On the Genesis and Emplacement of Ophiolites in the Oman Mountains Geosyncline

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With 17 figures and 2 tables in the text

Abstract

Geological and petrographical evidence suggests that the Oman Ophiolites are a polygenetic assemblage of igneous and metamorphic rocks. An important age hiatus is inferred separating the basaltic intrusive-extrusive suite from the older ultrabasic host rocks: the gabbroic-basaltic suite ranges in age from Middle Permian to lower Upper Cretaceous and covers the whole geosynclinal cycle, whereas the bulk of ultramafic rocks is thought to be pre-geosynclinal, i. e. pre-Middle Permian in age. The gradual transitions between both groups of rocks are thought to be the product of assimilation as a result of gabbroic injection into peridotites at great depth. Observations in magmatic breccias, the presence of high-grade metamorphic rocks and subvolcanic intrusions into peridotites and gabbros suggest that large amounts of plutonic products have been expelled from depth in a solid state during the geosynclinal phase. With reference to modern oceanic ridges a new model of emplacement is discussed which incorporates these observations and explains the genesis of the "ophiolite stratigraphy" ranging from plutonic rocks at the base to extrusives at the top.

Zusammenfassung

Geologische und petrographische Beobachtungen lassen darauf schliessen, dass die Ophiolithe von Oman (Persischer Golf) eine polygenetische Assoziation magmatischer und metamorpher Gesteine darstellen. Ein Hiat trennt die intrusiven und extrusiven gabbroiden Gesteine von den Peridotiten. Der gabbro-basaltische Magmatismus war während der gesamten Geosynklinalphase, d. h. vom mittleren Perm bis zum Beginn der oberen Kreide tätig. Die Peridotite ihrerseits scheinen prägeosynklinal, d. h. mindestens präpermisch zu sein. Die Kontakte zwischen beiden Gesteinsgruppen werden als Intrusionskontakte gedeutet, und die ultrabasischen Gesteine als Intrusionsrahmen der Gabbrointrusionen interpretiert. Die gelegentlich graduellen Übergänge zwischen Gabbro und Peridotit werden als Folge von Assimilationsprozessen des Rahmengesteins durch basaltisches Magma in grosser Tiefe angesehen. Beobachtungen an magmatischen Brekzien und die Anwesenheit metamorpher Gesteine in der Hornblende-Granulitfazies lassen

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darauf schliessen, dass während der geosynklinalen Phase grosse Mengen des ophiolithischen Materials in festem Zustand aus grosser Tiefe an die Oberfläche gefördert worden sind. In Anlehnung an das Vorbild moderner ozeanischer Rücken wird ein neues Modell für die Platznahme der Ophiolithe vorgeschlagen, das den gemachten Beobachtungen und auch der Entstehung der „Ophiolith-Stratigraphie" Rechnung trägt.

Résumé

De nouvelles observations géologiques et pétrographiques tendent à prouver que les ophiolites d'Oman (Golfe Persique) constituent un ensemble polygénique de roches ignées et de roches métamorphiques. L'auteur suggère qu'un important hiatus sépare le groupe de roches intrusives-extrusives des roches ultrabasiques: Tandis que les premières cristallisaient pendant toute la période géosynclinale qui durait du Permien Moyen au Crétacé Supérieur, la plupart des roches ultrabasiques semblent être d'âge pré-géosynclinal, c'est-à-dire d'âge pré-Permien Moyen. Les passages graduels observés entre les deux groupes sont interprétés comme les résultats d'une assimilation due à des injections gabbroïques dans les péridotites à grande profondeur. Les observations effectuées dans les brèches magmatiques, dans les intrusions subvolcaniques très différenciées à l'intérieur des péridotites et des gabbros ainsi que la présence de roches à métamorphisme très élevé permettent d'affirmer que de larges masses de produits plutoniques ont été expulsées à l'état solide pendant la phase géosynclinale. Se référant aux cordillères médio-océaniques actuelles, l'auteur propose un nouveau modèle pour la mise en place des ophiolites. Ce modèle tient compte des nouvelles observations présentées et explique en même temps l'origine de la zonation à l'intérieur des ophiolites.

Contents

INTRODUCTION

The idea that the ophiolite suite could be a polygenetic assemblage has been expressed clearly by HESS (1955), DE ROEVER (1957 and 1961) and ROST (1959). According to these authors, the ophiolite sequence is composed of plutonic members (peridotites and gabbros) which have been derived in solid state from the Earth's Upper Mantle, and of subvolcanic and extrusive members which have crystallised from a basaltic magma. Many geologists are still reluctant to accept this model because field observations do not suggest such a genetic hiatus: often there are gradual transitions between the "plutonic" and the hypabyssal and extrusive rocks. In such cases the ophiolite sequences display what may be called a stratigraphy, ranging from ultrabasic rocks with coarsely granular textures at the base to successively more intermediate igneous rocks with fine-grained textures at the top. This highly organised relationship seems to suggest an internally differentiated pluto-volcanic flow, and this is how it has been interpreted by ROUTHIER (1946 and 1953), DUBERTRET (1953) and BRUNN (1954, 1956 and 1960).

On the other hand, new analytical investigations on ophiolitic peridotites (PETERS, 1967) support the idea that these rocks reached their mineralogical equilibrium at a depth of more than 30 km, which is well within the mantle in oceanic regions. Consequently these rocks seem to have been expelled in solid state before they were associated with extrusives. If this should prove to be generally so in the case of ophiolite peridotites the geologist would find himself in the difficult situation of having to re-interpret field results which apparently contradict the results based on experimental petrology. Under such circumstances it appears to be useful to point to some new geological and petrographical observations which may help to remove the apparent contradictions.

GENERAL SITUATION

Fig. 1 shows the geographical situation of the Oman Mountains and the distribution of outcropping ophiolites. The bulk of the ophiolites form an individual nappe (Semail Nappe) which is the highest tectonic unit visible in the mountains. This nappe overlies other imbricated nappes of geosynclinal[1]) sediments which lack any regional metamorphism. The total volume of the nappe is of the order of thousands of cubic kilometres (a minimum of 450 km axial extension, 50 km average width and ca. 1 km average thickness), Fig. 2 shows a cross section through the Semail Nappe. The additional structural features found in the Oman Ophiolite Nappe that have not been described from other ophiolite sequences are as follows:

[1]) The term "geosyncline" is used here in the sense of "part of an ocean, including its floor and sediment cover, that is involved in the development of a mountain range".

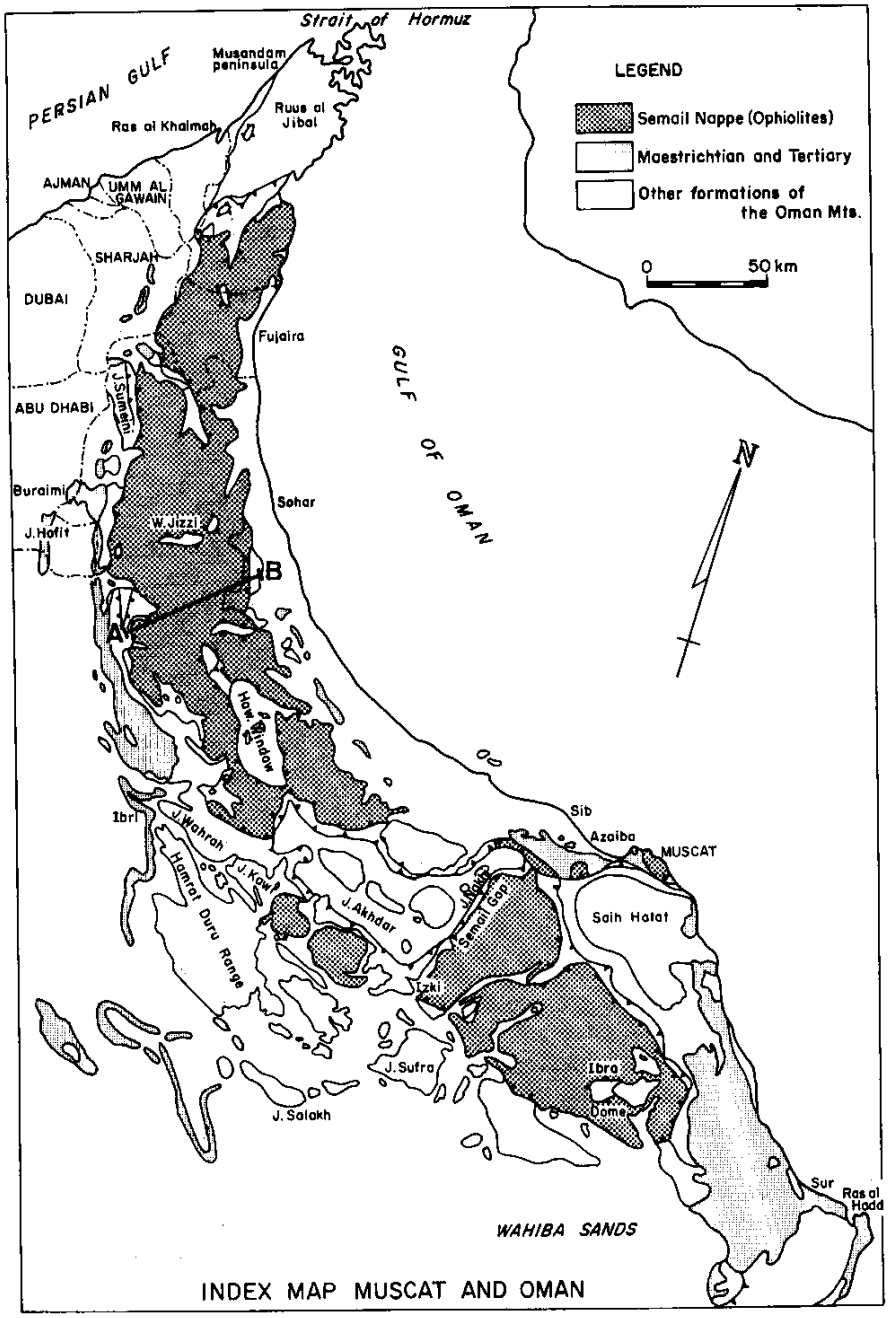
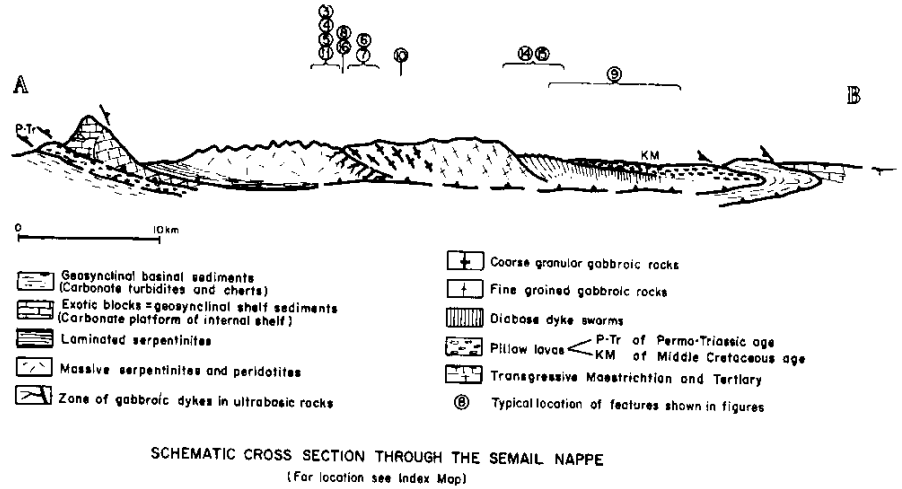


