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Metamorphism in the Mid-Atlantic Ridge near 24° and 30° N†

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Metabasites (metabasalts and metagabbros) occur abundantly in association with serpentinites in transverse fracture zones and on walls of the median valley. These metabasites were formed by burial metamorphism probably in deeper parts of the crust and the upper mantle beneath the Ridge crest, and were brought up to the surface of the crust probably by serpentinites rising along fracture zones and by normal faulting along the median valley.

The metabasalts are in the zeolite and greenschist facies and a transitional state from the greenschist to the amphibolite facies, whereas metagabbros tend to have been recrystallized at higher temperatures, being in the greenschist and amphibolite facies. Compositionally the metabasites are divided into two groups, I and II. Group I comprises those which retain the approximate composition of the original rocks except for water content, whereas group II comprises those which underwent marked chemical migration, as regards sodium in zeolite-facies rocks and calcium and silicon in greenschist-facies rocks. In rocks of group I, calcic igneous plagioclase remains unaltered, and albite and epidote did not form. This fact, along with the absence of epidote-amphibolite facies rocks, would be due to the low rock-pressure during metamorphism. In some rocks of group II, albite and epidote occur.

Burial metamorphism takes place probably mainly beneath the Ridge crest where the geothermal gradient is great. The resultant metamorphic rocks are probably of the low-pressure type, and move laterally by ocean-floor spreading to form the main part of the oceanic crust.

Contact metamorphic gneisses, probably derived from gabbros, have been found. Some metagabbros were subjected to cataclasis by fault movements along fracture zones and the median valley.

1. INTRODUCTION

Since 1966, metamorphosed basalts, dolerites and gabbros have been reported to occur in mid-oceanic ridges. Melson, Bowen, van Andel & Siever (1966), Melson & van Andel (1966) and Melson, Thompson & van Andel (1968) discussed a collection of more or less sheared metabasalts in the greenschist and lower facies dredged from a wall of the median valley near 22° N on the Mid-Atlantic Ridge. Aumento & Loncarevic (1969) described more or less schistose metabasalts in the greenschist facies from Bald Mountain about 60 km west of the median valley on the M.A.R. near 45° N.

Cann & Funnell (1967) have reported the occurrence of metabasalts, metadolerites and metagabbros, preserving original igneous textures but recrystallized in the lower amphibolite facies, from Palmer Ridge near 43° N and 20° W on the eastern flank of the M.A.R. Cann & Funnell (1967) believe that the pertinent metamorphic recrystallization took place beneath the crest of the M.A.R., and that the resultant rocks have been moved laterally by ocean-floor spreading.

Metabasalts in the greenschist facies, having relict igneous textures, have also been obtained from a crestal mountain adjacent to a fracture zone on the Carlsberg Ridge near 5° N by Cann & Vine (1966) and Cann (1969).

A series of dredge hauls made by one of us on the M.A.R. near 30° N during *Atlantis* cruise 150 (in 1947) was petrographically described as containing basalt, dolerite, gabbro and serpentinite (Shand 1949; Quan & Ehlers 1963; Muir & Tilley 1966). Our recent re-examination of

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TABLE 1. METAMORPHIC ROCKS AND ASSOCIATED ROCK TYPES IN DREDGE HAULS FROM THE MID-ATLANTIC RIDGE NEAR 24° AND 30° N.

cruise	dredge	latitude (N)	longitude (W)	depth m	geological environment	meta-basalt	meta-gabbro	serpentinite	breccia and cataclasite	gabbro	dolerite	fresh basalt	weathered basalt
Atlantis 150	RD6	30° 06′	42° 08′	1460	c.r.	—	a	a	—	—	—	—	—
	RD7	30° 01′	42° 04′	4280	mv.-f.z.	s	—	s	—	—	—	a	s
	RD20	30° 04′	42° 16′	4144	f.z.	a	s	a	s	—	s	s	s
	RD21	30° 08′	42° 37′	4200	f.z.	—	s	a	—	—	—	—	—
Vema 25	RD5	23° 31.7′	45° 07′	3109 or 3384	m.v.	a	a	—	s	s	—	—	—
	RD6	23° 44.7′	45° 33.6′	4207	f.z.	a	a	s	a	s	s	s	a
	RD8	23° 46.7′	46° 04.2′	3841	f.z.	a	—	s	s	s	—	s	a
	RD9	23° 46.1′	46° 37′	3073	f.z.	s (?)	a	a	—	—	—	—	—

