THE MINERALOGICAL MAGAZINE
AND
JOURNAL OF
THE MINERALOGICAL SOCIETY

No. 139. December, 1932. Vol. XXIII.

On the metamorphism produced by the combustion of hydrocarbons in the Tertiary sediments of south-west Persia.[1]

(With Plates IX and X.)

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[Read June 7, 1932.]

THE present communication deals with a peculiar series of rocks found in association with the Tertiary sediments so extensively developed in south-west Persia at the head of the Persian Gulf. At one or two localities in that region the marls and limestones are baked, fused, and in some cases so thoroughly recrystallized that at one time they were suspected to be igneous material arising from localized volcanic action. Careful examination of the field occurrences has, however, failed to disclose any trace of volcanicity, whilst petrographical and chemical examination has shown that even the most coarsely crystalline types bear no resemblance to any known igneous rock.

My attention was first directed to these rocks by Mr. H. T. Mayo in 1926 when I was permitted to examine the material collected by Mr. B. K. N. Wyllie, to whom belongs the credit of first discovering these apparently unique occurrences, and to visit the localities, where

[1] Communicated by permission of the Director, H.M. Geological Survey and Museum.

additional material was obtained. The cause of the alteration of the sedimentary rocks at these localities is no longer operative, and is not apparent; that it may most probably be ascribed to the combustion of gas or oil long since extinguished has been made clear by the subsequent investigation of other localities where similar rocks have been, and are being, exposed to such action and have undergone similar changes in structure and mineral composition.

The material on which the present descriptions are based was collected in part by myself in May, 1926, and in part by Messrs. B. K. N. Wyllie, R. S. Mackilligan, J. McAdam, and N. L. Falcon of the Anglo-Persian Oil Company, to all of whom I am indebted not only for specimens but also for most valuable information regarding field occurrences.

Field Occurrence.

The most interesting of the localities and the one where the metamorphism of the sediments seems to have been most extensive and prolonged is a small hill, known as Tul-i-Marmar, situated about 52 miles north-east of Ganaweh, a settlement on the eastern shore near the head of the Persian Gulf (fig. 1). This hill lies on the northern extension of a long anticlinal axis—the Chillingar axis—which is one of the numerous structural lines, trending north-west to south-east, along which the massive accumulation of Tertiary sediments of south-west Persia has been folded. The anticline pitches towards the north-west bringing up the Middle Fars [1] division of the Mio-Pliocene rocks in the core of the fold.

Tul-i-Marmar (fig. 2) forms a conical-shaped hill, rising rather abruptly to a height of about 250 feet above the general level which is here from 1,700 to 1,800 feet above sea-level. The hill is built up of red and green marls with gentle easterly dips of 3–5°. On its western and south-western faces, which are steep, there occurs a curious mass of breccia measuring roughly 100 by 100 feet with highly inclined junctions against the adjacent sediments. The field relations, the nature of the material, and, in places, its roughly centroclinal arrangement strongly suggest at first sight the occurrence of a volcanic vent. The breccia consists of angular blocks of varying size set in a matrix of porous, reddish to pink gypsum. In the field the blocks can be readily divided into two types: (*a*) sedimentary rocks consisting of red and green marl, often very hard and clinkery, black limestone,

[1] Cf. The structure of Asia. Edited by J. W. Gregory, London, 1929, p. 111.

red sandstone or grit; and (*b*) rocks which are either slaggy or essentially and sometimes quite coarsely crystalline. It is the presence of these lava-like slags and crystalline rocks which gave rise to the view that the breccia was volcanic, but the petrographical evidence detailed below shows that they are merely fused and, in some cases, almost thoroughly recrystallized calcareous marls. Traced eastwards over the top of the hill, the breccia is seen to consist more and more of blocks of shattered red mudstone with a gypseous matrix, and it finally grades off into hardened solid mudstone.

The significant features of this interesting occurrence are: (1) the strictly localized nature of the metamorphism; around the base of the small hill are undisturbed and unaltered mudstones; (2) the undoubted sedimentary origin of all the material found in the breccia; (3) the complete absence of any rocks of volcanic origin. These facts seem to indicate that the vent-like structure owes its origin to the escape of gas and oil, probably with explosive force, which shattered the rocks surrounding the orifice and, becoming subsequently ignited, in places fused, recrystallized, and metamorphosed them.

About 3½ miles south-east from Tul-i-Marmar on the north-east side of the river-course known as Darreh Harrachi, and situated above a vertical cliff of limestone of Middle Fars age, there occurs a mass of greenish, vesicular, crystalline rock, roughly about 12 by 8 feet in area. It is surrounded by red and yellow, slightly brecciated marls into which it appears to grade. The mass resembles a dike or rather a plug in its mode of occurrence, but no chilled margins are present and the petrographical character of the rock shows it to be an altered marl. My visit to this locality was somewhat hurried, but since then Mr. N. L. Falcon has made a fresh examination, in the course of which he exposed the base of the crystalline rock by blasting and excavation and proved that it was continuous downwards with baked mudstone underlain by black, bitumen-stained limestone with well-developed vertical joints carrying bitumen. The largest of these joints has blackened walls and it leads up to the area of most intense metamorphism which has thus been proved to be superficial and to be due most probably to the combustion of oil or gas. At one or two other localities in the neighbourhood the sedimentary rocks show secondary jointing, reddening, and hardening, to be ascribed to the same cause, but in no case is the metamorphism accompanied by the extensive brecciation and signs of explosive activity so apparent at Tul-i-Marmar.

