Contact metasomatism in a Neogene evaporitic sequence of the central Jordan valley—northern Israel

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SUMMARY. Gypsum and anhydrite from the Neogene of the central Jordan valley associated with basalt bodies in the Menahamiya area contain abundant euhedral magnetite and diopside crystals and rarer grossular. The original calcareous shales above the gypsum were transformed into hydrogrossular cemented by secondary calcite and gypsum. The mineralization is assumed to be due to low-temperature, high water-pressure metasomatic activity similar to the process of rodingization. The described occurrence is unusual in that the hydrothermal solutions may have been partly formed in situ by thermal dehydration of the gypsum. In a nearby locality, Tel Shaharit, the mineralization occurred in a calcareous environment producing thomsonite, natrolite, and hydrogrossular.

THE Neogene section of the Jordan valley south of the Sea of Galilee, Israel, displays a succession of clastic, calcareous, and, in places, evaporitic (gypsum and anhydrite) rocks. The whole section is characterized by thick basalt flows. In one of the gypsum outcrops, the 'Menahamiya Quarry' (fig. 1), an unusual occurrence of euhedral magnetite crystals was found floating within the gypsum and anhydrite and was previously described by Schulman (1962).

The present paper describes in more detail this uncommon association, as well as the occurrence of other associated minerals, which we attribute to contact metasomatism. It also describes a somewhat similar metasomatic association, even though in marl, which was found in a nearby outcrop, Tel Shaharit (fig. 1).

Geological setting. The vertical sequence of the Neogene section in the Jordan Valley from bottom to top is (Schulman, 1962): the 'Lower Basalt', more than 500 m; the 'Um Sabune Conglomerate' (0–200 m); the 'Bira Formation', consisting of lagoonal marine rocks (up to 75 m); the 'Gesher Formation' of freshwater lacustrine origin (20–50 m); and the 'Cover Basalt', some 150 m thick.

In addition to the thick basaltic units that start and cap the section, many basaltid intercalations are found in the sedimentary section. These Neogene basalts are almost exclusively of extrusive origin (Schulman, 1954, 1962).

Intrusive activity is very rare and the only intrusive rocks previously described from the area are tiny sills, which were auto-injected into basaltic flows within the Bira Formation (Schulman, 1962).

The marine Bira formation is mostly composed of thinly laminated calcareous shales, which pass gradually upwards into evaporitic gypsum and anhydrite, to which Schulman (1962) gave the name 'Menahamiya Gypsum'. The gypsum is known to extend over a belt 20 km long along the western margin of the Rift Valley, and is locally quarried for building purposes.

The Menahamiya outcrop. A detailed description of the regional geological setting of the Menahamiya Gypsum is given by Schulman (1962). A more detailed description of the Menahamiya quarry (coord. 20135/22925) is given by Beyth and Weissbrod (1965) and Beyth (1966).