Note. c.r., on a crestal mountain adjacent to the junction of the median valley with the Atlantis Fracture Zone; m.v.–f.z. at the junctions of the median valley with fracture zones; f.z., within fracture zones across the crest province; m.v., east wall of median valley near the junction with a fracture zone. a = abundant, s = scarce.

this collection has revealed the presence of abundant metabasalts and metagabbros. A new series of dredges made on the M.A.R. near 24° N during *Vema* cruise 25 (in 1968) gave us abundant metabasalts and metagabbros as well as serpentinites. These metamorphic rocks were dredged largely from transverse fracture zones, but partly from a crestal mountain and from the median valley. Some metagabbros were found to have been subjected to later cataclasis.

This paper gives an outline of our petrologic study on these metamorphosed basic rocks. Detailed descriptive data will be published later. *Atlantis* cruise 150 and *Vema* cruise 25 will be denoted as A 150 and V 25 respectively. RD means rock dredge.

2. Modes of occurrence

Our dredge stations are summarized in table 1. It is noted that most of our metamorphic rocks occur in association with serpentinites in transverse fracture zones (A 150–RD 20, 21; V 25–RD 6, 8, 9). Metagabbros from a crestal mountain adjacent to the Atlantis Fracture Zone (A 150–RD 6) are also associated with serpentinites. These facts suggest that the metamorphic rocks occur in and near fracture zones as inclusions in serpentinites. The metamorphic recrystallization should have taken place at some depth, and fragments of the resultant rocks would have been torn and brought up to the surface of ocean floors by intrusions of serpentinites or their parental peridotites along fracture zones (Miyashiro, Shido & Ewing 1969, 1970*a*). This interpretation is consistent with the view that the M.A.R. serpentinites were formed by hydration of upper mantle peridotite (Miyashiro *et al.* 1969). Cataclastic metagabbros occurring in a fracture zone (V 25–RD 6) would have been formed by shattering due to movements along the zone.

A dredge haul (V 25–RD 5) from a wall of the median valley near the junction with a fracture zone contains metabasalts, metagabbros and cataclastic metagabbros but no serpentinite. This mode of occurrence resembles that in the median valley near 22° N (Melson *et al.* 1968). In such cases, the rocks metamorphosed at some depths would have been exposed by normal faulting which would have caused cataclasis on some rocks.

3. Burial metamorphism of basalts

Metabasalts of A 150 and V 25 are usually non-schistose, preserving their original igneous textures. Recrystallization is incomplete in most cases. The structures of pillow lavas and tuff breccias are noticeable in some specimens. These suggest that basaltic eruptions produced thick volcanic piles, the lower parts of which became sufficiently hot to undergo metamorphic recrystallization, i.e. burial metamorphism.

A classification of burial metamorphic rocks from the M.A.R. near 24° and 30° N is shown in table 2. The rocks comprise metabasalts and associated metagabbros. Most of the metabasalts belong to the zeolite and greenschist facies. Some metabasalts from the Atlantis Fracture Zone (A 150–RD 20), however, have very small amounts of blue-green hornblende in association with greenschist-facies minerals, and are considered to be in a transitional state between the greenschist and amphibolite facies. The temperature of metamorphism for such rocks would be as high as 400 to 500 °C. Such high temperatures would have been reached somewhere in the deepest part of the crust and in the upper mantle beneath the crest of the M.A.R.