The material collected from the above-mentioned localities has been compared with interesting results with specimens from other

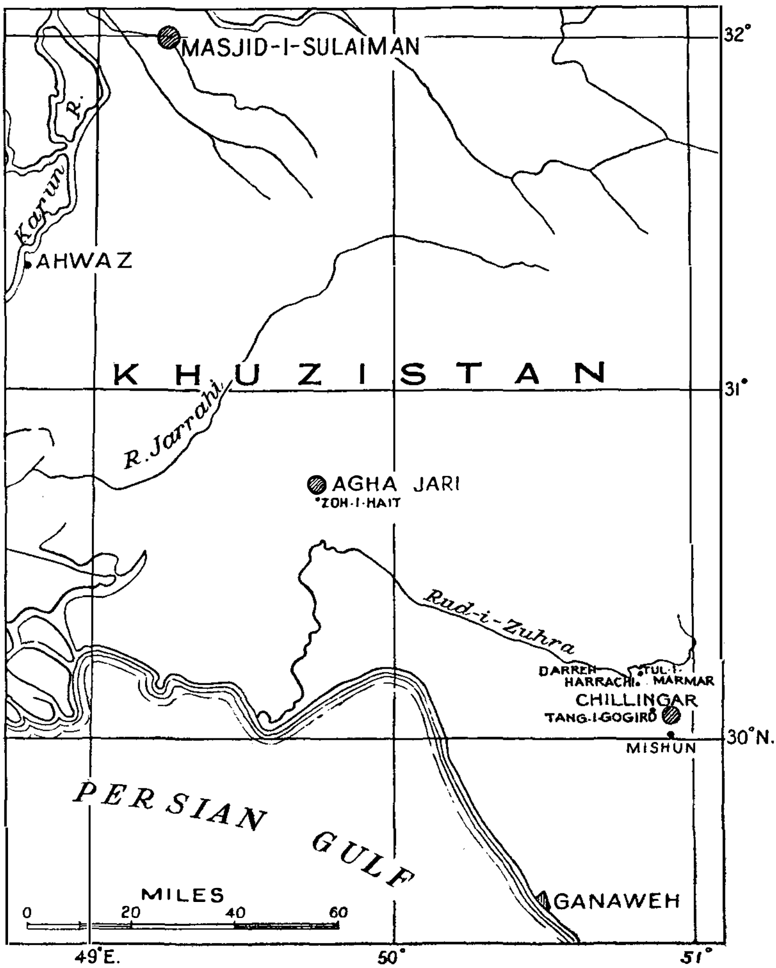


FIG. 1. Sketch-map showing localities referred to in the text.

localities in Persia where burning gas or oil is known to have metamorphosed the Tertiary sediments.

At Zoh-i-Hait, near Agha Jari, about 80 miles north-west of Tul-i-Marmar, spontaneous combustion is still in progress, with the formation of hydrogen sulphide, sulphur dioxide, and sulphur. Partially burnt bituminous matter and a dark-brown powdery ash which covers the hill-side give rise to a conspicuous black landmark on the edge

FIG. 2. Western and south-western aspects of Tul-i-Marmar, Persia.

of the plains. The horizon is the base of the Middle Fars and the limestones and marls are, according to Mr. A. J. Goodman, to whom I am indebted for the foregoing particulars, very much indurated by the heat. Specimens submitted from this locality show that fusion and recrystallization of the marls have taken place with the production of types even more coarsely crystalline than those at Tul-i-Marmar, one remarkable specimen showing large augite crystals up to 2 cm. in length. Mr. B. K. N. Wyllie informs me that similar phenomena occur in Tang-i-Gogird, about 8 miles south-east from Tul-i-Marmar, and he is of the opinion that they arise from the exhalation of hydrocarbon gases and hydrogen sulphide from oil or gas accumulations in or below the Lower Fars strata. By oxidation the hydrogen sulphide gives rise to sulphates forming a grey, powdery gypseous clay containing some aluminium sulphate, and known locally as gach-i-tursh (= sour gypsum). In such areas crater-like holes lined with sulphur crystals and emitting sulphurous gases are common. Should the gases leak to the surface and ignite, the conditions necessary for the metamorphism seen at Zoh-i-Hait and Tang-i-Gogird are set up, whilst if there is a sudden release of gas accumulated and held at high pressure the phenomena of Tul-i-Marmar are produced.

At various places in the oil-fields fused and partially crystallized rocks have been produced from Tertiary sediments by the action of burning gas or crude oil during the process of drilling wells. Samples have been examined from such artificial occurrences at Masjid-i-Sulaiman, the principal Persian oil-field, and at Naft Khaneh, about 22 miles south of Khanaqin, on the Persian-Iraq frontier. Owing to the short time during which the fire lasted and the necessarily rapid rate of chilling of the molten material, the metamorphosed material tends to be glassy and slag-like, yet it shows in places a mineral development quite comparable with that of the more thoroughly crystallized and, presumably, more slowly formed, products of the natural occurrences.

Petrography.

I. Tul-i-Marmar.—The rocks found in the breccia of Tul-i-Marmar comprise a considerable variety of types. The sediments present include gypsiferous rock-salt, hardened green and red marls and mudstones, calcareous fine-grained and reddish grits showing under the microscope angular grains of quartz, felspar, and mica set in a calcareous matrix. Blocks of a peculiar dense-black fine-grained limestone are plentiful. Under the microscope this rock is seen to be a fossiliferous limestone with numerous organic remains set in a recrystallized matrix of calcite. The organic fragments are surrounded and frequently completely permeated by a black deposit of carbon which sometimes forms lustrous reniform masses on the surface of specimens and resembles the carbon deposited on the walls of high-temperature gas furnaces. The rock is obviously a recrystallized limestone, originally impregnated with hydrocarbons which have been decomposed by heat, leaving residual carbon which imparts the jet-black colour.

The most interesting rocks in the breccia are, however, the marls and calcareous sandstones which have undergone fusion and recrystallization. They vary in texture from exceedingly fine-grained, greenish, flinty looking types to comparatively coarsely crystalline rocks, with constituent minerals measuring up to 2–3 mm. in length. Vesicles, either empty or lined with calcite or gypsum, or both, are common, and not infrequently are so abundant as to give the rock a pumiceous appearance. In the less altered specimens the original structure of the marl is tolerably well preserved, the only apparent changes being a recrystallization of calcite and the development of yellowish clots and strings composed, apparently, of extremely minute, granular crystals of yellowish-green pyroxene (F. 3052,[1] F. 3040, F. 3053). With advancing alteration and fusion the marl gives place to a granular aggregate of greenish-yellow, finely crystalline pyroxene with glass in which are set irregular crystals of turbid wollastonite with corroded outlines and granular inclusions of pyroxene. The rock is now highly vesicular, the vesicles containing calcite and a turbid, finely crystalline substance, probably anhydrite. Clots of turbid, undigested marl are also present (F. 3041, F. 3043).