Fig. 1.



SCHEMATIC CROSS SECTION THROUGH THE SEMAIL NAPPE
(For location see Index Map)

Fig. 2.

— the sequence gabbro-dolerite-diabase forms a fan structure;
— the gabbroid rocks are layered, but the diabases form dyke swarms; the dykes cut each other; the transition between layering and dyke swarm is gradual;
— the subhorizontal extrusives overlie disconformably the subvertical dyke swarms of diabases and are fed by these dykes; the diabase dyke swarms are, therefore, regarded as the uppermost part of a volcanic feeder and the subvertical attitude is thus a primary feature.

PETROGRAPHY

Ultrabasic rocks

The most common type is an *enstatite peridotite* which may contain some diopsidic clinopyroxene (olivine = Fo_{80-100}/Fa_{20-0}; enstatite = $En_{90-95}/Ferr_{10-5}$, with (100)-lamellae of clinopyroxene). Small subhedral grains of picotite are regularly present in minor quantity. The texture is coarsely granular to cataclastic. All peridotites are partly serpentinised and there are gradual transitions to pure serpentinites.

The serpentinites, for the main part composed of lizardite and chrysotile, are well developed along the base of the nappe. They are preferentially schistose, but massive types are also found that still display the texture of the coarsely granular parent rock.

These two rock types form more than 60% of the total volume of the ophiolites.

Basic rocks

The gabbros are layered. In the basal part of the gabbroic sequence the *dark layers* have a troctolitic mineralogy (olivine and plagioclase ca. An_{90}/Ab_{10}) whereas the *light layers* are eucritic (plagioclase ca. An_{80-95}/Ab_{20-5} and endiopside) to plagioclasitic (An_{80}/Ab_{20})[2]).

The gabbros grade into *hornblende-gabbroid types with parallel texture*. The gradation is characterised by:

a) change in the succession of crystallisation: as opposed to the granular gabbros where plagioclase crystallises contemporaneously with mafic minerals, the plagioclase of the hornblende-gabbroid rocks precedes the mafic minerals. As a result of this,
b) increasing idiomorphism of plagioclase (plates (010)) and arrangement of these phenocrysts parallel to layering,
c) increasing presence of brown basaltic hornblende that intergrows with endiopside and surrounds it,
d) appearance of normal zonation in plagioclase laths. The compositions range from $An_{90}Ab_{10}$ in the centres to $An_{85}Ab_{15}$ along the rims,
e) disappearance of dark troctolitic layers. The layering in the hornblende-gabbroid rocks is more a result of textural variation than of compositional difference.

The term *dolerite* has been reserved for rocks which range between hornblende gabbro and fine-grained diabase. The main mafic minerals are brown and light green hornblendes that surround the subparallel plagioclase laths. These are strongly zoned (centre $An_{80}Ab_{20}$, rim $An_{45}Ab_{55}$). Chlorite and skeletal ilmeno-magnetite are regularly present. The texture is coarsely ophitic. These rocks are found as a quantitatively increasing member in the top part of the layered gabbros and also in the succeeding sequences of diabase.

The *diabases* are fine-grained and have an intersertal-ophitic texture. The plagioclase is zoned ($An_{50-75}Ab_{50-25}$ in the centres, $An_{0-40}Ab_{100-60}$ at the rims) or it may be albitised, the result of which is a "cloudy albite" speckled with microlithic inclusions. Diopsidic pyroxene is present as a relict mineral of early crystallisation but is surrounded by mostly light green hornblende. Skeletal ilmeno-magnetite is regularly present and surrounded by younger products such as "leucoxene" and sphene. The mesostasis (originally interstitial glass) is usually filled with chlorite with which fibrous hornblende and leucoxene may be associated. These rocks are best represented in the subvertical dyke swarms that follow the layered gabbroic sequences.

Most of the *extrusives* are spilitic pillow lavas, a great part of which are rich

[2]) Measured by universal stage methods as outlined in BURRI, PARKER and WENK (1967).

in hematite. Many spilitic rocks, however, are also found together with diabases in the subvertical dyke swarms. Breccia lavas with hyaloclastic matrix and angular components of pillows are also quite common, especially amongst the vesicular extrusive rocks. The *sediments* associated with the subhorizontal lavas found on the back of the Semail Nappe are mudstones and cherts of early Upper Cretaceous age. However, the extrusives found in the sediments of the lower tectonic units (see fig. 2) are Upper Permian to Lower Jurassic in age.

The hiatus between ultrabasic and gabbroid rocks

Regionally a sharp line of separation exists between the gabbros and the underlying ultramafic rocks. In places this is due to secondary decollement, but well preserved igneous contacts between both types suggest that the gabbros are intrusive into the peridotites. On the ultrabasic side of the contact a zone of peridotites and serpentinites has been mapped that is characterised by the presence of large quantities of dykes. The dyke rocks are eucritic gabbros, plagioclasites, dolerites, porphyrites, gabbro pegmatites and diabases. The zone has a thickness of up to 500 m and represents the "edge-facies" of the ultramafics along the gabbro contact. Although *petrographically* intermediate rock types between ultrabasic rocks and gabbros are found within the dyke zone as well as within the basal gabbro sequence, the *geological* line of separation is an easily mapped feature. The suggestion that the contact reflects a hiatus separating the ultramafic frame rock from the gabbroic intrusions is based on observations of:

— the dyke relationships;
— the relationships along the igneous contacts.

The dyke relationships

Table 1 is a summary of the relationships observed between dykes and host rocks. It shows that all basic rocks (gabbros, dolerites, diabases and spilites) may be found as dyke rock in any other member. The ultrabasic rocks are cut by all of them, without themselves occurring as dykes in any other member of the suite. Additionally, the diabase dykes cutting through ultramafic rocks often follow a pattern which suggests fracturing of the peridotites and serpentinites before the intrusion of the gabbroic magma.

Assimilation of host rock by the gabbroic magma

Near to the contacts with the surrounding ultramafics the plutonic gabbroic rocks contain large amounts of peridotitic host rock fragments. This has been observed in dykes as well as in the basal part of the gabbro sequence. Usually

Table 1. *Occurrence of dyke rocks and related host rocks in the ophiolites of the Oman Mountains*

Host rocks	Dykes				
	Peridotites Serpentinites	Gabbros	Dolerites	Diabases	Spilites
Ultrabasics		X	X	X	O
Serpentinites					
Peridotites					
Gabbros			X	X	O
Dolerites		O		X	X
Diabases		O	X		X
Spilitic lavas				X	X

X = frequent
O = present, not very frequent
void = not observed

these xenolithic "Schollen" are elongated and preferentially aligned parallel to the contact plane and to the plane of layering in the gabbros. Fig. 3 illustrates this situation in a eucritic dyke. Often the intrusive gabbroic magma has infiltrated the xenoliths as well as the wall rock to form dark "migmatites"[3]). These are characterised by the presence of small veins and capillaries of eucrite or plagioclase that give the ultrabasic rock a dotted or veined appearance.

Depending on whether the intrusive rock is eucritic or leucocratic (plagioclase only) the dark "migmatite" is either a dark variety of olivine gabbro (olivine, bytownite-anorthite and diopsidic clinopyroxene) or a troctolite (olivine and bytownite-anorthite). Fig. 4 shows such dark "Schollen" of host rock surrounded by the various products of gradually increasing assimilation.