As shown in table 2, metabasalts and metagabbros that underwent burial metamorphism are compositionally classified into two groups. The members of one group, here called *group I*, preserve their approximately original igneous composition except for H_2O contents. The members of the other group, called *group II*, suffered intense chemical migration during metamorphism. The migration is probably due to flow of a hot aqueous fluid through the crust. With emphasis on this interpretation, we may well call the latter group hydrothermally modified metabasalts and metagabbros.

TABLE 2. CLASSIFICATION OF BURIAL-METAMORPHIC BASALTS AND GABBROS FROM THE MID-ATLANTIC RIDGE

facies	composition		
	group I compositionally virtually unchanged	group II compositionally intensely changed	
zeolite facies	none	metabasalt (abundant) metagabbros (zeolitized only by retrogressive change)	Na-introduction
greenschist facies	metabasalts (abundant) metagabbros (abundant)	metabasalts (abundant) metagabbros (abundant)	Ca-decrease Si-variation
transitional between greenschist and amphibolite facies	metabasalts (abundant) metagabbros (abundant)	none	
amphibolite facies	metagabbro (abundant)	none	

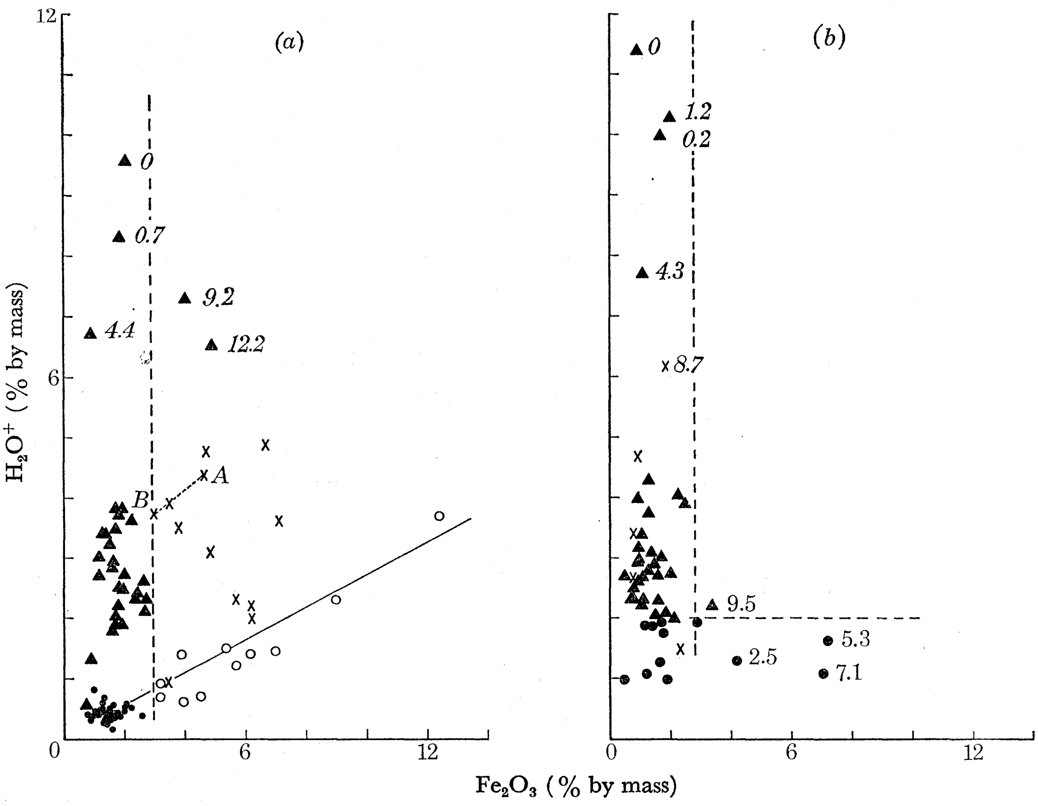

FIGURE 1. Relation between Fe_2O_3 and H_2O^+ contents in (*a*) basalts and metabasalts and (*b*) in gabbros and metagabbros. The numbers in italics represent CaO contents and those in upright type represent TiO_2 contents. In (*a*): ●, unweathered, unmetamorphosed basalt; ○, weathered basalt; ▲, metabasalt in greenschist facies; ×, metabasalt in zeolite facies. ——, trend of compositional variation in weathering.
In (*b*): ●, virtually unmetamorphosed gabbro; ▲, metagabbro in greenschist and amphibolite facies; ×, metagabbro containing zeolites.

