MINERALOGICAL MAGAZINE, MARCH 1975, VOL. 40, PP. 13–24

# Petrogenesis of the Tarr albitite–carbonatite complex, Sinai Peninsula

ARYEH ERVIN SHIMRON[1]
Dept. of Geology, Hebrew University, Jerusalem, Israel

SUMMARY. Large albitite bodies associated with explosive brecciation, fenite aureoles, intrusive carbonate rocks, olivine dolerites, and copper mineralization are described from the Dead Sea rift region in the south-eastern Sinai Peninsula. The main carbonate phases comprise breunnerite and dolomite with actinolite the main phase in the fenites. Field and isotopic evidence indicates that the intrusive carbonate rocks are of carbonatitic origin. The cogenetic, almost monomineralic main phases can be attributed to fractional crystallization and liquid immiscibility acting on a highly gas-charged, slow-cooling gabbroic magma. The complex, which is probably of Cretaceous (or older) age, appears to be related to early continental separation along the Dead Sea branch of the African rift system. The porphyry-type copper deposits resemble others that are located along crustal accretion (Iceland) or subduction (Chile) zones.

ALBITITES in large masses are rarely found, exceptions being the masses at Kragerö and Bamble in South Norway (Bodart, 1968) and those in Western Siberia (Kurzerajte *et al.*, 1963). Commonly they are found associated with plutonic and low-grade metamorphic rocks, while others have been described as minor parts of alkalic-carbonatite complexes with related fenites. In the formation of the latter type albitization may be significant. This has been shown by Deans *et al.* (1971) for an area along the Great Glen of Scotland where there is evidence of fenite-type soda-metasomatism, while Heinrich (1966) has recorded albitized clastic sediments near both the Ikomba carbonatite of Western Tanganyika and the Lueshe carbonatite, Congo. A small plug of albitite is found associated with carbonatite at Magnet Heights near Spitskop, South Africa (Heinrich, 1966).

## *Geological setting*

The Tarr albitite–carbonatite complex occurs in the southern portion of the Wadi Kyd region in the south-eastern Sinai Peninsula. It is bounded in general by Wadies Samra in the north-eastern portion and Tarr in the south-west. The complex comprises three major albitite masses with closely related explosion-breccias, fenite aureoles, intrusive carbonate bodies, olivine dolerite and lamprophyre dykes, and copper mineralization. The disposition of the complex defines a general NE. trend, which is about 35° to the trend of the rift about 5 to 10 km to the east (fig. 1). The three main albitite bodies are referred to (from SW. to NE.) as the Tarr, Hatamiya,

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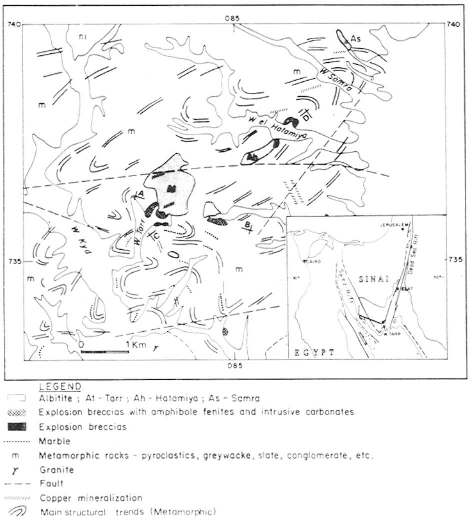
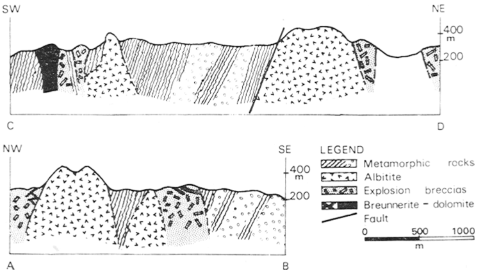
[1] Presently at St. Joseph Exploration Ltd., 90 Eglinton W., Toronto.

and Samra masses with two smaller bodies occurring to the east and south of the Tarr albitite.

The whole complex has been emplaced into polyphasaly folded, young Precambrian metamorphic rocks comprising mainly slaty pyroclastic rocks, volcanic meta-conglomerates, meta-andesites, pelitic schists, and meta-greywackes. A narrow folded band of tremolite marble is present near the Tarr albitite. The grade of metamorphism of the host rocks is greenschist facies near the Tarr mass but increases progressively to mid-amphibolite facies towards the north-east near the Samra albitite. About 2 km to the south-east of the Tarr albitite a superimposed contact aureole against granites locally brings the grade up into the hornblende and pyroxene-hornfels facies. Here the marbles contain forsterite and spinel, and black slates have been converted to cordierite hornfelses (Shimron, 1973). Three major and a number of minor faults cut across the complex with one (NW. trending) being a conspicuous lineament that can be traced across the Sinai Peninsula to the Gulf of Suez on the west side and the Straits of Tiran on the east.