All dark "migmatites" have in common a very characteristic texture: sub-round corroded olivine grains are imbedded in a xenomorphic matrix of either pure plagioclase or combined plagioclase and diopside (fig. 5). This texture suggests strongly that the corroded olivine phase represents an older generation which has been penetrated by intergranular capillaries of a younger gabbroic liquid.

The result of very advanced assimilation is the formation of gabbroic rocks with regularly distributed olivine nodules (fig. 4 and fig. 6). A large part of the olivine grains found in the layered gabbros might, by analogy, also represent partly assimilated host rock material.

[3]) The term is used here to designate a mixture of host rock and injected melt.

Fig. 4. Partial assimilation of peridotite-"Schollen" by leucocratic gabbro.

A = unaltered enstatite peridotite; host rock.
B = peridotite with capillaries of anorthite; dark "migmatite" (compare with fig. 5).
C = troctolitic olivine gabbro; light "migmatite" (compare with fig. 6).
D = genuine intrusive rock; leucocratic anorthite eucrite.

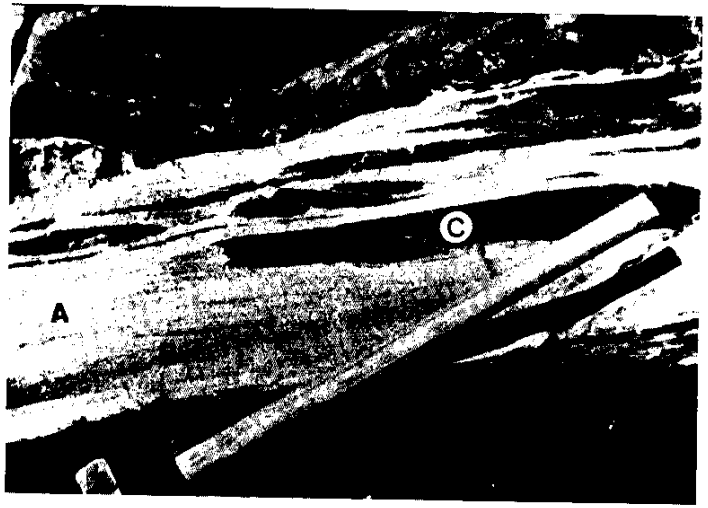


Fig. 3. "Schollen" of host rock peridotite in a dyke of anorthite eucrite. The lighter parts of the dyke rock (A) are purely eucritic (anorthite and diopside). The darker "Schlieren" (B) contain variable amounts of olivine. The black fragments (C) and the host rock of the dyke are enstatite peridotites. Rustaq Area, Central Oman Mountains.

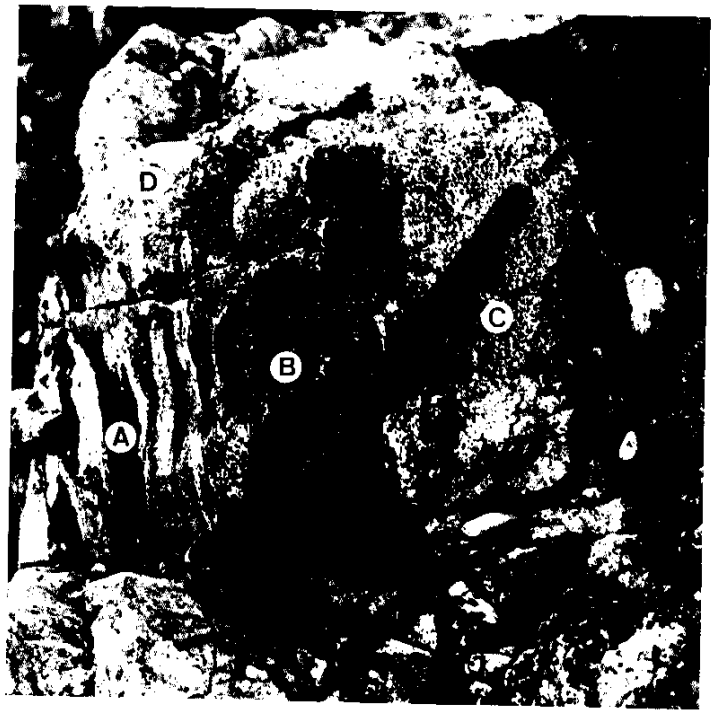


Fig. 4.

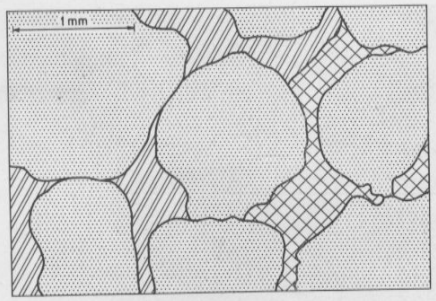


Fig. 5. Texture of dark "migmatite" (olivine gabbro). Round corroded grains of olivine (dotted) in a groundmass of xenomorphic anorthite (linear hachure) and diopside (cross hachure).

Special attention has been paid to the layered gabbros at the base of the feldspathic sequence, because there, the dark layers have petrographically much in common with the dark "migmatites" described above (same mineralogy and texture). It was often noted that the dark layers are not continuous, but that they may grade laterally into gabbroic rocks in a similar way as the partly assimilated "Schollen" (fig. 7). The thought that the dark layers really

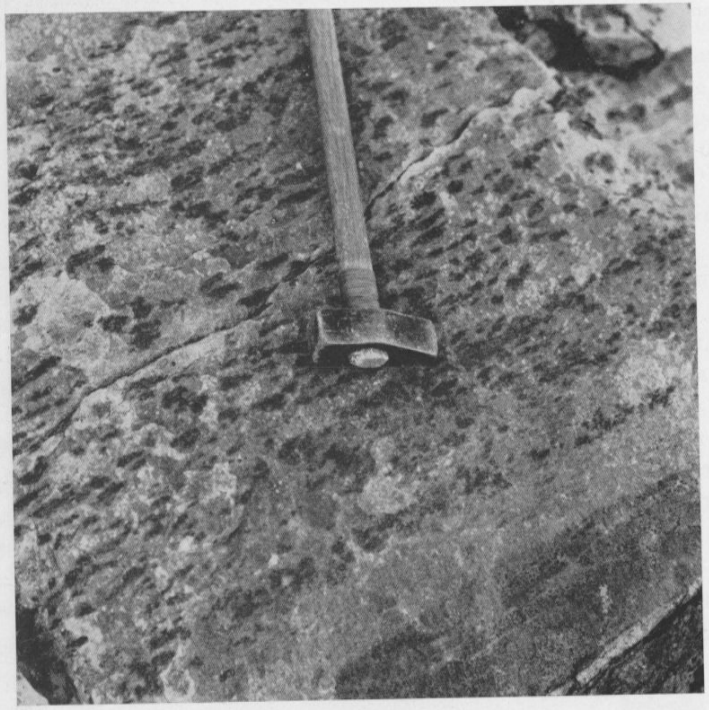


Fig. 6. Anorthite-eucritic gabbro with nodules of olivine. This rock type is a common member of the layered gabbro sequences. Compare with "C" in fig. 4. South of Bahlah, Central Oman Mountains.

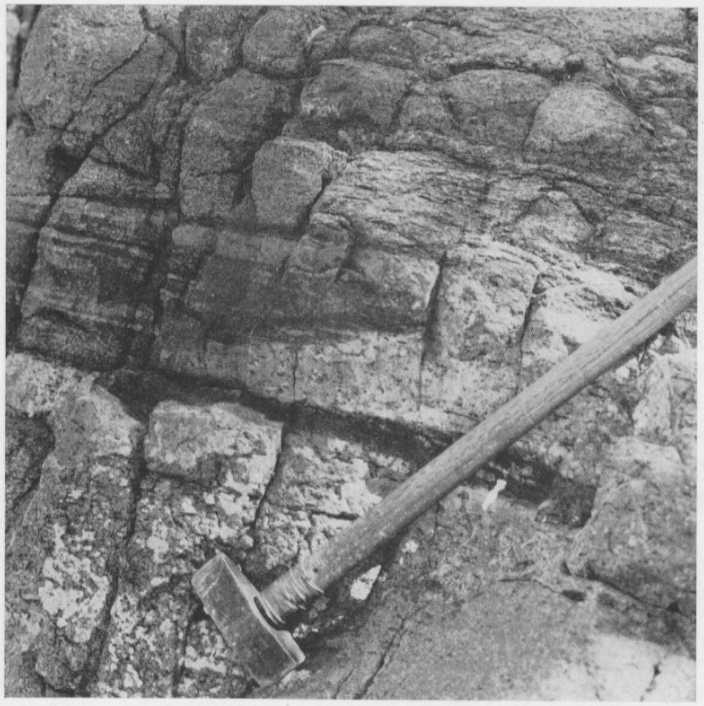


Fig. 7. Dark, olivine-rich member of layered gabbros grading laterally into leucocratic anorthite-eucrite. North of Ibra, Eastern Oman Mountains.

could represent fragments of host rock peridotite is supported by observations made in outcrops where the light and dark rocks are neatly divided by a clear line of separation and only locally grade into each other. Fig. 8 shows such a situation: the dark bands are locally broken and the disconnected parts are displaced relative to each other. The leucocratic bands of fresh granular gabbro smoothly fill the ruptures. This suggests that the dark sheets behaved in a brittle way before or during the intrusion of the gabbroic magma; they may well be regarded as solid fragments sheared off the peridotitic host rock during the gabbroic igneous activity.