Greenschist-facies metabasalts

The greenschist-facies metabasalts of group I show chemical features of tholeiitic basalts except for H_2O content. This probably means that they were derived from abyssal tholeiites without marked migration of materials except for H_2O. It is noted that the Fe_2O_3 contents of unweathered greenschist-facies metabasalts are more or less similar to those of unweathered, unmetamorphosed abyssal tholeiites, that is, below 3.0 %, as shown in figure 1*a*.

On the other hand, weathered abyssal tholeiites show higher contents of Fe_2O_3 as well as H_2O^+, and are plotted along the full line in figure 1*a*. Accordingly, greenschist-facies metabasalts are clearly distinguished from weathered tholeiites by their Fe_2O_3 contents, even though they both have high H_2O^+ contents.

The greenschist-facies metabasalts of group II suffered intense chemical migration during metamorphism, commonly resulting in a decrease of CaO and an increase of H_2O^+ content. Their CaO contents approach zero in some rocks (figure 2). Such rocks are represented by metabasalts with H_2O^+ contents higher than 6 % and with Fe_2O_3 contents less than 3 % in figure 1*a*. Mineralogically they are chlorite–quartz rocks. The high contents of H_2O^+ are due to high contents of chlorite. The SiO_2 contents are variable. Some metabasalts of group II, however, do not show a decrease of CaO. These are represented by metabasalts with H_2O^+ contents higher than 6 % and Fe_2O_3 contents higher than 3 % in figure 1*a*, and are mineralogically epidote–chlorite rocks. They are relatively rare in the Ridge and may have been produced where oxygen pressure was high during metamorphism.

Zeolite-facies metabasalts

Zeolite-facies metabasalts are characteristically penetrated with networks of veinlets (usually less than 2 mm wide) composed mainly of one zeolite or more. Similar zeolites occur also in dispersed state in the metabasalts. In these rocks, not only the H_2O^+ but also the Fe_2O_3 contents are high, as shown in figure 1*a*. All the zeolite-facies metabasalts so far dredged, however, appear to be rather intensely weathered. Their high Fe_2O_3 contents are considered to be due to weathering post-dating metamorphism for the following reason: The pair of A and B in figure 1*a* represents a weathered rim and a less strongly weathered core of a zeolitized metabasalt (V25–RD8–T47). It can be seen that the Fe_2O_3 content of the core is close to that of greenschist-facies metabasalts. Hence, there appears to be no great difference in oxidation condition between the greenschist-facies and zeolite-facies metamorphism.

Zeolite-facies metabasalts show Na_2O contents generally higher than those of abyssal tholeiites as shown in figure 2. The Na_2O content varies sympathetically with the H_2O^+ as shown in figure 3. Those high in Na_2O and H_2O^+ give normative nepheline, whereas those low in Na_2O and H_2O^+ approach the composition of abyssal tholeiites. All these zeolite-facies metabasalts are considered to have formed by recrystallization of abyssal tholeiites with varying amounts of Na_2O and H_2O introduced. Hence, all the zeolite-facies metabasalts belong to group II. Relict igneous pyroxene and the low TiO_2 contents (1.49 % on an average of 13 analyses) also support their tholeiitic origin. The introduction is perhaps due to permeation of an Na-containing fluid rising from greater depths.