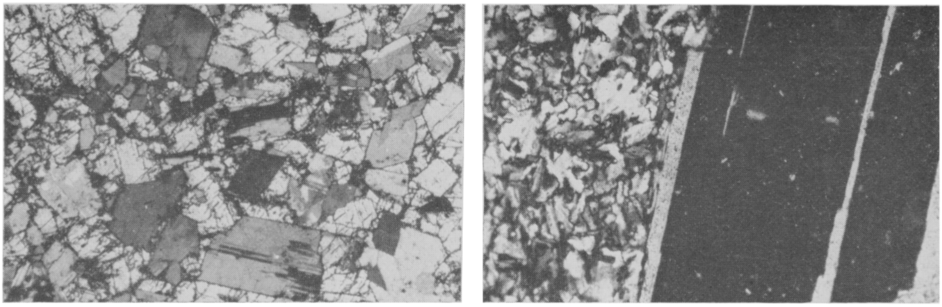
FIGS. 1 and 2: FIG. 1 (left). Generalized geological map of the Wadi Tarr area (lower Wadi Kyd), showing locations of the major geologic and structural elements and the Knayah lineament (WNW., inset); FIG. 2 (right). Geological cross-sections (A–B and C–D) of the Wadi Tarr area (ref. fig. 1).

The cross sections (A–B and C–D, fig. 2) show the main rock units between Wadies Tarr and Hatamiya and the field relationship of the albitites to the breccias and intrusive carbonate masses. The two carbonate bodies on top of the central breccia mass (section A–B) constitute the cone sheet mentioned at a later stage.

## *Petrography*

*Albitites.* Of the three albitite bodies the southernmost (Tarr) and central (Hatamiya) are clearly intrusive plutons, each about 1 km diameter, of almost pure monomineralic albitite, whereas the northern (Samra) is of metasomatic derivation. The intrusive albitites are pale yellow rocks, more rarely white or grey, the albite is twinned (albite-

Carlsbad and albite), not zoned, and replacement phenomena such as relict cores are not present. The albite has about 2·5±1 % An and 1±1 % Or and has been identified as a low-temperature albite (D. Bahat, personal communication). In the Tarr body the albite is generally of uniform size whereas the Hatamiya albitite is porphyritic with crystals of albite up to 2 mm in size or crystal clusters set in a matrix of lath-like to amoeboid small albites (fig. 4). A little interstitial sphene, quartz, zircon, chlorite, sericite, and tremolite are often present. Rutile±sphene is ubiquitous and pyrite is characteristic in the Hatamiya pluton. Apatite is rather typical in most rocks but is most abundant together with rutile in breccia fragments of albitite near the Tarr pluton (fig. 6). The Samra albitite is essentially an albite–tremolite–rutile gneiss showing the palimpsest foliation of the metamorphic host rock. There are also some pegmatitic albite–rutile bodies present and those are similar to the krageröites of Bodart (1968).



FIGS. 3 and 4: FIG. 3 (left). Albitite–carbonatite breccia. Broken albite crystals float in a coarse dolomite carbonatite matrix. Pol. light (×16); FIG. 4 (right). Porphyritic albitite, W. Hatamiya. Pol. light (×40).

*Explosion breccias.* A marked feature of the albitite masses is the occurrence of an up to 200 m thick marginal border zone (inner fenite zone) consisting of mega-breccias, breccia pipes and veins, and closely related massive amphibolitization. From the albitites outwards the breccias are generally albitite–actinolite breccia, carbonatite–actinolite breccia, carbonatite-tuff breccia, and coarse tuff mega-breccia. In the first angular fragments of brown, comminuted (vitrified?) albitite float in a matrix composed of medium to coarsely crystalline pale green actinolite (Table I). Further outwards the breccias consist of small to large angular to sub-angular (partially rounded) blocks of country rock tuff in a matrix of comminuted country rock or tuffisite, often with coarse carbonate cement, carbonatite dykes, and many iron oxides. Breccias are absent around the metasomatic Samra body, however a network of coarsely crystalline to pegmatitic cross-fibre veins of actinolite with rutile are ubiquitous. A notable feature of most of the border breccias and breccia pipes is the horizontal to sub-horizontal attitude of the blocks and channel-ways now filled with actinolite. Near the Tarr albitite a quartz-albitite breccia is also present. The pale and dark brown flinty albitite fragments consist of comminuted, almost crypto-crystalline, albite embedded in strained quartz or tuffisite matrix or in a matrix of actinolite with quartz. The albitite fragments are riddled with fine grains of rutile and apatite and cut by latter stringers of sphene and carbonate. A conspicuous flow banding in the fragments is defined by trains of rutile and by the dimensional orientation of some larger albite and apatite grains (fig. 6 and Table II). The brown colour of the albitite fragments is a function of the high rutile content in the rock. Actinolitization developed to various degrees is characteristic in the vicinity of most of the smaller and larger faults and associated breccias throughout the region, very often with intrusive carbonate stringers or carbonate cement.