Two distinct types of structure, probably to be ascribed to different fusibilities and rates of cooling, are present. In the one type where fusion was presumably more gradual, the structure might fittingly be termed porphyroblastic, turbid porphyroblasts of wollastonite and yellowish augite being set in an exceedingly fine-grained, undifferentiated matrix which invades the porphyroblasts (F. 3031). With more complete recrystallization a rock consisting of a mosaic of more or less equant subidiomorphic crystals of wollastonite, greenish augite, and plagioclase (var. bytownite) is produced. Irregularly-shaped spaces between these minerals are filled by a colourless glass of low refractive index, enclosing laths of wollastonite and bytownite with

[1] The numbers refer to the collection of slides of the Geological Survey and Museum.

rounded crystals of augite. Vesicles filled with recrystallized calcite are common, and a few residual clots of turbid marl with cloudy porphyroblasts of wollastonite occur sporadically throughout the rock (F. 3025, F. 3037). The coarser-grained types showing this structure are not always the most thoroughly crystalline. Thus, in the fine-grained types, with crystals measuring 0·2 by 0·06 mm., the amount of residual, undigested sediment may be negligible, whilst specimens in which the porphyroblasts of wollastonite and augite measure up to 1·5 by 0·4 mm. may contain quite a substantial proportion of turbid marl showing as its only recognizable signs of alteration recrystallization to calcite, particularly in zones surrounding and invading the wollastonite (F. 3028).

Rocks showing the second type of structure are composed of crystals of *acicular* habit and resemble much more closely the artificial products arising from the fusion of marls at the oil-fields (see below). The finer-grained types of these rocks, which are usually highly vesicular, consist of very minute acicular crystals of pyroxene, wollastonite, and plagioclase, measuring 0·1 mm. in length, and even less, set in a turbid, undifferentiated matrix with patches of recrystallized calcite (F. 3033). Some of them contain original quartz grains incompletely digested; these exhibit all degrees of corrosion and are surrounded either by isotropic rims or by confused aggregates of wollastonite, augite, and recrystallized calcite, which ultimately replace them. Inversion to tridymite or cristobalite has not been observed (F. 3035, F. 3038). In the coarser types the same minerals are present, but the turbid matrix is now replaced by patches of isotropic glass in which crystals of wollastonite, augite, and plagioclase have developed. The vesicles are filled with recrystallized calcite, often surrounded by a zone of isotropic glass, and occasionally containing crystals of the silicate-minerals already mentioned (F. 3026). As in the case of the porphyroblastic types, here also the more coarsely crystalline rocks may show a larger proportion of residual marl than the finer-grained ones (F. 3037).

Although pyroxene, wollastonite, and plagioclase (var. bytownite) are the silicates most commonly developed in the recrystallized sediments of Tul-i-Marmar, other minerals are exceptionally present either in some of the more coarsely crystalline rocks or in those which, whilst of very fine grain, seem to have been almost completely recrystallized. Thus some of the coarser, acicular types, in hand-specimens resembling fine-grained syenites, under the microscope are seen to consist of pale-green aegirine-augite, as crystals measuring up to 3 mm. in length, clear laths of wollastonite, 1·2 by 0·12 mm., and rectangular, leather-brown crystals of melilite, 1 by 1 mm. There are no traces of turbid residual sediment in the sections, but the angular spaces between the crystals are filled with an aggregate of needles of deep-green pleochroic pyroxene, wollastonite, turbid melilite, recrystallized calcite, and isotropic glass (F. 3030). Other sections show areas of clear transparent glass in which are developed large crystals of colourless pyroxene, clear wollastonite, plates of bytownite felspar, and large exceedingly turbid imperfectly-formed crystals of melilite enclosing recrystallized calcite and occasional crystals of the other minerals. Vesicles filled with microcrystalline anhydrite, into which project crystals of augite, wollastonite, and melilite, are common (F. 3061). A still more remarkable rock consists of crystals of honey-yellow to green pleochroic aegirine, clear yellowish-brown melilite as crystals up to 2 mm. in length, clear wollastonite, and large clear patches of a mineral which is not quite isotropic but shows the characteristic anomalies and refractive index of leucite; included in these clear areas are crystals of aegirine and wollastonite, veins and patches of recrystallized calcite, and dark turbid rod-shaped masses altering in places to wollastonite, and representing, probably, vestigial sediment (F. 3062).

Similarly, in the coarse-grained porphyroblastic types the areas of turbid marl give rise in the first place to rectangular elements full of inclusions surrounded by clear isotropic glass and finally to leather-brown melilite (F. 3060, F. 3068, F. 3029). Fine-grained vesicular rocks, consisting of irregularly-shaped porphyroblasts of yellow aegirine set in a clear colourless matrix of finely-crystallized melilite, have also been noted and recall the types so common at Darreh Harrachi (F. 3065, F. 3096).

II. Darreh Harrachi.—The altered rocks at this locality are fine-grained tough greenish porcellanous types with minute vesicles which are usually empty. Under the microscope they occasionally show acicular crystals of green pyroxene, wollastonite, and bytownite with glass and recrystallized calcite (F. 3088), but typically they are fine-grained porphyroblastic rocks consisting of a matrix of colourless melilite built up of exceedingly minute square-shaped crystals in which are set spongy imperfectly-crystallized masses of pyroxene and wollastonite, riddled with inclusions of melilite. When the pyroxene is colourless, wollastonite is rare and the melilite is distinctly birefringent, but when the pyroxene is yellow and, apparently, approaching aegirine in composition, wollastonite is abundant and the melilite is almost isotropic (F. 3080, F. 3090, F. 3084, F. 3093).

Some of these rocks are unique amongst natural occurrences in that they contain pseudo-wollastonite, a mineral hitherto known only in artificial material. It has been detected in three slides (F. 3083, F. 3085, F. 3092), where it builds irregularly-shaped crystal grains, 0·1 by 0·05 mm., showing typical cleavage and optical properties (p. 219). It occurs in intimate association with melilite, yellow pyroxene, and with wollastonite, a point of considerable interest bearing on the conditions under which the rocks were formed. Wollastonite and pseudo-wollastonite have been noted, not only in the same microscopic field but also in the same mineral grain, which may consist of a core of pseudo-wollastonite surrounded and apparently in process of replacement by the other modification (F. 3083).