All these observations suggest that the gradual transitions occasionally observed between peridotites and gabbros are not only the result of differentiation but also the result of mixture of intrusive gabbroic magma with ultramafic host rock.

Hybrid rocks in the intrusive-extrusive suite

Many of the hypabyssal and extrusive members of the suite (dolerites, diabases and spilites) contain considerable amounts of phenocrysts that are

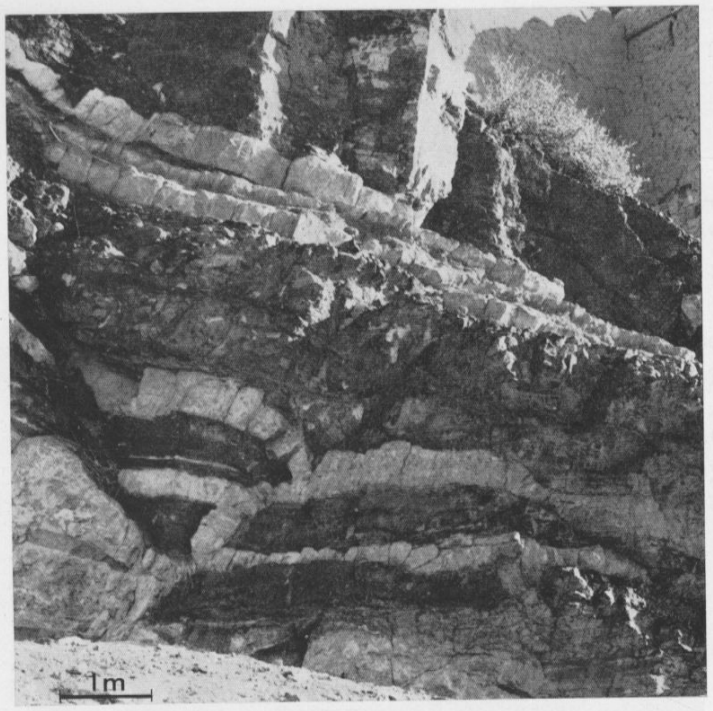


Fig. 8. Intrusion of leucocratic gabbro into peridotites. The gabbroic liquids have been injected between sheets of the ultramafic host rock. Local gradual transitions between the two rock types occur (right-hand side, lower part). Castle of Samad, Central Oman Mountains.

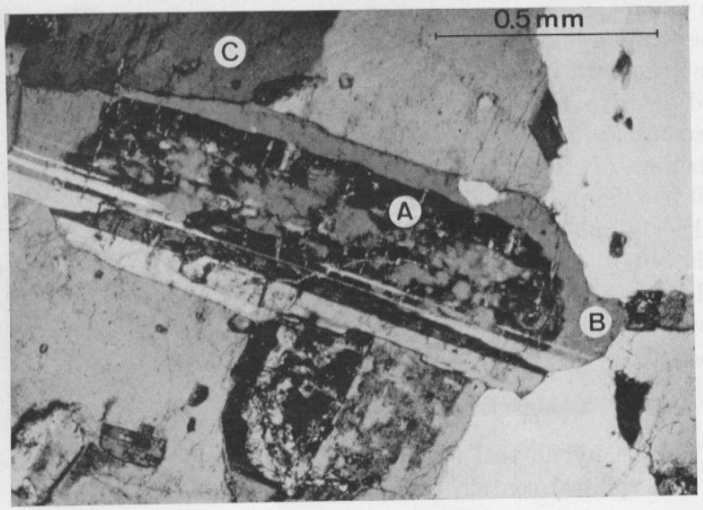


Fig. 9.

compositionally similar to the constituents of peridotites and plutonic gabbros. These are olivine, diopsidic clinopyroxene with (100)-lamellae of orthopyroxene and plagioclase. Depending on the amount of such phenocrysts the rocks are mineralogically hybrid as in the case illustrated below.

Fig. 9 shows a plagioclase phenocryst as commonly found in quartz- and albite-rich porphyrites. These leucocratic rocks are assumed to have been intruded at rather shallow depth because they are regularly found within diabase dyke swarms or as plugs within extrusive sequences. In such rocks the plagioclase phenocrysts form about 50% of the rock volume. They usually show traces of strong corrosion. From figure 9 two phases of corrosion can be inferred: the earliest plagioclase at the centre is extremely calcic (An_{80-90}/Ab_{20-10}). The second shell of plagioclase that envelops the corroded centre has a composition ranging between An_{43}/Ab_{57} and An_{50}/Ab_{50}. This shell is again slightly corroded and surrounded by a groundmass of quartz, albite and some chlorite (in fig. 9 only quartz is visible). The quartz and albite of the groundmass may display graphic intergrowth suggesting the presence of a eutectic residual melt.

Similarly, large corroded and strongly deformed diopside phenocrysts and corroded grains of olivine are found in diabases and spilites with fresh and undisturbed igneous textures. The strong disequilibrium between phenocrysts and groundmass may be levelled out by secondary ("autometamorphic") reactions and the compositional discrepancies may, therefore, disappear. Still, the recognisable crystals of "abyssal" origin found in hypabyssal and extrusive rocks are estimated to represent an average of around 10% of the total rock volume.

"Autometamorphic" reactions

Apart from alterations such as albitisation, uralitisation and chloritisation which are common in basic igneous rocks, some reactions have been observed that also are quite peculiar to the Oman Ophiolites.

Contacts olivine-plagioclase

In many feldspathic rocks (such as dark gabbroid rocks, dolerites and diabases), olivine and plagioclase are commonly associated. Usually both members have reacted with each other intensively to form halos of low grade

Fig. 9. Plagioclase phenocryst in a quartz-rich porphyrite (subvolcanic ophiolite member; compare with fig. 16). The phenocryst shows two phases of magmatic corrosion. The oldest corroded plagioclase phase (A) ranges in composition between 80 and 90 Mol-% An. The composition of the surrounding shell (B) is 43 to 50 Mol-% An. This generation is again corroded and surrounded by quartz (C) and albite (the latter is not visible in this picture). Sample Rht 415. Crossed polarisers.

metamorphic minerals. As a result of this two types of pseudomorphs can be recognised depending on the relative amount of the parent minerals olivine and plagioclase: in plagioclase rich rocks, pseudomorphs after olivine are found, whereas in olivine rich rocks the feldspar is altered.

Pseudomorphs after olivine

The following reaction products are regularly found: clinozoisite, chlorite I[4]) (sheridanite-type), actinolitic hornblende, talc, serpentine and magnetite. Their relative position is illustrated in fig. 10. The rim of chlorite I is only

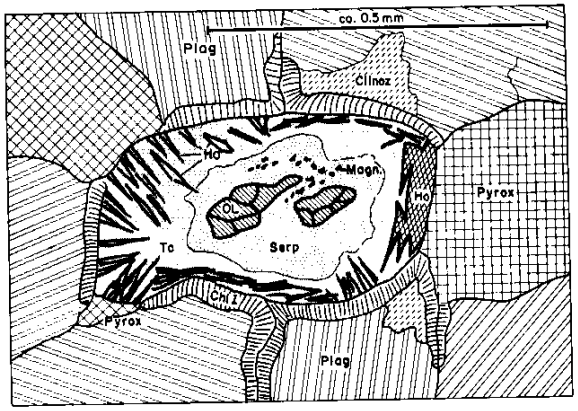


Fig. 10. Pseudomorph after olivine in a oueritic gabbro. Olivine (Ol) is largely altered to chrysotile and lizardite (Serp) and to magnetite (Magn). Further alterations led to the assemblage talc (Tc), actinolitic hornblende (Ho) and penninite-chlorite (not present here). Along the contacts with plagioclase (Plag) the pseudomorph is surrounded by sheridanite-type chlorite (Chl I) and clinozoisite (Clinoz). The diopsidic clinopyroxene (Pyrox) does not take part in the reactions.

developed along direct contacts olivine-plagioclase. In cases where diopside is in contact with the olivine pseudomorphs, the actinolite needles grow directly on the surface of the pyroxene grain and extend from there into the talc-serpentine assemblage. In more advanced stages the assemblage olivine-serpentine-magnetite-talc is consumed and chlorite II (penninite-type) has developed instead. The result is a felty mixture of chlorite II and actinolite surrounded by the rim of chlorite I. It is interesting to note that the more advanced stages are found in the more differentiated and fine-grained members of the gabbroic sequence (dolerites, diabases), whereas the less advanced stages are characteristic for the plutonic gabbros.

[4]) As opposed to chlorite II, the occurrence of which is described later.

Pseudomorphs after plagioclase

In olivine rich rocks where plagioclase is an accessory (dark "migmatites", peridotites with plagioclase capillaries) the following reaction products are found: serpentine, magnetite, actinolitic hornblende, rim of chlorite I, garnet rim I (pyrope-almandine intergrowing with brown-red iron oxide), garnet rim II (pyrope-almandine intergrowing with grossular), very fine-grained intergrowth of prehnite, clinozoisite, mica, chlorite, an unknown Ca-Al-hydrosilicate and finally a zone of pure prehnite. The relative order of these minerals is shown in fig. 11.