TABLE I. *Chemical analyses, Tarr complex*

| | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| $SiO_2$ | 65·81 | 54·54 | — | 45·08 | 49·70 |
| $TiO_2$ | 0·28 | 0·14 | — | 2·11 | 1·64 |
| $Al_2O_3$ | 19·98 | 1·82 | — | 14·83 | 14·62 |
| $Fe_2O_3$ | 0·28 | 2·60 | — | 5·73 | 5·86 |
| FeO | 0·11 | 3·53 | 12·56 | 5·24 | 3·85 |
| MnO | 0·01 | 0·29 | — | 0·14 | 0·16 |
| MgO | 0·34 | 22·20 | 35·52 | 7·69 | 6·55 |
| CaO | 0·79 | 12·11 | 0·18 | 8·62 | 6·48 |
| $Na_2O$ | 10·76 | 1·00 | — | 2·54 | 2·75 |
| $K_2O$ | 0·46 | 0·35 | — | 1·32 | 3·03 |
| $P_2O_5$ | 0·22 | 0·05 | — | 0·39 | 0·77 |
| $H_2O^+$ | 0·32 | 1·05 | 1·67 | 3·03 | 3·30 |
| $H_2O^-$ | 0·48 | 0·27 | | 0·55 | 0·44 |
| $CO_2$ | — | — | 46·58 | 1·52 | — |
| Insol. res. | — | — | 1·17 | — | — |
| Total | 99·84 | 99·95 | 97·68 | 98·79 | 99·15 |

Atomic ratios to 24 (O,OH) for actinolite, anal. 2

$$\left.\begin{array}{ll}\mathrm{Si} & 7{\cdot}72\\ \mathrm{Al^{iv}} & 0{\cdot}28\end{array}\right\}8{\cdot}00 \qquad \left.\begin{array}{ll}\mathrm{Ca} & 1{\cdot}84\\ \mathrm{Na} & 0{\cdot}27\\ \mathrm{K} & 0{\cdot}06\end{array}\right\}2{\cdot}17$$

$$\left.\begin{array}{ll}\mathrm{Al^{vi}} & 0{\cdot}03\\ \mathrm{Ti} & 0{\cdot}02\\ \mathrm{Fe^{3+}} & 0{\cdot}28\\ \mathrm{Fe^{2+}} & 0{\cdot}42\\ \mathrm{Mn} & 0{\cdot}03\\ \mathrm{Mg} & 4{\cdot}69\end{array}\right\}5{\cdot}47 \qquad \left.\begin{array}{ll}\mathrm{OH} & 0{\cdot}99\\ \mathrm{O} & 23{\cdot}01\end{array}\right\}24{\cdot}00$$

Molecular ratios for breunnerite, anal. 3

| | |
|---|---|
| $FeCO_3$ | 16·53 % |
| $MgCO_3$ | 83·19 |
| $CaCO_3$ | 0·28 |

Anals. 1, 2, 4, and 5, Geochemical Laboratories, Dept. of Geology, Hebrew University; anal. 3, Y. Nathan, Israel Geol. Survey.

The rocks, in chronological order of emplacement, are: 1, albitite; 2, actinolite, massive, from the inner fenite zone; 3, breunnerite; 4 and 5, dolerites.

| | Norms | | |
|---|---|---|---|
| | 1 | 4 | 5 |
| Ap | 0·511 | 0·906 | 1·789 |
| Il | 0·232 | 4·007 | 3·115 |
| Or | 2·718 | 7·801 | 17·907 |
| Ab | 91·024 | 21·487 | 23·264 |
| An | 2·482 | 25·166 | 18·600 |
| C | 0·372 | 0·000 | 0·000 |
| Ru | 0·158 | 0·000 | 0·000 |
| Mt | 0·000 | 8·308 | 7·655 |
| Hm | 0·280 | 0·000 | 0·581 |
| DiWo | 0·000 | 6·284 | 3·556 |
| DiEn | 0·000 | 5·145 | 3·074 |
| DiFs | 0·000 | 0·377 | 0·000 |
| HyEn | 0·443 | 10·939 | 13·238 |
| HyFs | 0·000 | 0·802 | 0·000 |
| Q | 0·000 | 0·000 | 2·470 |
| OlFo | 0·283 | 2·150 | 0·000 |
| OlFa | 0·000 | 0·174 | 0·000 |
| $H_2O^+$ | 0·320 | 3·030 | 3·300 |
| Total | 98·823 | 96·576 | 98·547 |

| | Niggli values | | |
|---|---|---|---|
| Al | 48·11 | 21·09 | 22·95 |
| Fm | 3·39 | 48·64 | 46·32 |
| C | 3·55 | 22·29 | 18·49 |
| Alk | 44·95 | 7·98 | 12·25 |
| Si | 275·80 | 108·79 | 132·36 |
| K | 0·03 | 0·25 | 0·42 |
| Ti | 0·88 | 3·83 | 3·28 |
| Mg | 0·63 | 0·57 | 0·56 |
| W | 0·70 | 0·50 | 0·58 |