III. Zoh-i-Hait, near Agha Jari.—Only two specimens are available from this locality, where, as already mentioned, marls are at present in process of metamorphism by spontaneous combustion. One of these (F. 3095) is a greenish-grey rock with irregularly-shaped masses of a brown substance scattered throughout the specimen. Vesicles are common and are either empty or filled with a white chalky-looking substance. A section shows large crystals of colourless idiomorphic pyroxene, up to 2 mm. in length, with occasional laths and plates of bytownite set in a matrix consisting of finely granular pyroxene and large brown masses of turbid isotropic glass enclosing crystals of pyroxene and plagioclase felspar. The vesicles are filled with recrystallized calcite and turbid gypsum and are invaded by the surrounding material. Wollastonite is rare, but throughout the slide there are fibrous turbid aggregates, showing very rarely incipient wollastonite. This rock bears a remarkable resemblance to one from Tul-i-Marmar (F. 3061) from which it differs in having brown turbid glass in place of melilite, gypsum in place of anhydrite in the vesicles, and an aggregate of turbid fibrous material in place of wollastonite. Otherwise the rocks are identical in structure and mineral development, the one being merely a more thoroughly recrystallized representative of the other.

The other specimen (F. 3094) is the exceedingly coarse-grained rock already referred to (p. 212). Under the microscope large idiomorphic crystals of colourless augite (up to 2 cm. in length) are set in a turbid matrix consisting of acicular crystals of augite, very occasional plagioclase felspar, and long turbid fibrous growths which appear to consist of recrystallized calcite and a finely fibrous or granular aggregate of anhydrite.

IV. Masjid-i-Sulaiman and Naft Khaneh.—The fused and partially recrystallized marls from these two localities were produced by jets of burning oil and gas playing on surface material and, in consequence of the rapid chilling, are never coarsely crystalline. They consist essentially of acicular crystals of pyroxene, colourless to pale-yellow, and wollastonite in an isotropic matrix which may be clear and transparent or turbid and full of inclusions. In the more slowly cooled and more crystalline types the rocks resemble the finer-grained acicular types from Tul-i-Marmar, and there can be no doubt that with more prolonged heat and slower cooling rocks identical with the more coarsely crystalline ones from that locality would have been produced.

Pseudo-wollastonite has been detected in three of the specimens. In the first (F. 3098), from Masjid-i-Sulaiman, it forms a black selvage, 0·5 cm. thick, on a dark-green vesicular rock. Under the microscope this selvage is seen to consist of pure pseudo-wollastonite as sheaf-like aggregates, prismatic crystals, and skeletal growths, with subordinate glass; the rock itself consists of acicular wollastonite and augite with the usual turbid matrix.

In two sections from Naft Khaneh (F. 3102, F. 3104), showing yellowish pyroxene and wollastonite as acicular crystals in turbid glass, pseudo-wollastonite occurs as minute prisms and irregularly-shaped grains in isolated areas.

Mineralogy of the Metamorphosed Sediments.

(*a*) *Pyroxene.*—The pyroxene, which is always present in the slides, shows considerable variation in optical properties. When idiomorphic, its habit is prismatic parallel to the *c*-axis and the typical (110) cleavage is well developed. It varies from colourless to fairly deep greenish-yellow and is frequently zoned, crystals occurring with colourless cores and greenish margins; it is always fresh and shows no signs of decomposition. The colourless variety appears to be a typical *diopside*, optically positive, with approximate refractive indices $\alpha = 1{\cdot}665$, $\beta = 1{\cdot}680$, $\gamma = 1{\cdot}700$. The maximum extinction $\gamma : c$ is 42°. With increasing refractive index and decreasing extinction-angle the colour gradually deepens through pale-green to a honey-yellow variety which appears to be a true *aegirine*, or at least an aegirine-augite very rich in the aegirine molecule. It occurs as prisms, (100) and (010), with well-developed cleavage and pronounced pleochroism, α = pale-green, β = yellowish-green, γ = honey-yellow. The approximate refractive indices are $\alpha = 1{\cdot}760$, $\beta = 1{\cdot}800$, $\gamma = 1{\cdot}810$, $2V = 84$–$90°$, optically negative with pronounced inclined dispersion, $\rho > v$. From approximate measurements on the universal stage, $\alpha : c = 14°$, and the cleavage-angle $(110) : (1\bar{1}0) = 86°$. Unfortunately this interesting mineral, which occurs in association with leucite, melilite, and wollastonite, has been detected in quantity only in one small specimen and, although renewed search has been made, sufficient material for a satisfactory analysis is not at present available; but that it approaches an aegirine in composition is certain.

(*b*) *Wollastonite*.—This mineral is a common constituent of the altered rocks, in some cases being developed as crystals up to 2 mm. in length. They are usually elongated along the *b*-axis and tend to be tabular parallel to (100). The faces recognized in the sections are (100), (001), (102), $(\bar{1}01)$, and cross-sections show the three typical cleavages parallel to (100), (001), and $(\bar{1}01)$. Such sections show the maximum birefringence and peculiar mottled extinction noted by Dr. Osborne,[1] with extinction $\alpha : c = 33°$. Twinning on (100) is common and is sometimes repeated. The mineral is optically negative with small, and slightly variable, axial angle; $\alpha = 1{\cdot}617$, $\beta = 1{\cdot}628$, $\gamma = 1{\cdot}630$.

In the more completely crystallized specimens the crystals are clear and transparent but are frequently veined with crystalline calcite. In the rocks with a considerable proportion of residual sediment the crystals are always turbid and show rounded corroded outlines against the matrix which invades them. At the junction there is usually a sheath of turbid recrystallized calcite, and the inclusions of marl in the crystals show all stages of recrystallization to that mineral. The turbidity of the wollastonite is due to minute gas cavities; whilst the rounded outlines, and the sheaths, veins, and inclusions of calcite seem to have arisen from reaction between the marl and the wollastonite when the rock was heated up, rather than from ordinary weathering subsequent to cooling. Otherwise it is difficult to explain the fresh condition of the wollastonite in the more completely recrystallized material (F. 3027, F. 3028, F. 3030, F. 3060–3).