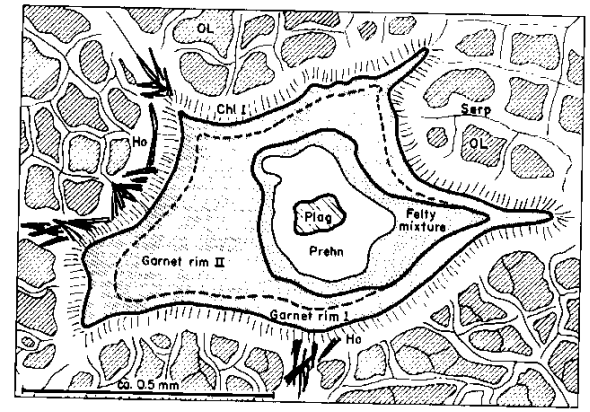


Fig. 11. Pseudomorph after plagioclase in a peridotite. The composition of the plagioclase relicts (Plag) ranges between 87 and 95 Mol-% An. Here, the relict mineral is surrounded by zones of pure prehnite (Prehn) and of a felty intergrowth of prehnite, clinozoisite, mica, chlorite and an unknown Ca-Al-hydrosilicate (felty mixture). The peripheral areas are composed of garnet which in turn is rimmed by sheridanite-type chlorite (Chl I) and actinolitic hornblende (Ho). These two minerals prograde into the mesh-type serpentine of the surrounding ultrabasic assemblage.

The transition from serpentine to chlorite I seems to be gradual. All secondary minerals inside the rim of chlorite I are extremely fine-grained. Even with 1000 x magnification (electron-probe microanalyser), homogeneous phases are difficult to see. The alteration is more advanced in rocks that are strongly serpentinised than in rocks with much fresh olivine. The secondary minerals have been determined by optical methods, by X-ray diffraction and by means of an electron-probe microanalyser.

The results of the determinations are given in table 2.

Fig. 12 illustrates the results obtained by scanning across a plagioclase-olivine contact with the electron-probe microanalyser. The distribution of iron shows a marked concentration along the contact where the garnet of the pyrope-almandine series is developed and associated with red-brown Fe-hydroxides. The chlorite-serpentine zone, however, is rather poor in iron

Table 2

Prehnite:	confirmed by X-ray		
Clinozoisite:	confirmed by X-ray; results from electron microanalyser (EM)*):		
	SiO_2	present	(38–40% assumed)
	CaO	23–26 %	
	MgO	< 1 %	
	Al_2O_3	present	(ca. 30% assumed)
	Fe_2O_3	1–5 %	
Mica:	confirmed by X-ray		
Hydro-garnet:	confirmed by X-ray; water content suggested because of broad reflections		
Hydrogrossular:	EM-results:		
	SiO_2	present	(35% assumed)
	CaO	28–35 %	
	MgO	2–3 %	
	Al_2O_3	20–25 %	
	Fe_2O_3	5–8 %	
Pyrope-almandine:	EM-results:		
	SiO_2	present	(35–40% assumed)
	MgO	10–20 %	
	Al_2O_3	16–19 %	
	Fe_2O_3	20–24 %	
Chlorite I (sheridanite-type):	"chlorite" confirmed by X-ray; EM-results:		
	SiO_2	present	(ca. 30% assumed)
	CaO	< 1 %	
	MgO	25–30 %	
	Al_2O_3	18–25 %	
	Fe_2O_3	8–13.5%	
Actinolitic hornblende:	"hornblende" confirmed by X-ray; EM-results:		
	SiO_2	present	(50–55% assumed)
	Na_2O	ca. 1.4 %	
	CaO	11.5 %	
	MgO	20 %	
	Al_2O_3	7–10 %	
	Fe_2O_3	5 %	
Chlorite II (penninite-type):	inferred from optical properties		

*) Type: JEOL JXA 3, Beam $\varnothing \approx 1\,\mu$. Beam current $\approx 50\,\mu$ A. Sample current $\approx 0.1\,\mu$ A. Int. time = 1'. Crystals: Quartz: Fe, Ca. KAP: Al, Mg, Na, Si.

compared with the unaltered olivine. This suggests migration of iron away from the olivine member towards the plagioclase contact. The distribution curve of Al suggests migration in the opposite direction into the serpentine area.

The products of these "autometamorphic" reactions have much in common with the pseudomorphs after olivine known from the Allalin Gabbro in the Swiss Alps (Bearth, 1967). There, the alterations have been interpreted as a result of the Alpine regional metamorphism. However, the widespread occurrence of less advanced but very similar reactions in the Semail Nappe suggests that part of the alterations observed in regionally metamorphosed ophiolites may be inherited features of an early phase.

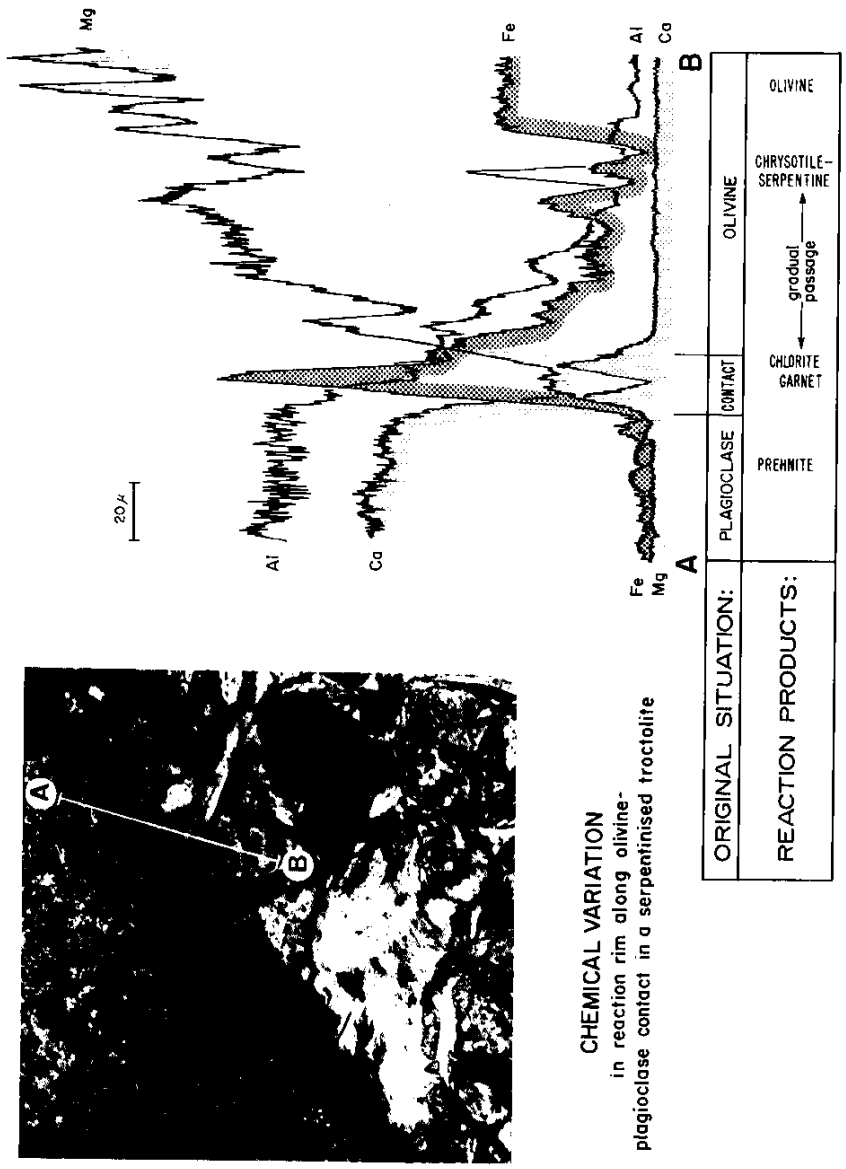


Fig. 12. Results obtained by scanning with electron probe microanalyser.

Prehnitisation of gabbroic rocks

Prehnite is a very common mineral in all feldspathic members of the ophiolite suite. It is always developed at the expense of plagioclase. The degree of alteration is extremely variable; as a rule, fractured and sheared rocks are more prehnitised than undeformed rocks. Also does prehnite preferentially develop along microscopical rock fractures and shear planes. This suggests a close relationship between the prehnitisation and a deformation phase. A systematic variation of the degree and quality of alteration on a regional scale has not been noticed.

The alteration of plagioclase-rich dykes to "rodingites"

Feldspathic dykes that cut through ultrabasic rocks are always altered to some degree. It has been noted that there is some direct relation between degree of serpentinisation of the host rock and degree of alteration of the dyke rock. The reaction products are the same as those described from the olivine-plagioclase contacts in olivine-gabbroic rocks.

A very characteristic feature is the development of a chlorite-actinolite-serpentine rim[5]) along the dyke contact. Within the dyke rock the most common product of alteration is prehnite, but chlorite, clinozoisite, garnet, diopside and other Ca-Mg-rich minerals are also present. Again, the iron rich garnet develops near to the contact with the ultrabasic neighbour (compare w. fig. 11).

Contacts enstatite/plagioclase

The rare enstatite grains found in feldspathic rocks are always altered and usually only few remnants are left. The reaction products are actinolite which is surrounded by a fine rim of Mg-rich chlorite (? clinochlore). Fig. 13 shows the result of this process in a less advanced stage.

All "autometamorphic" reactions described here have the following in common:

a) the products are assemblages of very low grade metamorphic minerals;

b) a close relationship seems to exist between the "autometamorphic" reactions and rock deformation;

c) the reactions seem to have taken place in the same environment as the serpentinisation of ultrabasic rocks, which reaction is also strongly related to deformation.