*Fenites.* Fenitization here is used in the sense of McKie (1965) as 'metasomatism of rocks of varied composition in the immediate vicinity of carbonatite complexes'. The terminology for fenite and fenitization is extensively discussed by Heinrich (1966) and others and clearly in its wider scope it encompasses an alkalic-type of metasomatism near alkalic complexes or carbonatites. In this area it is manifest mainly in border amphibolitization, which is on the whole only conspicuous in the vicinity of explosion-breccias or entirely marginal to the albitites or carbonate bodies. Locally, however, fenitization extends a few hundred metres beyond the breccias and tourmaline veins in greywacke and latites are found 2 km east of the Tarr albitite. However, the relation of the tourmaline to the complex is not clearly established. Besides the ubiquitous and often massive actinolitization and in the case of the Samra body cross-fibre veins of actinolite, fenitization around the latter also connotes intense sodium and potassium metasomatism whereby rocks are massively replaced by albite, phlogopite, and K-feldspar. Around the Tarr mass it is reflected in widespread amphibolitization and albitization, the introduction or alteration to Ca and Mg-Fe carbonates, and higher than normal concentration of Ti, P, B, Cl, Fe, Mg, Na, and Cr. These are mainly evidenced in various quantities of micas, rutile, apatite, sphene, scapolite, actinolite, magnetite, hematite, talc, and others.

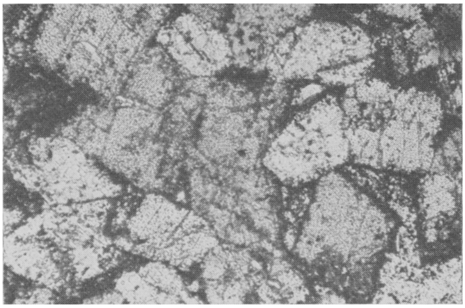
TABLE II. *Trace-element data, Tarr complex (in ppm)*

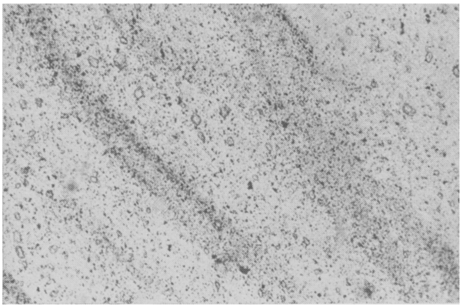
| Rock | Ba | Ce | Cl | Co | Cr | Ga | La | Nb | Rb | S | Sr | Th | Zr | Ni |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Albitite | < 20 | < 10 | 502 | 119 | 30 | 17 | < 10 | 51 | 5 | 90 | 105 | < 5 | 315 | 7 |
| Alb.-rutile rock | < 20 | < 10 | 460 | 261 | 1200 | 10 | < 10 | 96 | < 5 | 280 | 35 | < 5 | 595 | 12 |
| Alb.-rutile rock | < 20 | 50 | 345 | 298 | 128 | 21 | 15 | 63 | < 5 | 125 | 40 | 13 | 155 | 4 |
| Calcite | < 20 | < 10 | 215 | < 3 | 15 | 5 | < 10 | < 3 | < 5 | 670 | 240 | < 5 | 20 | 6 |
| Dolomite | < 20 | < 10 | 216 | < 3 | 18 | 4 | < 10 | < 3 | < 5 | 440 | 165 | < 5 | < 10 | 10 |
| Breunnerite | < 20 | < 10 | 265 | 16 | 82 | 5 | < 10 | < 3 | < 5 | 275 | 140 | < 5 | < 10 | 89 |
| Dolomite | < 20 | < 10 | 802 | < 3 | 188 | 5 | < 10 | < 3 | < 5 | 115 | 240 | < 5 | 25 | 9 |
| Actinolite | < 20 | 65 | 195 | 14 | 97 | 10 | 80 | 9 | 10 | 130 | 170 | < 5 | 90 | 57 |
| Mag.-talc carb rock | < 20 | 15 | 148 | 18 | 59 | 5 | < 10 | < 3 | < 5 | 600 | 140 | < 5 | 10 | 190 |
| Alb.-rutile pegmatite | < 20 | < 10 | 231 | 164 | 22 | 19 | < 10 | 32 | 20 | 300 | 120 | < 5 | 100 | 6 |

Analyses were done at the geochemical laboratories, Dept. of Geology, University of Glasgow.

*Carbonatites.* In the present work the term 'carbonatite' is employed in the sense of Heinrich (1966) as a 'carbonate-rich rock of apparent magmatic derivation or descent'.