[1] G. D. Osborne, The contact metamorphism and related phenomena in the neighbourhood of Marulam, New South Wales. Geol. Mag., 1931, vol. 68, p. 295.

(*c*) *Pseudo-wollastonite.*—The rarity of this modification of calcium metasilicate in the fused and recrystallized marls affords some indication of the maximum temperature at which the minerals separated out, it being the stable form above 1200° C.[1] It builds irregular grains, 0·1 by 0·05 mm., or irregular prisms, with corroded outlines and traces of a cross-cleavage parallel to the basal plane. It is fresh and undecomposed and may be readily identified by its high birefringence, its practically uniaxial figure in basal sections, optically positive sign, and its refractive indices (determined in oils) $\omega = 1{\cdot}614$, $\epsilon = 1{\cdot}648$. Basal sections might be mistaken for granular calcite but the positive optical sign is diagnostic. In the specimens from Darreh Harrachi it always occurs in sporadic areas throughout the aggregate of melilite crystals comprising the bulk of the rock and associated with a deep-brown isotropic material which is probably glass. Partial reversion to wollastonite has been noted, the two forms being readily identifiable in the same grain.

(*d*) *Plagioclase.*—The felspar noted in the slides is always a plagioclase of the composition of bytownite. It seems to have been the last of the silicate-minerals to form and occurs as clear irregularly-shaped plates between the other minerals, which it encloses. It shows the usual cleavage and polysynthetic twinning, and is optically negative with a large axial angle and a mean refractive index of 1·573 (F. 3063). In the rocks where the felspar is best developed there is usually a considerable amount of clear, colourless, isotropic glass containing crystals of pyroxene. This glass has probably the approximate composition of bytownite which appears to have replaced it when cooling was sufficiently slow (F. 3027).

(*e*) *Melilite.* This mineral shows considerable variation in optical properties and doubtless several varieties are present in the specimens. In the coarser types of rocks from Tul-i-Marmar it builds leather-brown crystals up to 2 mm. in length showing good cleavage in the rectangular sections. Such crystals may be transparent and free from inclusions (F. 3052), but usually they are turbid and enclose calcite, wollastonite, and pyroxene. Peg-structure is common. In some sections large rectangular individuals are composed of leather-brown birefringent rims surrounding turbid cores of unidentified material, and all stages occur from such perimorphs to tolerably homogeneous crystals with brown doubly refracting rims and isotropic

[1] G. A. Rankin and F. E. Wright, The ternary system $CaO–Al_2O_3–SiO_2$. Amer. Journ. Sci., 1915, ser. 4, vol. 39, p. 5.

cores. The deep-brown material is distinctly pleochroic, and in prismatic sections showing cleavage the ray vibrating parallel to the cleavage, i.e. the ordinary ray since the cleavage is presumably basal, is pale-brown, whilst the ray vibrating across the cleavage is deep-brown; in the paler and more homogeneous crystals, however, the ordinary ray is the more deeply coloured. Between crossed nicols sections extinguish straight and show the usual blue polarization colours, but they are rarely uniform and show mottling and zoning. In the blue-polarizing zones, the ray of lesser velocity vibrates parallel to the cleavage and the mineral is negative; the reverse relation holds good for zones showing grey polarization colours and the mineral is positive. In parallel light these sections may appear quite uniform but they seem to be built up of zones of melilite of slightly different optical properties and composition, arranged roughly parallel to the basal plane. For this reason the mean refractive index is difficult to determine; it varies from 1·632 to 1·635 (F. 3030, F. 3061–2), the brown melilite being probably a mixture of åkermanite and humboldtilite in variable proportions.[1]

A colourless melilite, as exceedingly small rectangular crystals, is well developed in the material collected from Darreh Harrachi and sometimes forms the major portion of the altered rocks. It polarizes in pale greyish-blue colours with straight extinction and is always optically positive with a mean refractive index of 1·643 (F. 3084).

(*f*) *Leucite.*—In one slide (F. 3062) this mineral occurs as large irregularly-shaped plates, up to 2·6 by 2·1 mm., clear and colourless, showing under crossed nicols characteristic polysynthetic twinning. The birefringence is in the majority of cases very weak but the twin-structure is usually revealed by the gypsum plate. The leucite is in intimate association with aegirine, wollastonite, and pale-brown melilite; and it encloses crystals of these three minerals. Other inclusions consist of rod-shaped turbid bodies which sometimes enclose small crystals of aegirine or wollastonite. The refractive index is 1·509. Irregular cracks traversing the plates are filled with finely crystalline calcite.

(*g*) *Vesicle Minerals.*—In the finely crystalline types the vesicles are usually filled with crystalline calcite associated with a finely crystalline aggregate of gypsum (optically positive, refractive indices 1·52–1·53), but with increasing alteration and crystallization the

[1] A. F. Buddington, Natural and synthetic melilites. Amer. Journ. Sci., 1922, ser. 5, vol. 3, pp. 66 and 78.

character of the vesicle minerals changes. Gypsum becomes rarer and is replaced by a turbid finely crystalline material with much higher refractive index, in some cases up to 1·614, which approaches anhydrite in character; calcite may give place to a zone of isotropic, slightly turbid glass containing crystals of plagioclase, pyroxene, and wollastonite, with a core of calcite showing highly irregular outlines against the glass which appears to be invading it. In some slides all stages can be seen from vesicles filled entirely with calcite to those filled with glass containing small crystals of the silicate-minerals and having at the centre a minute scrap of crystalline calcite. Such vesicles are not so sharply demarcated from the surrounding rock as those filled entirely with calcite; their boundaries are replaced by crystalline aggregates of pyroxene, wollastonite, and plagioclase until finally the vesicle is practically obliterated by an aggregate of these minerals with glass and occasional calcite (F. 3026). It thus seems clear that the calcite present in the vesicles, and throughout the slides, is not a product of weathering but has resulted from the recrystallization of carbonate of lime in the marl and has participated in the reactions brought about by increasing temperature.

