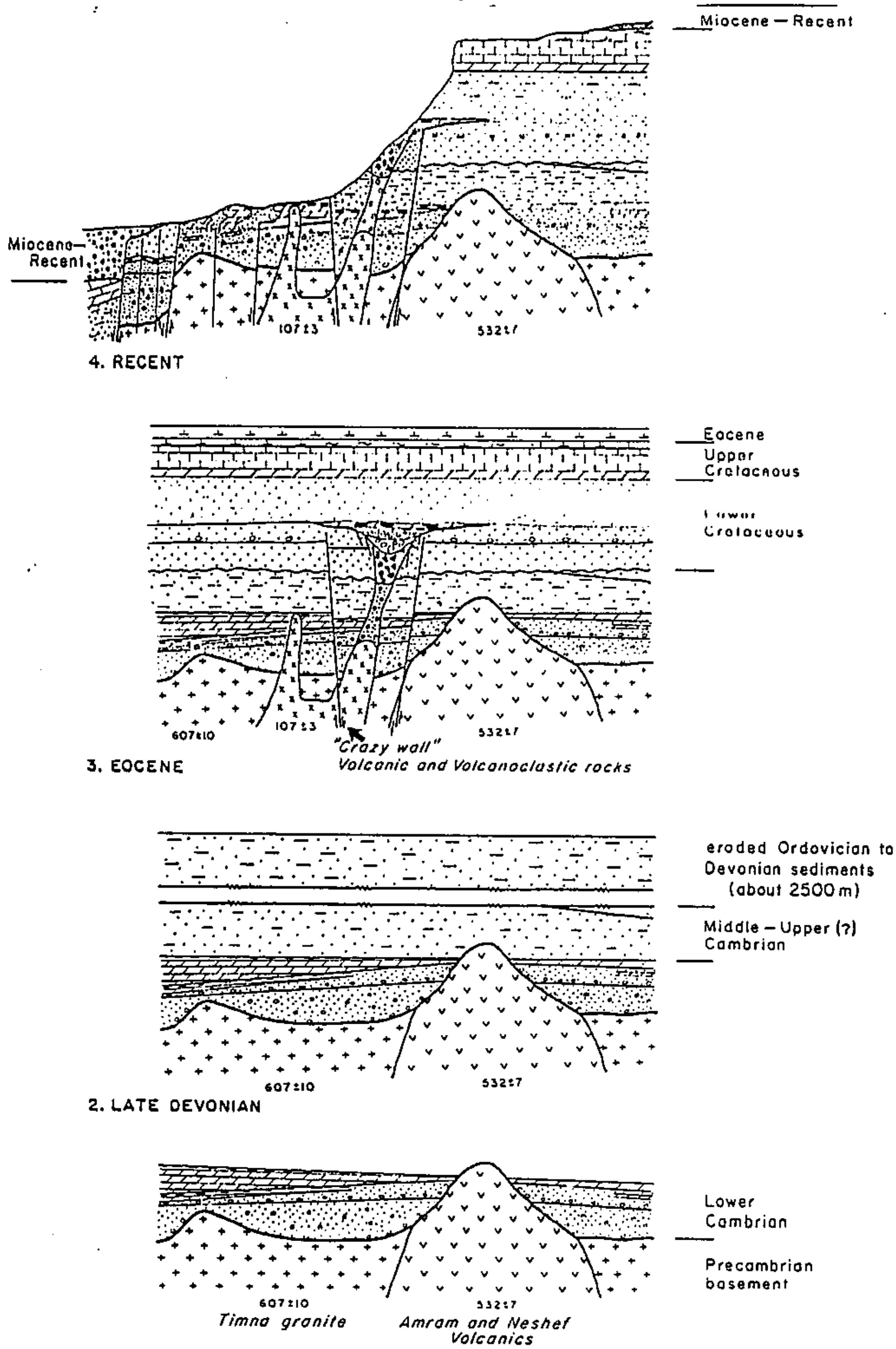


Fig. 8. Geological events at Timna Valley: 1) Late Lower Cambrian, after marine regression. 2) Late Devonian, before uplift, maximal depth of burial about 2.5km. 3) Eocene, the end of the Tethyan transgression. 4) Recent. For legend see also Fig. 6