Coarsely crystalline to pegmatitic dolomite and breunnerite (Table I) are the main carbonate phases, with calcite last in the crystallization sequence and very much subordinate. These are present as dykes, cement in breccias, small pipes, and at least one cone sheet within albitite–actinolite breccia east of the Tarr albitite (section A–B). Two small pipes are present in Wadi Tarr in the outer fenite zone, they are in excess of 10 m thick and the cone sheet is about 5 m thick and about 150 m in its long diameter; most dykes are a few cm to one metre thick. Normally pure dolomite and breunnerite coexist in individual dykes. Magnetite and haematite are present in pods, coarse bands, and fine dust, some of which seems to be the product of breunnerite alteration to dolomite or calcite following crystallization (fig. 5). Talc, phlogopite, actinolite, apatite, chlorite, and unknown crypto-crystalline material are present in small amounts. Rhythmically banded textures due to alternating crystallization of dolomite and breunnerite or breunnerite, dolomite, and calcite can be seen, together with pegmatitic fabric, sharp intrusive contacts, and flow banding; they imply emplacement of the carbonates by liquid injection in the form of a melt.





FIGS. 5 and 6: FIG. 5 (left). Dolomite-carbonatite (beforsite). Opaque rims around the coarse dolomite crystals suggest alteration of breunnerite-carbonatite. Plain light (× 16); FIG. 6 (right). Flow-banded rutile–apatite albitite fragment from albitite-actinolite breccia. Albite (colourless mass) is comminuted, flow banding is defined by dark rutile trains and the preferred dimensional orientation of apatites (high relief). Plain light (×40).

*Dolerites.* The last-emplaced olivine-dolerite and lamprophyre dykes cut across the whole complex (breccias included) but are rarely found here in the metamorphic country rocks. In chemical composition, one (Table I, no. 4) falls fairly close to Nockold's (1954) alkali basalt and tholeiitic dolerite, whereas another (no. 5) is closer to tholeiitic andesite with $K_2O > Na_2O$. Normally they consist of augite, calcic plagioclase, minor brown hornblende, serpentinized olivine, and apatite with smaller amounts of ore and chlorite present. In some, many granules of probably spinel are localized within the serpentine pseudomorphs. Of considerable interest, however, in some of these dykes, is the presence also of many perfectly rounded globules consisting of skeletal opaques, serpentine, some pyroxene and plagioclase and possibly chromite, spinel, and much unknown crypto-crystalline material (fig. 7). It is pointed out that the dykes differ considerably from the normal intermediate Precambrian dykes in Sinai

FIG. 7. Olivine-dolerite dyke rock. Circular structure with skeletal opaques suggests ocelli. Plain light (×63).

in the sense that they are olivine- and pyroxene-bearing (the latter tend to be microdioritic), in their alkalinity, and in the abundant carbonitization of the constituents.

*Copper ores.* The Samra copper deposit has been locally worked in ancient and more recent times (Bogoch, 1972). The main ores (essentially chalcosine-bearing quartz veins) trend NNW. in a number of ore shoots and occur about 2 km east of the Tarr albitite. Others, recently discovered by the writer and R. Bogoch of the Israel Geological Survey, are present as quartz–chalcopyrite ± molybdenite fissure veins near the Hatamiya albitite, Cu-sulphide veins and stringers in the Tarr albitite and the abundant disseminated pyrite in the Hatamiya albitite. Of some interest and perhaps genetically related are at least 4 or 5 copper occurrences along the major lineament (the 'Knayah' lineament) that trends NW. across the peninsula, mentioned previously. Brecciation, silicification, feldspathization, epidotization, chloritization, and locally actinolitization of the metamorphic host rocks are normally associated with the ores.