Wollastonite is another mineral which seems to show reaction phenomena. In some of the more coarsely crystalline, porphyroblastic types it is rarely idiomorphic and shows obvious signs of corrosion against the turbid matrix. The actual junctions are marked by sheaths of recrystallized calcite, and when a crystal adjoins a calcite-filled vesicle the latter invades the wollastonite.

The reaction $CaCO_3 + SiO_2 = CaSiO_3 + CO_2$ is a reversible one, but no signs of free silica have been detected around the margins or in the neighbourhood of the inclusions of the wollastonite crystals. There is, however, a large amount of turbid material into which silica may have disappeared.

Chemical Analyses.

The analyses indicate that the rocks bear no relation to known eruptive types and are merely fused and recrystallized sediments whose non-volatile constituents were silica, lime, alumina, magnesia, with subordinate amounts of alkalis and iron oxides. This is most clearly brought out when the Niggli values in the appended table are plotted on a standard diagram (fig. 3), from which it will be seen that the rocks lie in the area of chemical sediments and well beyond the eruptive field.

	1.	2.	3.	4.	5.
SiO_2	44·73	45·11	43·29	42·35	41·69
Al_2O_3	10·30	9·63	9·27	8·71	9·59
Fe_2O_3	3·89	3·64	4·01	2·78	0·76
FeO	1·28	1·22	0·56	0·72	3·75
MgO	5·77	5·87	8·40	8·67	5·32
CaO	24·19	25·17	28·83	31·77	32·82
Na_2O	1·60	2·26	1·37	1·53	4·76
K_2O	2·72	0·83	2·16	1·51	0·68
$H_2O > 105°$	0·48	2·46	0·33	0·20	0·29
$H_2O < 105°$	0·42	0·72	0·15	0·20	0·05
TiO_2	0·85	0·83	0·73	0·68	—
P_2O_5	0·15	0·14	0·15	0·07	—
CO_2	3·04	2·07	0·65	0·42	—
SO_3	0·95	0·40	0·14	0·25	—
Cl	0·02	0·00	0·00	0·00	—
Cr_2O_3	0·02	0·02	0·02	0·02	—
Li_2O	0·00	0·00	0·00	0·00	—
Total	100·41	100·37	100·06	99·88	99·71

1. Fused Marl. Tul-i-Marmar, Chillingar, Persia. (Analyst, B. E. Dixon.) F. 3027. Composed essentially of wollastonite and green augite, subordinate bytownite and glass, together with remnants of unfused marl. Vesicles are filled with calcite and gypsum.

2. Fused Marl. Tul-i-Marmar, Chillingar, Persia. (Analyst, B. E. Dixon.) F. 3030. Composed essentially of large crystals of wollastonite, aegirine-augite, and pale-brown melilite, with an interstitial mixture of calcite and isotropic matter containing small crystals of aegirine-augite, melilite, and wollastonite.

3. Fused Marl. Tul-i-Marmar, Chillingar, Persia. (Analyst, B. E. Dixon.) F. 3029. Composed of large crystals of augite and turbid wollastonite, with subordinate melilite, in a turbid matrix of small crystals of melilite, and isotropic material that occasionally shows the optical anomalies of leucite.

4. Fused Marl. Darreh Harrachi, Chillingar, Persia. (Analyst, B. E. Dixon.) F. 3084. Composed of porphyritic lath-shaped crystals of diopside in a matrix of minute rectangular crystals of melilite.

5. Humboldtilite from Monte Somma, Vesuvius. (Analyst, H. S. Washington.) See A. F. Buddington, Amer. Journ. Sci., 1922, ser. 5, vol. 3, p. 76.

Table of Niggli Values.

	1.	2.	3.	4.
al	12·6	11·75	9·9	8·9
fm	26·3	26·2	29·0	27·5
c	54·1	56·2	56·0	59·4
alk	6·9	5·75	5·1	4·2
c/fm	2·06	2·14	1·9	2·16

In the absence of separate analyses of the various crystalline phases present it is impossible to calculate even approximately the mineral proportions from the bulk analyses, any such calculation being rendered highly speculative by the complexity and, to some extent, the uncertain composition of melilite,[1] the presence of glass and turbid undifferentiated material of unknown composition, and the zoned

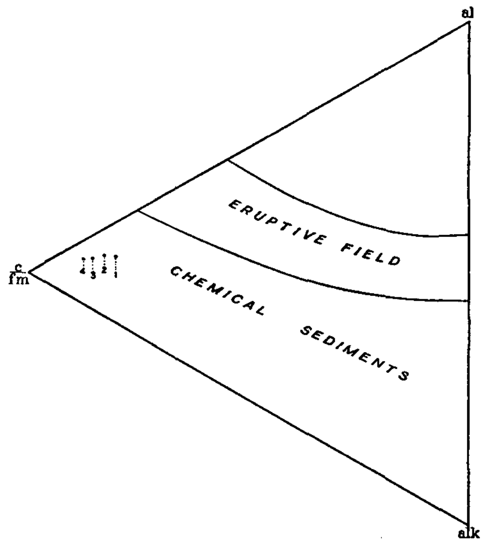


FIG. 3. Diagram showing the relation of the analysed rocks to known eruptive types.

structure of many of the crystals which are often full of inclusions. In the majority of cases the lime, magnesia, and silica combined to form diopside, wollastonite, and melilite, whilst the alkalis combined with the anorthite molecule to form bytownite or, alternatively, with the iron oxides and silica to form aegirine; occasionally the potash formed leucite.

The rock from Darreh Harrachi (analysis 4) contains no glass and represents perhaps the most metamorphosed of all the sediments. It consists of melilite in which are set crystals of colourless diopside showing highly irregular, corroded outlines against the melilite. In this case the alumina, alkalis, and iron oxides must be present in an exceedingly complex melilite consisting of a mixture of åkermanite

[1] A. F. Buddington, On some natural and synthetic melilites. Amer. Journ. Sci., 1922, ser. 5, vol. 3, p. 87.