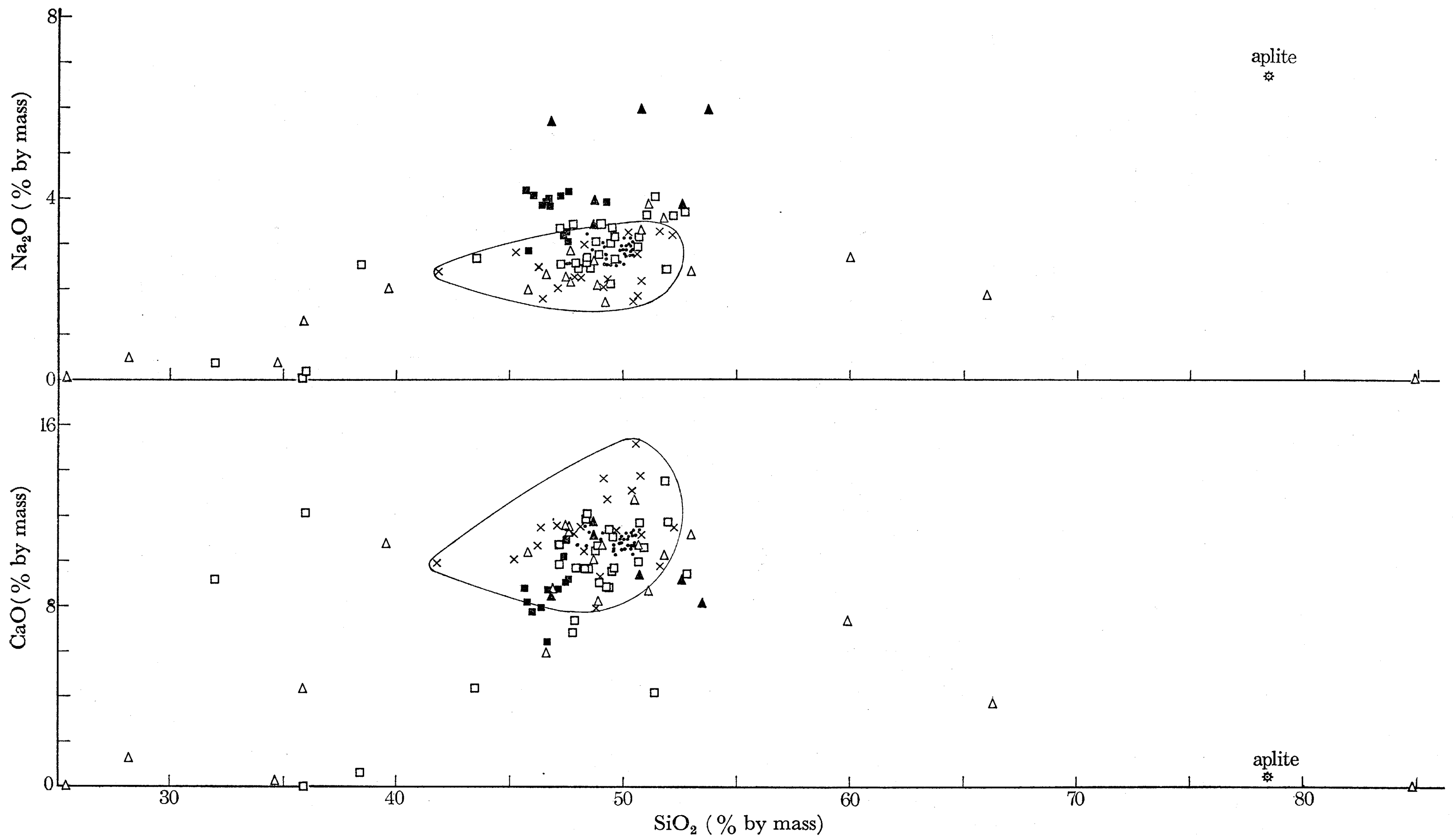

FIGURE 2. Relation between SiO_2, Na_2O and CaO contents in basalts, gabbros, metabasalts and metagabbros. The unweathered, unmetamorphosed basalts and gabbros fall in the outlined area. All the basalts now under consideration are abyssal tholeiites, and the gabbros show a much wider composition field than the basalts. ⊗, basalt (unweathered, unmetamorphosed); ×, gabbro (virtually unmetamorphosed); □, metabasalt in greenschist or higher facies; ■, metabasalt in zeolite facies; △, metagabbro in greenschist or higher facies; ▲, metagabbro containing zeolites.