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The sulphate body consists of a 9 m thick anhydrite lens near the base of the body, surrounded and overlain by massive gypsum. The gypsum itself is about 14 m thick at its maximum, The whole body has irregular margins, its length is about 180 m and its width about 120 m. the long axis tending in an east–west direction. Some 3 m above the gypsum, in the north and east faces of the quarry, a horizontal tabular body of basalt is exposed within the Gesher Fm.
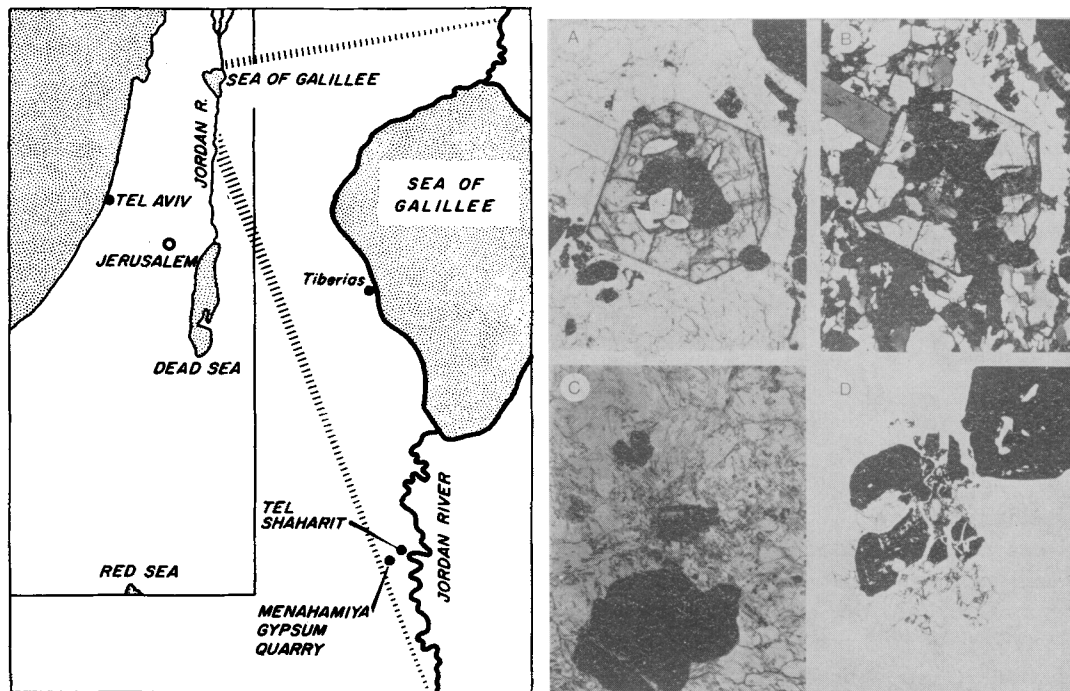
FIGS. 1 and 2: FIG. 1 (left). Location map for the Menahamiya gypsum quarry, and Tel Shaharit, Israel. FIG. 2 (right). Thin sections through gypsum from the Menahamiya quarry: (a) Grossular (grey) with gypsum (white) and magnetite inclusions in a gypsum matrix (parallel nicols × 32·5). (b) Same as (a) but with crossed nicols. Note sectorial anisotropy of the grossular. (c) Magnetite (black) and diopside (grey) in a gypsum matrix (white) (× 32·5, parallel nicols). (d) Shattered magnetite (black) and grossular (grey) in gypsum (white) matrix (× 32·5, parallel nicols).

The rock consists of highly altered alkaline basalt with the olivines altered to smectite, chlorite, and serpentine. It is of irregular thickness, from tens of cm up to 7 m. Due to weathering it has in places a brecciated appearance. Its upper and lower contacts have a vitrophyric texture, and small apophyses penetrate into the overlying and underlying rocks. Metasomatic minerals occur in the rock both below and above the basalt. The above evidence favours, in our opinion, an intrusive origin for the basalt. The field relationships, however, are not clear-cut, and it should be noted that Schulman (1962) regarded this basalt as a flow, on the basis of field appearance. In such a case the metasomatism of the overlying rock should be attributed to hydrothermal solutions that used the basalt body as a channel.

The 3 m thick rock unit between the sill and the gypsum has a complex mineralogy. It is composed of two major rock types:

A hard, dense, very fine-grained, dark green rock with black and white streaks: this unit, which directly overlies the basalt is about 80 cm thick; it contains chlorite and other clays (mainly mixed-layered), zeolites (mainly natrolite), calcite, gypsum, hydrogrossular, pyrite, and magnetite.

A yellow, granular, well-bedded rock, composed of hydrogrossular in a matrix of calcite and gypsum; local horizons of gypsiferous and calcareous shales rich in pyrite and magnetite occur, and in places, microlenses of jarosite and goethite can be found.

The sill is overlain by 6 to 8 m of light yellow granular rock, which consists, like the rock underlying the sill, mainly of hydrogrossular in a matrix of gypsum and calcite.

Mineralogy

Gypsum composes the bulk of the sediments in the quarry below the sill. It usually occurs as massive white rock with abundant euhedral magnetite crystals. In places, and especially towards the sill, the gypsum has a 'zebra'-like appearance due to magnetite laminations or internal reflections.

The *anhydrite* is usually white with occasional grey, bluish, or purple tints, and has a marble-like texture. The white or purple anhydrite is built of interlocking crystals, whereas the grey type contains 'mylonitized anhydrite'—crushed anhydrite between larger, well-crystallized anhydrite grains. The anhydrite is considered to be secondary due to the scarcity of euhedral crystals, even when the grains have well-developed cleavage. In several cases rehydration to gypsum can be seen, either as thin gypsum coatings around anhydrite crystals or in the occurrence of a gypsiferous matrix in which anhydrite relics are floating.