[5]) Minerals mentioned in the order as they occur from dyke towards host rock.

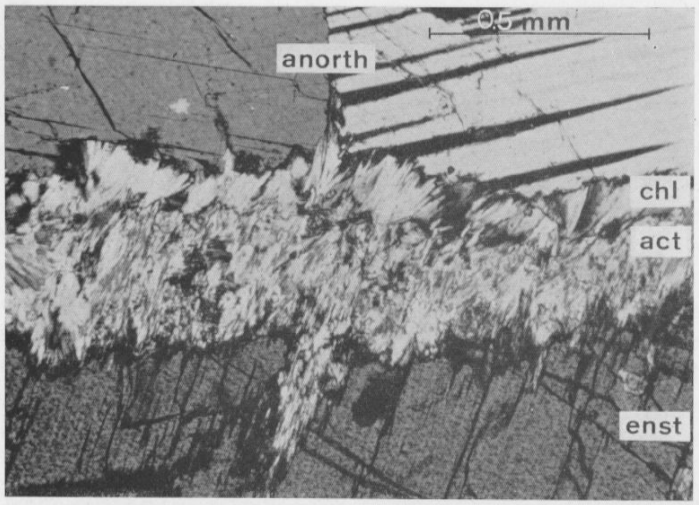


Fig. 13. Reaction rim of actinolitic hornblende and chlorite (clinochlore?) along the enstatite/anorthite contact in a eucritic gabbro. Sample Rht 252. Crossed polarisers.

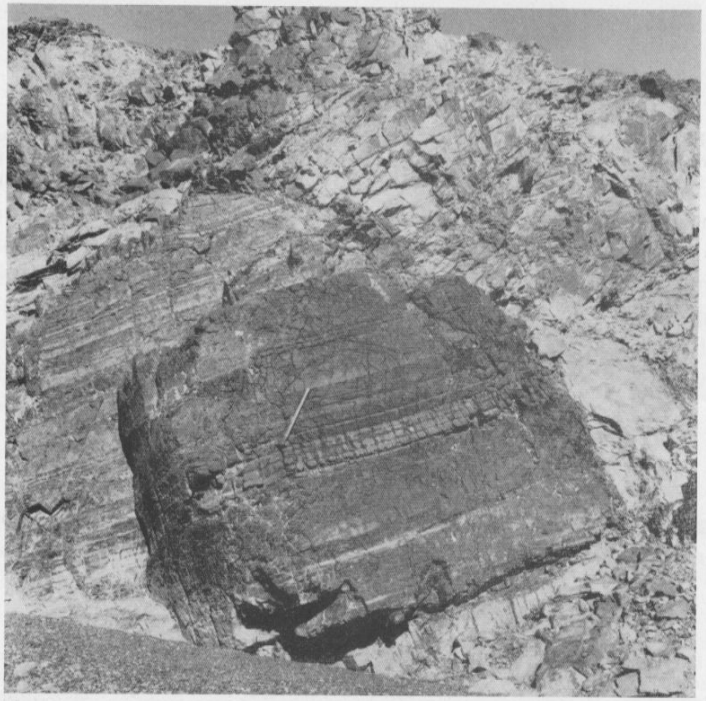


Fig. 14. Large block of coarsely grained layered olivine gabbro (dark "migmatite") imbedded in fine-grained diabase. Wadi Andàm, Central Oman Mountains.

Fig. 15. Magmatic breccia in the subvolcanic level of the ophiolite sequence. Fragments of medium-grained dolerite reworked in a matrix of leucocratic quartz- and albite-rich porphyrite (compare fig. 9). Note partial resorption of the dark fragments by the light residual liquid. North-West of Al Misfah, Central Oman Mountains.

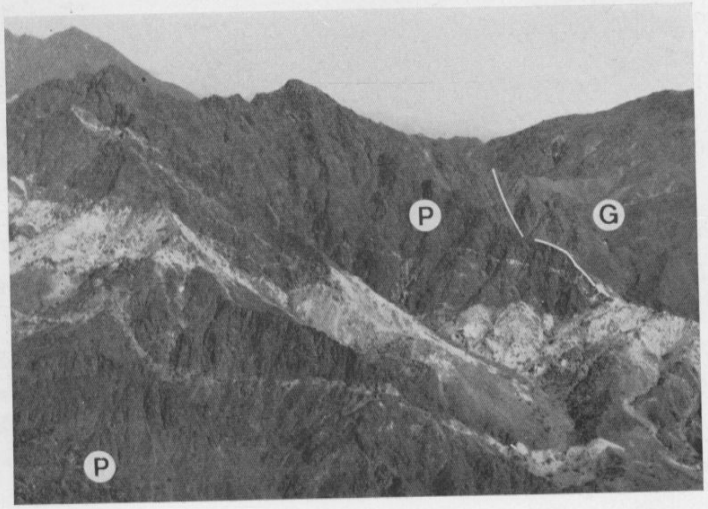


Fig. 16.

Deformation during igneous activity

Magmatic breccias

Magmatic breccias have been observed within all feldspathic members of the ophiolite suite. As a rule the angular components of these formations are represented by members that are less differentiated than the matrix by which they are surrounded: gabbro fragments may be found in a dolerite or diabase matrix, dolerite fragments in a diabase matrix, diabase fragments in extrusive or highly differentiated subvolcanic rocks. The size of the fragments is enormous in cases where gabbros and olivine gabbroic components are reworked. Fig. 14 shows a block of layered olivine gabbro (dark "migmatite") surrounded by diabase. Such blocks by no means represent the maximum size. Undisturbed sequences of fresh dolerites and diabases on the NW side of the mountain range include slices of coarsely grained gabbroic rocks of at least 500 m length. Smaller fragments in the cm to m size are very commonly found in diabase sequences. The latter sequence of breccias is a regionally mappable unit that ranges between gabbros and diabases in the ophiolite "stratigraphic column". A characteristic feature of this zone is the partial resorption and "secondary assimilation" of the breccia components by the residual liquids of the matrix. Fig. 15 shows an example of this process in an advanced stage.

Fracturing of the coarse-grained rocks

Gabbroic rocks are commonly fractured, and one tends to attribute this process to deformation connected with nappe transport. However, in many instances the fractures are rewelded with undeformed and highly differentiated dioritic to quartzdioritic rocks that are otherwise found in the subvolcanic sequences. This suggests that important movements and uplifts occurred while differentiation and crystallisation of the intrusive-extrusive suite was still not complete. The largest intrusions of such leucocratic residual liquids are found along impotant planes of décollement such as may be developed along the contacts between gabbros and ultrabasic rocks (fig. 16).

The shear planes in the dyke swarms

Subvertical diabase dyke swarms are often cut at about 20–45 degrees by normal faults. The displacement may be of much the order of some metres or

Fig. 16. Intrusion of quartz-rich labradorite-porphyrite into peridotites. The leucocratic intrusive rock is a common member of the subvolcanic assemblage and otherwise does not occur in relationship with abyssal igneous rocks. This large dyke follows a line of decollement that approximately follows the contact between peridotites and gabbros (right-hand side of photo). P = peridotites, G = gabbros. South of Wadi Ahin, Central Oman Mountains.

more; in the latter case, control over displacement distance is lost. Younger diabase intrusions follow these fault planes for some distance before they turn back to the general subvertical dyke direction.

The presence of garnet bearing "amphibolites"

At the base of the Semail Nappe a discontinuous thin sheet of strongly laminated metamorphic rocks has been mapped. The rocks involved are low grade dynamo-metamorphosed geosynclinal sediments and extrusives. Transitions to recognisable sedimentary formations are gradual, so that to some extent, the origin of the metamorphic members is known. However, the scattered occurrence of exotic "amphibolites" in this unit is somewhat enigmatic. The mineralogy and texture of these rocks show two phases of metamorphism: a late, very dynamic phase of low grade metamorphism, similar to that observed in surrounding sediments, and an earlier phase of very high grade recrystallisation. In cases where this first phase is well preserved, the following rock is recognised: coarse and rather massive "amphibolite" with granular texture and poor planar lineation (the term "amphibolite" is, therefore, inadequate and put between inverted commas). The composition of plagioclase ranges between $An_{50}Ab_{50}$ and $An_{65}Ab_{35}$ and the hornblende is of brown colour. Occasional garnet porphyroblasts of up to 1 cm size are surrounded by kelyphitic reaction rims composed of an intimate intergrowth of plagioclase and hornblende.

PALEOGEOGRAPHIC CONDITIONS DURING EMPLACEMENT

The following results from the geological investigation are relevant to the site, the mode and the time of the ophiolite emplacement:

1. From the extension of the Semail Nappe and from a palinspastic reconstruction of the geosyncline it appears that the site of ophiolite emplacement was a linear feature with a length of more than 450 km that flanked the geosyncline on its internal edge. The site of "extrusion" thus formed the internal limit of the geosynclinal realm.

2. From the presence of shallow water carbonates along this zone throughout Upper Permian and Triassic and during part of the Lower Jurassic, it is inferred that the ophiolite belt was a topographically positive feature (ridge).

3. The lack of sialic rocks associated with the Semail Nappe suggests that the site of emplacement was well within the oceanic realm. In these areas, spinel-bearing peridotites of the Earth's Mantle are thought to form a layer about 45 km thick, the top of which is assumed to be at only about five kilometres depth below sea bottom (Hess, 1962).