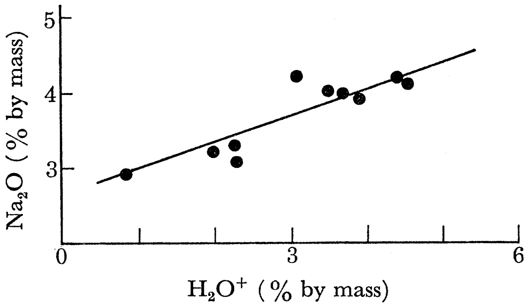

FIGURE 3. Sympathetic variation of H_2O^+ and Na_2O contents in zeolite-facies metabasalts.

4. METAGABBROS EXCEPTING THOSE OF CONTACT METAMORPHIC ORIGIN

Metagabbros are in the greenschist and amphibolite facies. However, some of them suffered retrogressive changes in the zeolite facies. They show high H_2O^+ contents but not high Fe_2O_3, as shown in figure 1*b*. It is noted that metabasalts are mostly in the zeolite and greenschist facies, whereas metagabbros are mostly in the greenschist and amphibolite facies. In other words, metagabbros tend to have been recrystallized at higher temperatures than metabasalts. This would mean that gabbroic intrusions are more common in deeper levels.

The typical amphibolite facies, corresponding to, say, 600 °C would be too high in temperature to be realized within the crust even beneath the crest of the M.A.R. The occurrence of such amphibolite-facies metagabbros, therefore, suggests the possibility that some metagabbros would have been consolidated and recrystallized in the upper mantle.

Most of the metagabbros approximately preserve their original texture and chemical composition, thus belonging to group I as defined above. They show a remarkable degree of magmatic differentiation in the tholeiitic trend, leading to the formation of high-iron, high-titanium gabbros in a later stage (Miyashiro, Shido & Ewing 1970*b*). We may consider that tholeiitic magma was intruded into volcanic piles beneath the M.A.R. to form gabbroic masses of considerable sizes, crystallization differentiation took place in them to a marked extent, and then the masses were subjected to burial metamorphism together with the surrounding volcanic piles.

Some metagabbros in the greenschist facies, however, underwent intense chemical migration, thus belonging to group II. Their CaO content decreases and their H_2O^+ content increases (figures 1*b* and 2). This trend is the same as that observed in greenschist-facies metabasalts. It leads to enrichment in chlorite, ultimately resulting in the generation of chlorite–quartz rocks and mono-mineralic chlorite rocks. The SiO_2 content decreases down to about 25 % in some rocks and increases up to about 85 % in others, though gabbroic textures still remain. A flowing aqueous fluid would have dissolved SiO_2 in some parts of the crust and re-deposited it in others during greenschist-facies metamorphism.

Metagabbros retrogressively modified in the zeolite facies show an increase of Na_2O content just as zeolite-facies metabasalts. Thus, we may consider that Na enrichment is characteristic of zeolite-facies metamorphism in the M.A.R.

5. Mineralogy of burial metamorphic rocks

Igneous plagioclase is very resistant against recrystallization in rocks of group I. In greenschist-facies metabasites of group I, igneous plagioclase (labradorite or bytownite) commonly remains intact after most of the igneous mafic minerals have been replaced by new metamorphic minerals. Therefore, albite is lacking in metabasites of group I. Probably relevant to it is the fact that epidote is absent in group I metabasites.