Sulphides and their alteration products. Euhedral crystals of pyrite are found in the gypsum and other rocks below the silt. Several crystals of chalcopyrite were found immediately below the sill. Jarosite and scarce malachite occur sporadically as alteration products of the sulphides.

Magnetite and hematite. Magnetite crystals are very abundant in the gypsum and anhydrite, giving the outcrop a peppered appearance. The concentration of magnetite is highly variable, but it usually ranges between 3 to 20 % by weight. The magnetite crystals float in the sulphate matrix, and are in places concentrated into thin laminae. Magnetite occurs as euhedral or subhedral crystals whose size varies from fractions of a mm to 1–2 cm. The dominant habit is octahedral, rarely rhombdodecahedral. Striations and twinning are very common. Although outwardly the magnetite crystals are almost perfect, intergrowths with gypsum, usually as concentric zones, are commonly observed under the microscope (fig. 2 c, d). Sometimes the magnetite has a 'shattered' appearance (fig. 2d).

Magnetite is also found in the rocks both above and below the sill, sometimes in pod-like concretions up to 10 cm across. However, these crystals are much smaller and also rarer than those in the sulphates.

Occasionally wisps of well-crystallized, small (up to 1 mm) specularite hematite crystals are found, giving the sulphate a reddish-violet tinge.

Rare euhedral crystals of *grossular*, up to 1 cm in diameter, were found in the gypsum. The crystals are transparent and have a honey-yellow colour. They are rhombodecahedral, frequently twinned, sometimes cracked, and are usually intergrown with gypsum and magnetite (fig. 2a). The grossular is anisotropic (fig. 2b) and according to the late Prof. J. Murdoch (personal communication) it may have an orthorhombic, pseudo-cubic structure and thus is not really a true garnet. Chemical analysis (Table I) shows an appreciable content of andradite. Grossular has not been found outside the gypsum.

Hydrogrossular is very abundant in the rocks below and above the sill, but has not yet been found in the gypsum. It usually occurs as small, up to 0·3 cm, white, opaque, rhombdodecahedral crystals. Chemical analysis (Table I) shows, as in the grossular, a considerable proportion of andradite. The edge cell is 12·0 Å, indicating a low degree of hydration.

Diopside crystals are quite abundant in the gypsum as discrete, subhedral, light to dark green prisms, 0·2–0·5 cm long (fig. 2c). Although the prismatic faces are well developed they are usually corroded at their terminals, giving a characteristic 'saw-tooth' effect.

TABLE I. *Chemical analyses of grossular and hydrogrossular from the Menahamiya Gypsum with comparisons*

	SiO_2	Al_2O_3	Fe_2O_3	FeO	MgO	CaO	Na_2O	K_2O	TiO_2	P_2O_5	MnO	CO_2	H_2O+	H_2O-	Sum
A	36.98	14.11	12.77	n.f.	0.40	34.17	n.f.	n.f.	—	n.f.	0.21	—	0.22	0.16	99.02
B	36.80	16.36	6.48	0.50	1.81	33.24	0.16	0.30	1.17	0.09	0.30	0.35	0.62	1.21	99.45
C	38.18	11.89	11.69	0.64	1.47	34.87	0.10	0.02	0.42	—	0.26	—	n.f.	n.f.	99.55
D	33.99	20.04	—	3.69	1.04	37.51	n.f.	n.f.	0.75	—	n.f.	—	—	—	97.02

A: Grossular, Menahamiya gypsum quarry   n.f., not found
B: Hydrogrossular, Menahamiya gypsum quarry   —, not determined
C: Metasomatic garnet, Indian Ocean sediment (Kempe *et al.*, 1974)
D: Hydrogrossular, Mid-Atlantic ridge (Hommorez and Kirst, 1975)

Erratum: line D, *for* Hommorez *read* Honnorez

Tel Shaharit outcrop

In Tel Shaharit, about 1 km NE of the Menahamiya quarry, two very small sills (up to 15 cm thick) have produced a similaı contact metasomatism of the bedded marl and carbonates of the Gesher Fm.