## *Petrogenesis*

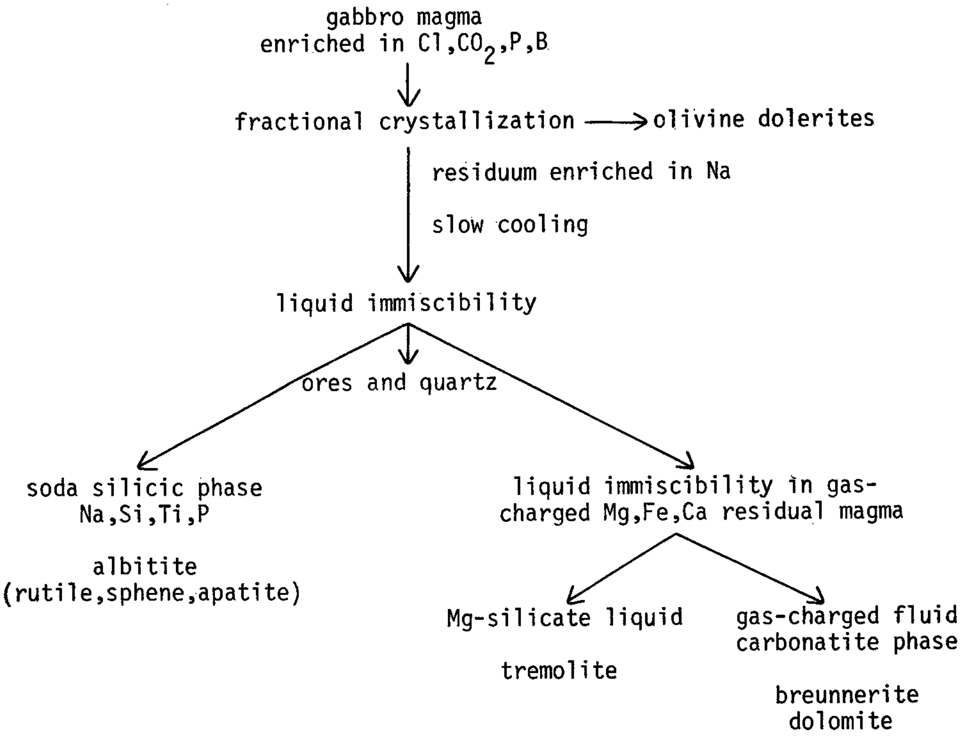
The major events in chronological order of emplacement comprise: albitite, explosive brecciation, fenitization (amphibolitization), breunnerite, dolomite, calcite, quartz veins (with or without sulphides), olivine dolerites. Fenitization seems to have taken place throughout the history of the complex; however, because of the over-all rarity of K-feldspar, sodic amphiboles, or pyroxenes, it is clearly atypical with regard to fenite aureoles around other alkalic-carbonatite complexes. Amphibolitization and the emplacement of the carbonatites was closely related to the explosive activity. All the rocks and fenites with their fairly high content of P, Cl, $CO_2$, Na, and locally K and B (Tables I and II) suggest a parental gabbroic, possibly hyperite magma, represented in its initial stages by the last emplaced olivine dolerites.

The early settling out of Ca-plagioclase, olivine, and pyroxene in the hotter and drier portions of the magma chamber (dolerites) may have resulted in considerable enrichment of Na and Si in the residual melt. Differentiation was at this time further facilitated by the upward diffusion of alkalis (mobile cations) and volatiles into regions of lower pressure and temperatures as suggested by Kennedy (1955) or by the formation of a vertical electric field as proposed by Saether (1948). Such a liquid, highly enriched in soda, silica, and volatiles (halogens) would probably fall within the field of exsolution and permit an alkali-aluminosilicate phase (albite) to separate out by immiscibility as shown by Bodart (1968). That liquid immiscibility provides a possible mechanism for the generation of alkalic carbonatites has also been shown experimentally by van Groos and Wyllie (1968). They showed that in the join $NaAlSi_3O_8$–$Na_2CO_3$–$H_2O$ the sodium fractions would also remain immiscible with a silicate magma.

The solidifying albitite, as the lightest fraction, was in all probability forced up because of its buoyancy and high gas pressures beneath it but above the residual, highly carbonated magma. The Samra albitite, related K-fenites, and pegmatitic krageröites may represent the most marginal movement of alkalis with volatiles.

Remarkably almost all Na and much of silica and alumina in the system was relegated to the formation of albitites. Nepheline and sodic pyroxenes could not form since Na was not available in excess of that required for the formation of albite with Si and Al. The actinolite and closely cogenetic carbonatites seem to represent a magnesium silicate liquid in immiscible equilibrium with a highly gas-charged fluid carbonatite phase. Since the stability field of amphiboles greatly expands with increasing $P_{H_2O}$, the presence of actinolite furthermore indicates a water-vapour pressure above the 1000 bars below which pyroxene would tend to form (it is noteworthy perhaps that some very fine needles of violet-blue riebeckite are present in some tuff fragments in the breccia pipes). Cooling of such a magmatic column must by necessity have been very slow in order to permit the sharp separation into the various monomineralic phases and furthermore to allow low-temperature albite to crystallize out. The differentiation of the carbonate melt into breunnerite, dolomite, and calcite was probably both pressure- (Wyllie, 1966) and temperature- (Johannes, 1969) dependent. However, high pressures in the explosion zones seem to have favoured the crystallization of dolomite and breunnerite (rather than calcite), with the latter taking up most of the iron in this system.

The whole differentiation scheme suggested is in part similar to that proposed by Bodart (1968) for the albitites of Kragerö and Bamble and would be:



Metal sulphides, which are often concentrated in the volatile constituents of a solidifying magma, appear to have migrated with these upwards and towards the cooler margins of the magma chamber as volatile metal-sulphide complexes. In part they are presently manifest in up to 1 % of disseminated pyrite in the Hatamiya albitite. Others were apparently trapped in channel-ways and fracture zones created by explosive brecciation and were emplaced as copper sulphides, silicates, and carbonates (secondary) in areas bordering the albitites and locally within them. A spectacular manifestation of this are the subhorizontal fissure veins of quartz–chalcopyrite with traces of molybdenite near the Hatamiya pluton. These trend roughly parallel between the latter and the Samra albitite. Others constitute the quartz–chalcosine veins with quartz, east of the Tarr pluton.