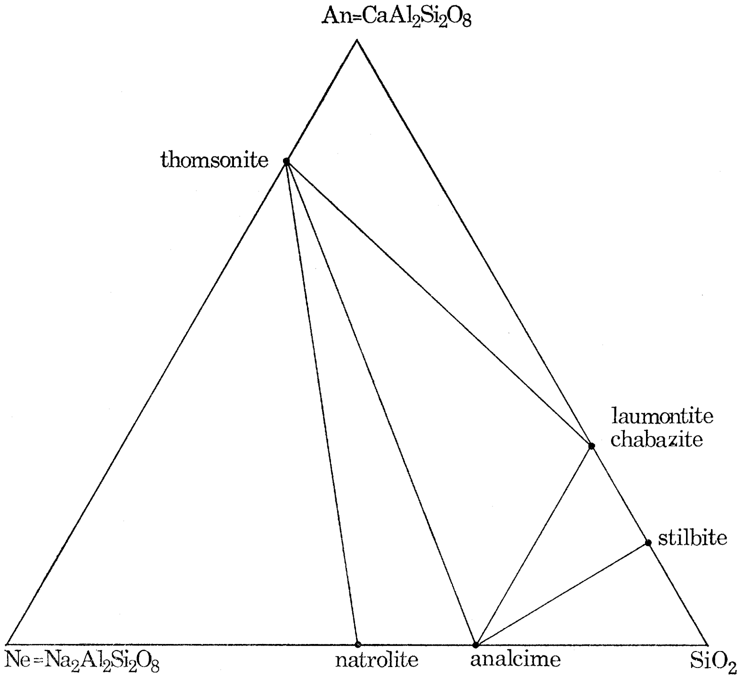

Figure 4. Zeolite parageneses in zeolite-facies metabasalts.

Igneous plagioclase is not so resistant in group II metabasites. Albite occurs in some greenschist-facies metabasites of group II. In zeolite-facies metabasalts of group II, plagioclase remains intact in some cases, but is partly replaced by analcime and other zeolites in many cases.

The following zeolites have been identified in zeolite-facies metabasites: natrolite, thomsonite, analcime, chabazite, laumontite, and stilbite, among which analcime is the most widespread (figure 4). Zeolite-bearing rocks contain no quartz. Hence, natrolite and thomsonite, both incompatible with quartz, occur commonly. Natrolite, being poor in silica, does not coexist with stilbite rich in silica. The zeolite assemblages are considered to be close to chemical equilibrium. The zeolites occurring in deep-sea sediments are phillipsite and clinoptilolite, neither of which was found in our zeolite-facies metabasites. The zeolite-facies rocks were formed at higher temperatures than deep-sea sediments (Miyashiro & Shido 1970).

Chabazite and laumontite have the same chemical composition except for H_2O content. Rising temperature would cause dehydration of chabazite to form laumontite. Therefore, the zeolite-facies metamorphism in the Ridge would include two stages: a lower temperature one characterized by chabazite and a higher temperature one characterized by laumontite.

All the identified clay minerals of the metabasites of the Ridge belong to the three component system: chlorite–smectite–vermiculite (figure 5). Weathered basalts contain mixed-layer mineral smectite–vermiculite. Zeolite-facies metabasites contain mixed-layer mineral chlorite–smectite with or without vermiculite layers, but they never contain chlorite as discrete crystallites. The appearance of discrete chlorite marks the entrance to the greenschist facies. Thus, the progressive change of clay minerals is consistent with the recrystallization temperatures suggested by other minerals. Smectite was found in metabasites of the zeolite and greenschist facies. However, it may be an unstable relict mineral in the high-temperature part of the greenschist facies.