4. The igneous activity lasted over a period of more than 100 million years. The oldest extrusives belonging to the Oman Ophiolites are associated with the earliest geosynclinal sediments of Middle to Upper Permian age - the youngest lavas are found together with sediments of early Upper Cretaceous age.

5. During the Jurassic the internal shelf platform was submerged. The shallow water carbonates were "moved" into environments of pelagic sedimentation and thus became "exotic blocks", now found together with a type of coloured mélange (chaotic mixture of pelagic sediments, extrusives and exotic blocks. In the case of the Oman mountains strong post-geosynclinal movements have considerably deformed the coloured mélange).

6. At about the same time, the basinal part of the geosyncline was separated from the volcanic belt by a continuous barrier. This is inferred from the fact that the younger lavas produced did not flow into the external part of the geosyncline. They were flowing on the internal side of the barrier, and from their palaeo-flow directions, it is inferred that they were following trends parallel to the orogenic belt. This could be an indication for the development of a volcanic submarine rift valley.

7. The fact that these younger lavas now form the extrusive cover of the Semail Nappe and that the older lavas are found exclusively in tectonic units lower than this nappe, suggests that the barrier developing in Jurassic time was formed by the slowly upwelling mass of peridotites and gabbros that now form the bulk of the Semail Nappe. Figure 17 summarises the history of emplacement as tentatively reconstructed from the geological and petrographical data. The various conclusions that have led to this model are discussed in the final chapter.

CONCLUSIONS

The "eversion" of oceanic basement; discussion of a new model for the emplacement of ophiolites in the Oman Geosyncline

From the observations made in the Oman Mountains it is concluded that this ophiolite suite is not the product of a single liquid-magmatic extrusion as assumed in the pluto-volcanic model of Routhier, Dubertret and Brunn. The Oman Ophiolites represent a polygenetic association of both igneous and metamorphic rocks. Of the igneous suite only a minor part has reached the geosynclinal environment as a magma. These are the mostly spilitic extrusives. Most of the other ophiolite members such as peridotites, the gabbros and the high-grade amphibolites have been expelled from great depth in a solid state.

The peridotites are part of the oldest generation of the whole suite. This is inferred from the contact relationships with the gabbros which suggest that the peridotites represented a regional frame of host rocks for the gabbroic-basaltic intrusions. The environment in which the ultramafic rocks reached their mineralogical equilibrium is assumed to be of high temperature (ca.

1400°C) and high pressure (10–20 kb, corresponding to 30–60 km depth) (PETERS, 1968). This is a physical environment in which, according to the experiments of KUSHIRO and YODER (1966), a melt of basaltic composition is unlikely to crystallise in the "gabbroic facies". However, since the peridotites are now intruded by abyssal, hypabyssal and subvolcanic gabbroic rocks, it is thought that at the time of intrusion (geosynclinal phase) they formed a thick layer close underneath the geosynclinal floor. Whatever mechanism brought them up from the site where they had reached mineralogical equilibrium to the site where they were intruded by gabbroic melt, a long time must have elapsed between their crystallisation and the gabbroic intrusions. On these grounds it is thought that an age hiatus separates the peridotites from the gabbroic suite. The peridotites are thought to be at least pre-Middle Permian in age.

The volumetrically unimportant but quite characteristic garnet bearing amphibolites could also be rocks derived in solid state from great depth. This is inferred from the fact that similar rocks are usually found in metamorphic sequences developed in the high-grade amphibolite facies and in the hornblende granulite facies (SCHMID, 1967).

The kelyphitic reaction rims surrounding the garnet porphyroblasts are likely to be a result of the transition from higher grade pressure-temperature conditions of the hornblende granulite facies to the more moderate conditions of the amphibolite facies. If this is so, these rocks display features acquired during their migration up to the geosynclinal floor.

The relationships between the various members of the gabbroic-basaltic igneous suite suggest that they are all products of differentiation of one common magma – they may thus be regarded as consanguinous rocks sensu stricto. However, the wide variation of igneous facies (abyssal, hypabyssal and extrusive members) strongly suggests that they did not crystallise within a small range of depth. Contrary to ROUTHIER, DUBERTRET and BRUNN we tend to interpret the considerable differences in grain size and texture as the expression of crystallisation at widely varying depths. Moreover, it is geologically reasonable to attribute the "migmatitic" intrusive contacts between the plutonic gabbros and the peridotites to a depth of crystallisation exceeding 10 kilometres. From these rocks there are petrographically gradual transitions to the extrusive members. Within this suite, the mechanism of differentiation has led to the following situation:

— the abyssal members are relatively poor in silica, rich in magnesium and have a "dry" mineralogy. Their chemical equivalent is not known amongst the subvolcanic rocks and extrusives,

— shallower rock types and lavas are more acid and rich in iron and volatiles. They, in turn, have a composition which does not occur amongst the abyssal members,

— there is thus a direct relationship between the stage of differentiation and the depth of crystallisation inferred from petrographical evidence,

— the dolerites and diabases seem to bridge the gap between these extremes in terms of both chemical evolution and depth difference,

— the extreme anorthite-eucritic mineralogy of the gabbros strongly suggests that their chemical composition is not "normal basaltic". If one assumes that the igneous suite developed from a basaltic magma, then these gabbros have also to be regarded as differentiated members. The normal basaltic composition of the original magma was intermediate with reference to the differentiated end members. The linking diabases best match the chemical composition of a basalt,

— large quantities of fragments of abyssal igneous rocks and phenocrysts of the abyssal "facies" are reworked in rock types of successively shallower "facies". This suggests that large amounts of solid matter have been dragged from depth into the shallower environments of the gradually more acid and volatile rich residual liquids. It also suggests that during the uplift of abyssal gabbroic members igneous activity was not interrupted. Continuous intrusions and subsequent differentiation produced the younger more differentiated members in which the uplifted fragments became reworked.

The process of differentiation seems, therefore, to by closely linked in space and time to the mechanism of emplacement. Strong movements of uplift are combined with a prograding evolution of the magma. Based on these observations and on the conclusions concerning the palaeogeographic conditions, the model of an "oceanic ridge s. l." has been tentatively chosen as a possible approach to illustrate genesis and emplacement of ophiolites in the case of the Oman Mountains Geosyncline.

Ocean ridges are the site of basaltic igneous activity. The vertical attitude of an abyssal fissure along the ridge that is filled with injected magma, allows for a rather unrestricted upward circulation of volatile matter contained in the undifferentiated magma. The emission of large quantities of gas at the surface (nearly all extrusives are vesicular) will encourage cooling in the upper part of the fissure. As a result of this, both temperature and chemical composition are likely to differentiate in a vertical direction. The rate of upward diffusion of some components of the magma such as iron and sodium may be increased by a strong temperature gradient. In addition, fractional crystallisation does, of course, also contribute considerably to differentiation of the gabbroic suite. The rocks crystallising along a large volcanic vent are thus likely to become differentiated into plutonic members at depth that have a different composition from the members near to and at the surface. Provided there is sufficient time available for differentiation to take place (very slow cooling), each depth level within the fissure will be characterised by a certain limited stage of

magmatic evolution, which is precisely the situation observed in ophiolite sequences.

In addition, oceanic ridges can be regarded as epidermal features created by the uprising columns of mantle convection cells. The hypothesis of gradual spreading of new crustal material away from the ridges has gained support from palaeomagnetic measurements (VINE, 1966). The ridges can thus be the sites of oceanic crust generation. By analogy, one may regard the ophiolite emplacement as a very active phase of crust production along these abyssal volcanic fissures. It is assumed here, that the piling up of large ophiolite masses during the geosynclinal phase is the result of a high rate of upwelling in the Upper Mantle that is not sufficiently compensated for by tangential transport away from the ridge.

Figure 17 illustrates the various phases of emplacement envisaged. In figure 17a the situation during the early geosynclinal phase (Middle Permian to Lower Jurassic), is shown. The basinal parts of the geosyncline are flanked on their internal side by a shallow water carbonate platform. Extrusives produced on this platform flow into the basinal areas. Erosional products from the internal shelf (shelf talus, oolites and volcanic debris) are transported into more external areas of sedimentation. It is assumed that during this early stage, gabbros already crystallised at greater depth within the frame of the older, ultrabasic host rocks.

Figure 17b shows the situation as developed during Jurassic times:

- the internal shelf is submerged and becomes a sheet of large exotic blocks associated with the extrusives and pelagic sediments. The volcanic belt is also submerged and a volcanic rift valley is assumed to have developed. The arrow indicates the movement that could explain;
- slumping of exotic blocks because of increasing steepness of the shelf slope,
- development of a barrier between the volcanic belt and the basinal part of the geosyncline,
- uplift of plutonic rocks that have crystallised in the abyssal fissure at an earlier stage (fig. 17a).