The metamorphosed rock is yellowish, laminated, and criss-crossed by white zeolite veins. The mineralogy is complex. Most of the laminae are composed of hydrogrossular and analcime in a calcite matrix. The hydrogrossular crystals are much smaller than those occurring in Menahamiya and range from 10 to 40 μm. They are rhombdodecahedral and have the same cell-edge, 12 Å, as the Menahamiya hydrogrossular. The analcime crystals are euhedral to subhedral and and also very small. A few very thin laminae are composed of chlorite with some illite and calcite. Some white laminae, relatively harder than the rest of the rock, also occur, displaying a sandwich-like structure; the two outer layers are composed of opaline-like natrolite, whereas the central part is fibrous thomsonite. The white veins that criss-cross the rock and cut through the laminae are similar in composition to the white laminae, although much thicker.

Discussion

The association gypsum(or anhydrite)–grossular–hydrogrossular–magnetite–diopside as found in the Menahamiya quarry is quite rare. Kargatev (1970) mentions anhydrite in garnet–diopside rocks from the Aldan shield, and considers the anhydrite to be metasomatic in origin, formed by the replacement of albite and epidote. Haapala (1953) and Nagel (1957) discuss the association of anhydrite with copper–lead–zinc–silver ores found in the Morococha district of central Peru. The Jurassic limestone of the district has been altered to a rock containing diopside, tremolite, serpentine, chlorite, talc, and anhydrite. The source of the anhydrite is controversial. Haapala (1953) assumes it to be sedimentary, but Nagel (1957) supports a hydrothermal origin.

In contrast to these cases, the Menahamiya gypsum is clearly of sedimentary origin. It is part of the regular sedimentary sequence of the Neogene in the Jordan Valley and occurs elsewhere without any basalt association. The unique mineralogical association observed in the Menahamiya quarry is here ascribed to localized metasomatic mineralization.

In order to explain the paragenesis of the Menahamiya mineralogical association we invoke a 'pressure cooker' mechanism, i.e. the combination of relatively high water pressure in a con-

fined space, with low to moderate heat. The gypsum in the Menahamiya outcrop occurs as a lens between relatively impervious shaley layers. We suggest that accidental occurrence of an intrusive event into gypsum enhanced hydrothermal activity. Under those conditions the sedimentary gypsum was transformed into a crystal 'mush' of anhydrite in superheated water, in effect creating authigenic hydrothermal solutions. The hydrothermal solutions mobilized iron, silica, and alumina from the basalt and calcium from the surrounding carbonate.

The crystallization of the skarn minerals in the cooling 'mush' resulted in the intimate inter-growth of the metasomatic minerals with the sulphates. It is possible that the anhydrite found at the base of the lens is the relic of the dehydration event. Elsewhere, subsequent rehydration took place, accompanied by volume increase, which probably caused the shattering observed in the magnetite and the grossular (fig. 2d).

The environmental conditions during the crystallization of the metasomatic minerals can only be guessed at. It has been demonstrated that the formation of hydrogarnet (or garnet) is mostly dependent on the temperature of formation rather than on water pressure (Yoder, 1950; Carlson, 1956; Pistorius and Kennedy, 1960; Shoji, 1975). In this case, the upper temperature limit for the formation of grossular in this silica-deficient environment would be at less than 400 °C (Shoji, 1975). The presence of water in the grossular (Table I) indicates that the actual temperature was much lower and could easily be in the 200 °C range or even lower (Shoji, 1975). The inferred temperatures for the hydrogarnet formation may have been even lower. Laboratory experiment indicates that hydrogarnet can be formed even below 100 °C as has been suggested for the occurrence of metasomatic hydrogarnets in Indian Ocean sediments (Kempe et al., 1974). At the Tel Shaharit outcrop the temperatures were also prob-ably quite low, as indicated by the occurrence of hydrogrossular and zeolites as the only metasomatic minerals. The formation of thomsonite is favoured by the scarcity of silica (Coombs et al., 1959). No magnetite or diopside has been found in Tel Shaharit, probably due to the lower temperature and the paucity of liquids in this highly calcareous environment. This supports the contention that a major part of the hydrothermal solutions in the Mena-hamiya outcrop were formed *in situ* by gypsum dehydration.

We conclude from our preliminary study that the contact metasomatic events in the Mena-hamiya gypsum resemble in many points the process of rodingization, and represent low-temperature hydrothermal activity in a Ca-rich, Si-poor, and water-rich environment. The exceptional situation in the Menahamiya gypsum is that the hydrothermal liquids may have an *in situ* origin due to dehydration of gypsum.

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