($2CaO.MgO.2SiO_2$) and gehlenite ($2CaO.Al_2O_3.SiO_2$) with the compounds $3CaO.Al_2O_3.3SiO_2$, $3CaO.Fe_2O_3.3SiO_2$, $3Na_2O.Al_2O_3.3SiO_2$, and $3K_2O.Al_2O_3.3SiO_2$. An analysis of such a melilite is quoted (no. 5) for comparison.

Tilley and Harwood[1] have shown that the incorporation of lime into a dolerite magma leads ultimately to the formation of åkermanite, gehlenite, and pseudo-sarcolite at the expense of diopside and anorthite. There can be little doubt that the abundance of melilite, the absence of bytownite and calcite, and the corroded appearance of the residual crystals of diopside in some of the Persian rocks are due to such reactions, which seem to mark the final stage in the metamorphism of the calcareous sediments. In summary, the initial effect of heat has been the production of diopside, aegirine, wollastonite, bytownite, and melilite (åkermanite), with residual recrystallized calcite; the final effect is the formation of abundant melilite, of complex composition, and colourless diopside. The fact that pseudo-wollastonite is occasionally present in the more altered types (p. 216) indicates that the temperature must have been high.

The literature contains numerous accounts of the occurrence of burning oil or gas, but petrological and mineralogical details of the metamorphic changes, if any, thereby induced are scanty. That the phenomenon may persist for a long time is proved by the account of the celebrated chimaera, in Lycia, which has apparently been in action for over 3,000 years.[2] Widespread alteration of the Monterey Shale from the spontaneous combustion of the hydrocarbon content is recorded by Arnold and Anderson,[3] who show that at widely separated localities the shale is hardened and reddened and eventually converted into a hard vesicular rock, the altered rock sometimes occupying an area of half a square mile. They also record the occurrence of such reddened shale from borings at a depth of 950–1,040 feet. Sir John Cadman[4] has described the formation of a mud volcano in Trinidad in November, 1911, accompanied by the violent eruption of enormous quantities of

[1] C. E. Tilley and H. F. Harwood, The dolerite-chalk contact of Scawt Hill, Co. Antrim. Min. Mag., 1931, vol. 22, p. 463.

[2] E. Tietze, Beiträge zur Geologie von Lykien. Jahrb. Geol. Reichsanstalt, Wien, 1885, vol. 35, p. 359.

[3] R. Arnold and R. Anderson, Geology and oil resources of the Santa Maria oil district, Santa Barbara County, California. Bull. U.S. Geol. Survey, 1907, no. 322, p. 48.

[4] J. Cadman, Notes on the development of the Trinidad oilfields. Journ. Inst. Petrol. Techn., 1915, vol. 1, p. 106.

inflammable gas. This became ignited, probably by sparks from the abrasion of pyritic fragments, and produced a flame 300 feet high which burnt for fifteen hours, when it subsided and became extinguished.

There is thus ample corroboration of the explanation suggested for the Persian occurrences, which, however, appear to be unique in that the rocks affected were originally calcareous marls of such composition that new mineral combinations were readily formed at the temperatures available.

I am greatly indebted to Sir John Cadman, G.C.M.G., through whose kindness I was enabled to visit Persia and who has given his consent to the publication of the results. My thanks are also due to my colleagues, Dr. J. Phemister, who accompanied me in the field, and Dr. W. Q. Kennedy for much helpful criticism.

Explanation of Plates IX and X.

Fig. 1. F. 3031.[1] Small corroded porphyroblasts of wollastonite (white) in a turbid undifferentiated matrix; large rounded white areas are empty vesicles. Ordinary light. × 39. Tul-i-Marmar, Chillingar, Persia.

Fig. 2. F. 3025. Clots of marl, dark in photograph, surrounded and in process of replacement by a mosaic of small crystals of wollastonite, augite, and plagioclase, which constitute the bulk of the rock. Ordinary light. × 39. Tul-i-Marmar.

Fig. 3. F. 3028. Large crystals of wollastonite, with irregular outlines sheathed with calcite, and augite in a turbid undifferentiated matrix. The vesicles are occupied by calcite or glass. Ordinary light. × 33. Tul-i-Marmar.

Fig. 4. F. 3093. Corroded crystals of diopside, light in photograph, in a fine-grained matrix of melilite, dark in photograph. Nicols crossed. × 37. Darreh Harrachi, Chillingar, Persia.

Fig. 5. F. 3027. Large acicular crystals of turbid wollastonite, augite, and bytownite, with residual clots of turbid marl. The vesicles are filled with crystalline calcite or, occasionally, leucite or glass. Ordinary light. × 34. Tul-i-Marmar.

Fig. 6. F. 3030. The large, rectangular, turbid crystal in the centre is leather-brown melilite. A large acicular crystal of aegirine-augite lies immediately above it. The white crystals are wollastonite. Interstitial material consists of wollastonite, augite, melilite, and calcite. Ordinary light. × 37. Tul-i-Marmar.

[1] The numbers refer to the collection of slides of the Geological Survey and Museum.

FIG. 7. F. 3062. The large crystal, with good cleavage, stretching across the centre is aegirine. Above it, to the left, is leucite with inclusions of aegirine and brown turbid material. Beneath it is leucite succeeded by laths of wollastonite and aegirine with clear melilite to the right. Ordinary light. × 31. Tul-i-Marmar.