Fig. 17c shows a further step of the emplacement. Products of deepseated, plutonic crystallisation have been slowly uplifted and brought into environments where finer grained rocks crystallise. The increasingly more differentiated products present in these shallower levels cover the plutonic rocks to form the well known zonation of the suite. As the uplifted rocks approach the surface they finally become covered with layers of extrusives. It should be remembered that the products of shallower crystallisation are assumed to be differentiates of younger magma that is continuously supplied from depth during the expulsion of already crystallised rocks. On the way through the shallower levels of the oceanic basement the solid rocks are fractured. As a result, fine-grained

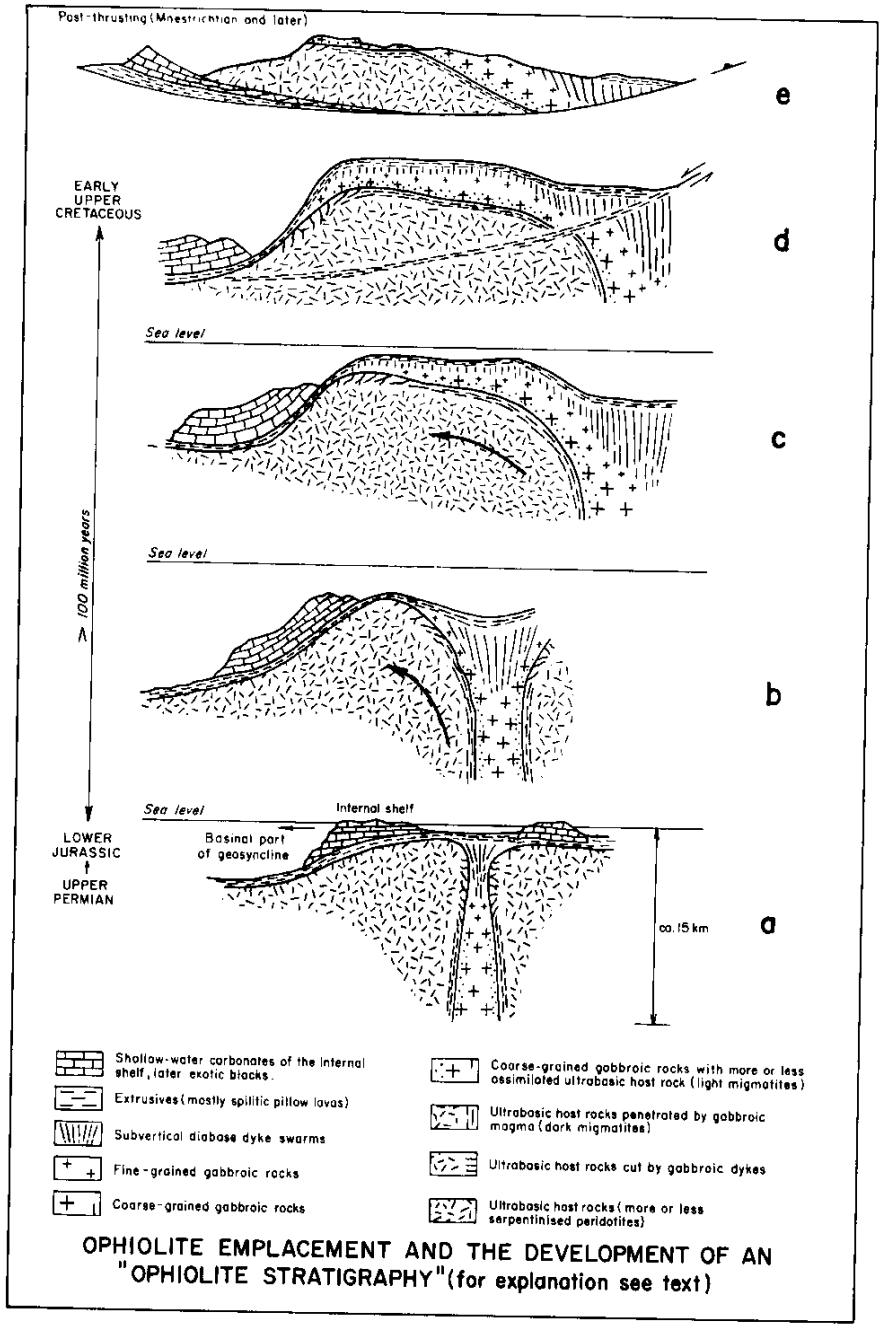


Fig. 17.

hypabyssal and subvolcanic rocks crystallise along the fractures to form dykes and the matrix of magmatic breccias. Further movement in the indicated direction removes the suite from the environment of igneous activity. The "eversion of oceanic basement" has created an ophiolitic sequence that now forms a type of oceanic crust.

Figure 17d illustrates the emplaced ophiolite mass shortly before the orogenic movements led to the formation of the nappes. A hypothetical low angle thrust plane indicates the base of the future Semail Nappe. The ophiolite nappe, after transport and partial erosion, is schematically outlined in figure 17e. On its way, it has overridden the exotic blocks, the early geosynclinal extrusives and the basinal sediments of the geosyncline. On its back it still carries the delicate volcanic structures developed in early Upper Cretaceous time.

The model discussed here also provides a satisfactory solution to the problem of strong "autometamorphism" observed in ophiolite gabbros. Such processes could be interpreted as the result of the transport of crystallised rocks up the still active igneous fissure. The close association of strongly altered gabbroic rocks with the beautifully preserved and unaltered basic extrusives as well as with unmetamorphosed sediments suggests that this type of metamorphism predates the geosynclinal phase. In this case similarities may again be found on the crust of modern ocean floors: MELSON and VAN ANDEL (1966) have reported the presence of "greenstones" composed of epidote, chlorite, actinolite and albite along the Mid-Atlantic Ridge at Latitude 22° N. CANN and FUNNELL (1967) dredged various samples of uralitised gabbros and amphibolites on the Palmer Ridge. In both cases it has been concluded that metamorphism took place at depths exceeding two kilometres and that considerable tectonic activity was necessary to expose these rocks on the ocean floor.

The "spilite problem" also appears in a new light if considered in connection with large scale differentiation in an abyssal fissure. From direct observations on modern floors (e. g. ENGEL et al., 1965) it appears that the conversion of basaltic lavas to spilites is not the "usual fate" of submarine extrusives. The reactions with sea water are thus not a dominant factor in the petrogenesis of spilitic rocks. "Secular" alterations are also unlikely to be responsible for the spilitisation since spilites are well known amongst modern submarine extrusives (HEKINIAN, 1968). In addition, the distribution of spilites in the Oman Ophiolites is not restricted to extrusives. A large proportion of the subvolcanic rocks in the vertical dyke swarms are also spilites. The occurrence of these rocks is therefore likely to be the result of advanced differentiation rather than the result of subaquatic alteration. Probably both primary crystallisation from hydrous residual liquids as well as secondary alteration by uprising sodium and volatiles are important factors in the genesis of spilitic rocks. AMSTUTZ (1968) has presented good arguments to suggest that a large

part of the "true spilites" are crystallisation products of a primary magmatic differentiation. Considering the possible size of an abyssal igneous fissure of which only the top part is finally involved in the formation of the ophiolite nappe, the quantitative aspect of concentration of volatiles and sodium is not a serious problem. The dominant condition is that enough time is allowed for differentiation on a very large scale. This, in turn, demands a very high geothermal gradient during the geosynclinal phase in order to prevent chilling of the upper part of the magma chamber, where the spilitic residual liquids continuously collect.

Finally, the world-wide association of cherts with ophiolites (GRUNAU, 1965) may be due to the fact that the sources of silica were large "ophiolitic" magma chambers, the top parts of which were in direct communication with the oceans. Similarly, as in the case of spilite genesis, the quantitative problem may be solved by assuming an intra-telluric differentiation of much larger amounts of basaltic magma than are now visible in the ophiolite suite.

There are thus quite a number of reasons for comparing an ophiolite belt with an active igneous fissure along an ocean ridge-system. On the other hand we are fully aware of the difficulties involved in the evaluation of the mechanical aspects of emplacement. To quite an extent this is a problem of scale and of time similar to those encountered in cases where deep parts of continental basement are involved in the formation of nappes.

In both instances the source of mechanical energy remains hypothetical because it escapes direct observation. Therefore, the proposed model is only an attempt to approach the ophiolite problems from a new direction. More geophysical and oceanographic research in the coming years will help to refine the picture that here has only been sketched.

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Etude comparative des diverses manifestations du volcanisme préorogénique au sud de Chypre

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Avec 3 figures et 2 tableaux dans le texte

Résumé

La comparaison porte sur deux ensembles volcaniques apparemment semblables mais très différents en réalité. Le premier fait partie du groupe de Mamonia. Les laves à structure en pillow-lavas largement développées, comprennent des trachytes alcalins, des latites, des andésites, des labradorites, des basaltes et des picrites. Ces roches sont souvent transformées et passent à des laves à pseudomorphoses et des spilites. Elles sont associées à des sédiments siliceux et carbonatés d'âge triasique.

Le second ensemble est la partie méridionale du grand massif pluto-volcanique du Troodos-Kellaki. La gamme des laves où prédominent aussi les pillow-lavas est plus restreinte: labradorites, basaltes et picrites, ainsi que des laves transformées et des spilites. L'âge n'est pas connu, mais probablement crétacé.

Le volcanisme préorogénique de Mamonia est alcalin sodi-potassique tandis que celui de Kellaki est calcoalcalin. Une opposition apparaît donc entre une série ophiolitique (Troodos-Kellaki) et une série hybride (Mamonia) dont les caractères originaux sont attribués à l'influence de la traversée d'un socle – dont on retrouve les fragments – par le magma basique initial.

INTRODUCTION

L'Ile de Chypre, située au carrefour de trois continents: africain, asiatique et européen, est formée de trois grandes unités géologiques et structurales qui sont du Nord au Sud: la chaîne côtière récente de Kérynia, la plaine quaternaire de la Mésaorée et le massif pluto-volcanique du Troodos (fig. 1).

L'un des traits dominants et le plus original de sa géologie est le grand développement du volcanisme sous-marin caractérisé par d'abondantes laves

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