These sulphide deposits may be considered late residual injections or immiscible fractions that were injected into regions of low pressure beyond the breccia zones. The close association of this mineralization with porphyritic rocks (albitites), the explosive brecciation, the disseminated nature of much of the mineralization and some of the hydrothermal-type alterations (fenitization in part) all suggest that this mineralization shows many similarities with the porphyry coppers.

Lack of rounding in most of the breccia blocks and no clearly identifiable foreign fragments implies that they formed mainly *in situ*. The peculiar horizontal to subhorizontal attitude of the blocks in breccias and the system of horizontal, actinolite-filled fractures and stockworks may be accounted for by a horizontal 'gas-streaming' beneath an impervious mass such as an already emplaced and solidified body (albitite). Such an accumulation of gas and the building up of high pressures could feasibly culminate in violent discharge and a resulting horizontal fracture set at depth upon the gas reaching the surface. None the less, the formation of separate, highly gaseous centres resulting in a radial system of fractures after explosion could also be expected. The horizontal sets that formed near the nucleus of expansion would now be exposed after deep erosion.

It is suggested that at least the inner fenite zone (near the albitites) with actinolite or vesicular quartz, containing flow-banded and comminuted albite–rutile (highly granulated)–apatite rock fragments, was emplaced as a fluidized system (Reynolds, 1954). Whereas explosion seems to have produced the more angular fragments and blocks in both the outer and inner aureole, fluidization is implied by the partial rounding (by attrition), flow banding, and vesicularity of many breccia fragments in the inner aureole.

Rounded globules in the olivine-dolerites are for the present interpreted as possible ocelli that formed from immiscible droplets of magma as has been suggested by Phillpots (1968) in the Monteregian petrological province and by Ferguson and Currie (1972) for the alkaline carbonatites in Ontario. The above globules are perhaps the only direct physical evidence that here liquid immiscibility had already acted early on the gabbroic parental magma.

### *Isotopic and trace-element data*

Although the intrusive carbonate rocks have for the present been referred to as carbonatites, some contradictory data (trace elements) are present. The $^{18}O$ and $^{13}C$

isotope values for the intrusive carbonates around Wadi Tarr (fig. 8) fall sufficiently close to the limits for carbonatites as set by Taylor *et al.* (1967). Recent work by Deines and Gold (1973) has shown that both $^{13}$C and $^{18}$O values for carbonatites show a wider range than Taylor suggested; hence the Tarr data may be referred to as carbonatitic. The closest possible limestones (Cretaceous) to Wadi Tarr that could have been a source for the Tarr carbonatites are over 60 km away and if any were present before removal they probably formed only a superficial cover above the Tarr complex. The location of Precambrian marbles near the carbonatites (fig. 1) possibly suggests marble syntexis to provide the material for the intrusive carbonates; however, the quantity appears to be insufficient and furthermore these are folded into an open synform and unlikely to have reached the depths necessary for syntexis. Additional isotopic data on other intrusive carbonates in Sinai, which provides the subject of another paper (Shimron *et al.* 1974, in press), show that the combined Sr, C, and O isotopic data suggest a carbonatite-affinity origin for many of the carbonates in veins and faults, although no *bona fide* carbonatites (i.e. low $^{87}$Sr/$^{86}$Sr, high total Sr) are found.

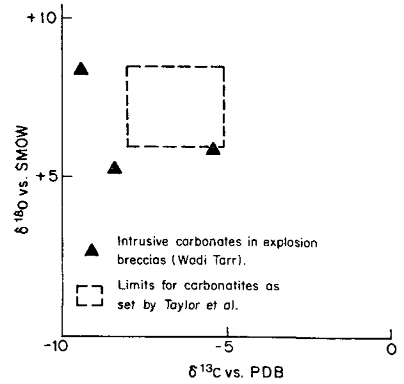


FIG. 8. $^{18}$O and $^{13}$C isotope values for some intrusive carbonate rocks in explosion breccias of Wadi Tarr. $^{18}$O concentrations are reported as per mil deviations from the SMOW (Standard Mean Ocean Water) standard. $^{13}$C concentrations are reported as per mil deviations from the PDB standard, the value of PDB is +30·4 per mil on the SMOW scale.