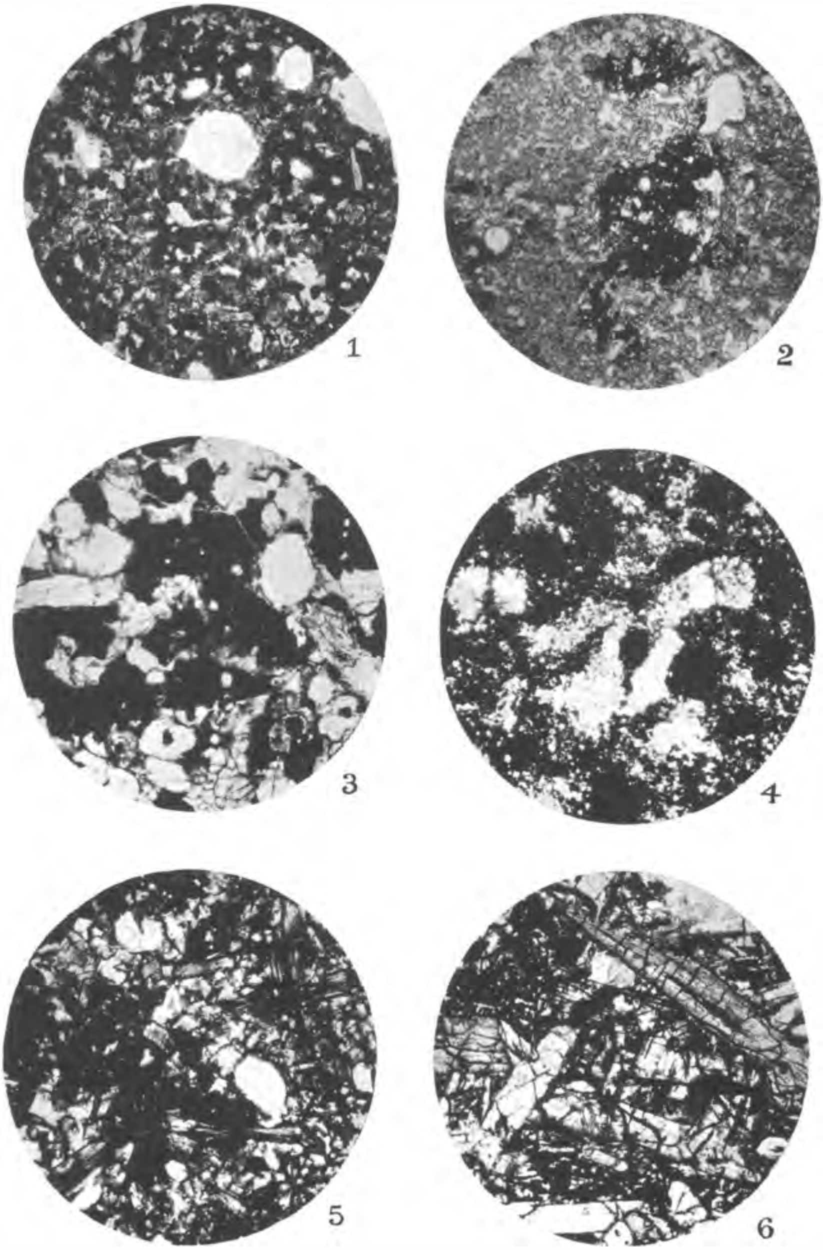
FIG. 8. F. 3061. Vesicle filled with anhydrite in a coarsely crystalline rock consisting of diopside, wollastonite, bytownite, melilite, and glass. A large cleaved prism of diopside projects into the vesicle at the left bottom corner; seated upon it is a crystal of wollastonite. Turbid melilite and, beneath it, clear diopside occupy the centre of the vesicle. The large white rectangular crystal on the top left margin of the vesicle is bytownite with its innermost corner replaced by turbid melilite. Ordinary light. × 33. Tul-i-Marmar.

FIG. 9. F. 3083. Pseudo-wollastonite, clear, as corroded grains and prisms, set in a vesicular matrix of partially isotropic melilite. Nicols crossed. × 45. Darreh Harrachi, Chillingar, Persia.

FIG. 10. F. 3026. Vesicular rock consisting of acicular crystals of augite, wollastonite, and bytownite. The lower vesicle is filled with calcite; the upper one has a rim of glass, black in photograph, with a core of calcite in process of replacement by the silicate-minerals. Nicols crossed. × 40. Tul-i-Marmar, Chillingar, Persia.

FIG. 11. F. 3094. Large idiomorphic diopside crystals in an imperfectly crystallized matrix consisting of diopside, occasional plagioclase, and turbid acicular growths suggesting incipient wollastonite. Ordinary light. × 32. Zoh-i-Hait, Agha Jari, Persia.

FIG. 12. F. 3098. The clear, upper area is pseudo-wollastonite. The rock in the lower part of the photograph consists of small acicular crystals of wollastonite and augite. Ordinary light. × 42. Masjid-i-Sulaiman, Persia.



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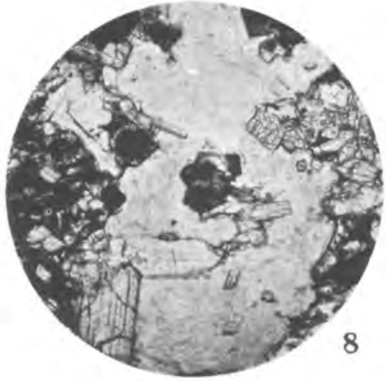
7



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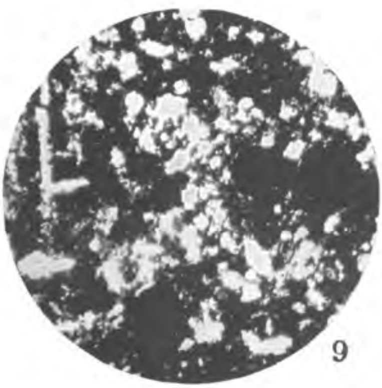

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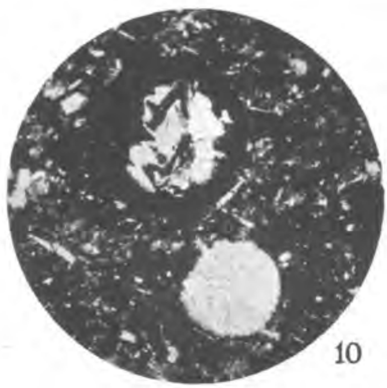

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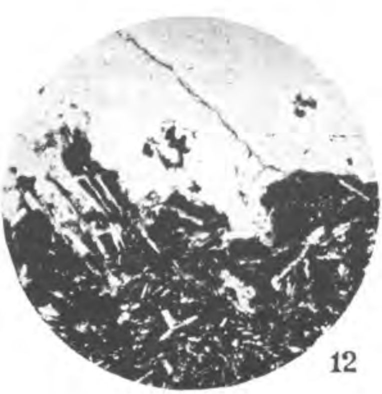

12

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