Trace-element data (Table II) for the main constituents in the complex show that Sr, Ba, Ce, Nb, and Zr are low and not compatible with 'true' carbonatites. This may imply a low-Sr source for the carbonates, which tend to show typical carbonatitic affinities in their O and C isotopes. Moderately high values, however, are shown in Co, Cr, Ga, Ni, and Cl in some specimens. The high Co, Cr, and Ni values may be a reflection of the upper mantle source for the complex. Cl is probably precipitated in the abundant apatite in the albitites and albite–rutile–apatite rock fragments in breccia and perhaps in traces of sphene and scapolite found in some rocks. Cr and Nb may be accommodated in rutile. Together with Zr, Cl, Ga, and Nb they seem to have concentrated preferentially in the late or residual liquid fraction (albitites).

Despite the assortment of contradictory data and as yet incomplete mineral studies, the complex is tentatively interpreted as an 'atypical carbonatite' complex. It is certainly an unusual association and future work may shed additional light on the problematic 'carbonatites'.

## *Tectonics and conclusions*

The spacial and temporal affinities between African rift valley alkaline magmatism and carbonatites are generally accepted. Kutina (1972) has observed certain regularities between rift structures and hypogene mineralization, suggesting these are also applicable to the East African rift system. The Tertiary porphyry deposits and related tourmaline-bearing breccia pipes in Chile can apparently be related to subduction of an oceanic plate (Guild, 1972), while hydrothermal copper–molybdenum mineralization of the porphyry-copper type (with explosion breccias) is present in Iceland on the Mid-Atlantic ridge (Jankovic, 1972). Hutchison and Hodder (1972) suggested that porphyry deposits formed at the edge of continental plates and Mitchell (1973) proposed that high-level porphyry coppers emplaced near continental margins are related to shallow-dipping Benioff zones.

Structural control of two types is suggested for the emplacement of the Tarr complex. On the one hand the complex is confined within the hinge zone of a NE.-trending antiform of Precambrian age, though there does not seem to be any lithological control for emplacement. Secondly the location of the complex immediately near the Dead Sea rift and near the locus of intersection of the conjugate lineament trends representing the Suez (NNW.) and Aqaba (NNE.) trends (Robson, 1971) suggests a close spatial and temporal relationship. It is pointed out that such apparently deep fractures were also the sites of emplacement of the Oligocene-Miocene dolerites in Sinai. Of considerable interest is the deep fracture ('Knayah' lineament) that trends WNW., seems to terminate just west of the Tarr complex, but continues beyond the Straits of Tiran into Arabia. Into this lineament dolerite dykes and carbonate veins have been emplaced with the latter showing distinct carbonatite affinities (Shimron *et al.*, 1974, in press). Besides these, a few copper occurrences and a major alkaline ring-complex (Gebel Tarbush, Nakhala, Madsus, Mussa) may also be related to this fracture. The possibility that this fracture with alkaline magmatism near or along it represents the continental manifestation of a (Dead Sea rift) transform fault-fracture zone must be seriously considered.

Fission track dates on epidotes (Barr, 1973) from the fenite aureole probably related to the emplacement of the Tarr complex give ages of 103±8·3 Myr, corresponding to the upper part of the lower Cretaceous. As such, the implication is that the Tarr complex may have formed at an early stage of continental separation since Freund *et al.* (1970) have attributed the early shear movements along the rift to the late Cretaceous. The over-all conclusion therefore is that the Tarr complex, and others such as the alkaline volcanism in the northern Negev, the mineral deposits of the Menuha Ridge (Shraga, 1971), and the metal-rich sediments associated with the hot brines in the Red Sea Deep (Degens and Ross, 1969) represent a continuous (or staged) event localized along accreting plate margins. The magmatic events commenced during the Cretaceous (Tarr), continued through the Oligocene-Miocene (basalts, dolerites, and oceanic crust) and are extending up to the present (hot brines, oceanic crust). The locus of intersection of NNW. and NNE. (trend of the Tarr complex) fault trends were the favourable sites of alkalic activity and metallogeny with Precambrian fold structures exercising some control on sites of emplacement. This magmatic activity may indeed be a smaller-scale manifestation of the Mesozoic-Tertiary taphrogenic basic and alkalic volcanism (with carbonatites) that has taken place along the African rift valley. The probability that the Tarr complex represents strongly differentiated upper-mantle material, tapped by deep fractures and emplaced within favourable structural zones is proposed.

*Acknowledgements.* Fieldwork in the Sinai Peninsula was made possible by a grant from the Bat-Sheva de Rothschild foundation. A postdoctorate fellowship from the Michael and Anna Wix Trust, London, allowed the writer to continue this work at the Dept. of Geology, University of Glasgow, where the kind assistance of Dr. D. Bowes, other colleagues and the technical staff is gratefully acknowledged. The author is most grateful to Dr. B. Leake for preparing the norm and formula calculations and to the referee for the many helpful suggestions, which were incorporated into this final version.

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[*Manuscript received 13 December 1973, revised 28 May 1974*]

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[1] This is a German transliteration; the original Russian has not been seen.