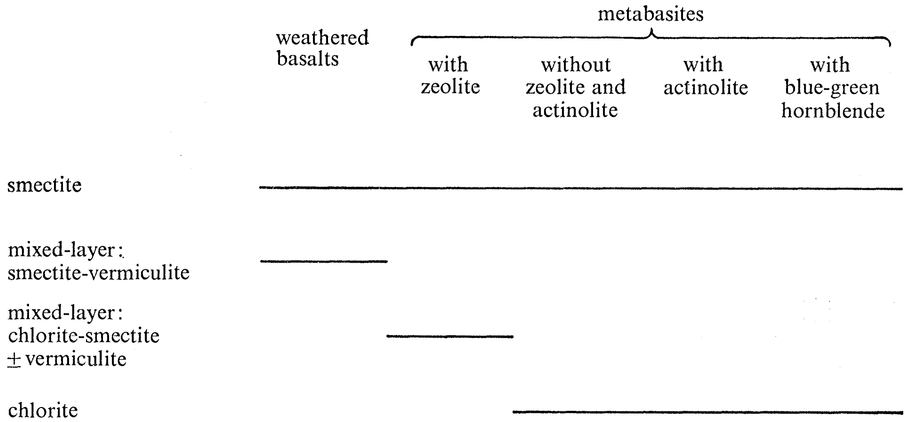

Figure 5. Variation of clay minerals in metabasites with metamorphic grade.

6. CHARACTERISTICS OF BURIAL METAMORPHISM IN THE MID-ATLANTIC RIDGE

The petrologic characteristics of burial metamorphism will be summarized below.

(1) The metabasalts and metagabbros belong to the zeolite, greenschist and amphibolite facies together with transitional states between them. We did not find rock groups that should be properly assigned to the prehnite-pumpellyite or to the epidote-amphibolite facies.

Prehnite was found in an unusual schistose amphibolite (A150–RD8–AM1), in which prehnite has replaced plagioclase. The prehnitization represents retrogressive change after the formation of the amphibolite. Pumpellyite was mentioned by Melson & van Andel (1966). However, the occurrence of these minerals so far known is not enough to warrant the presence of prehnite-pumpellyite facies rocks.

It is known that a zone of the epidote-amphibolite facies as defined by Eskola (1939) is lacking in regions of low-pressure type regional metamorphism in the island arc (Miyashiro 1961). The absence of this facies in the M.A.R. may also be a result of relatively low pressure.

(2) In all the metabasites of group I, calcic igneous plagioclase is very strongly resistant against recrystallization, and persists in rocks where mafic minerals were mostly or entirely recrystallized into low-temperature metamorphic minerals. These rocks, therefore, contain no albite and no epidote.

Such persistence of calcic plagioclase in group I rocks may be due simply to a very slow rate of recrystallization of plagioclase for some unknown cause. An alternative possibility is that calcic plagioclase may be stable in what have been so far called greenschist facies. If so, this facies cannot be the greenschist facies as defined by Eskola (1939), and should be a distinct metamorphic facies characterized by the mineral assemblage actinolite–chlorite–calcic plagioclase.

A metamorphic zone characterized by the assemblage actinolite–calcic plagioclase has been known to exist in the contact aureole of the Iritono area (Shido 1958), Arisu area (Seki 1961) and Sierra Nevada (Loomis 1966). It has been regarded as suggesting the existence of a new metamorphic facies under relatively low pressures (Shido 1958; Miyashiro 1961, p. 307). It is conceivable that the M.A.R. metabasites with the assemblage actinolite–chlorite–calcic plagioclase belong to this or closely related low-pressure metamorphic facies. Epidote is a mineral having a high density. At low rock-pressures, the composition field of rocks to produce epidote may become so small that calcic plagioclase may remain stable instead in ordinary metabasites. This is consistent with the absence of epidote-amphibolite facies rocks.

Since the heat flow at the crest of the Ridge is generally very high, the metamorphism beneath the crest would be of the low-pressure type. If the triple point of Al_2SiO_5 minerals lies at about 600 °C and 6 kbar (0.6 GN m^{-2}) (Richardson, Gilbert & Bell 1969), the average geothermal gradient to result in the coexistence of the three polymorphs at a depth in the earth is about 30 K km^{-1}. The low-pressure type metamorphism, including the andalusite–sillimanite type defined by Miyashiro (1961), should correspond to geothermal gradients higher than it. The crest of the M.A.R. probably has such geothermal gradients.

The basalt–serpentinite association in the M.A.R. was compared with ophiolites by some authors (Hess 1965; Thayer 1968). Typically developed ophiolites such as those in the Alps and the Franciscan formation of California, however, are commonly accompanied by high-pressure type regional metamorphism (Miyashiro 1968, p. 827) which has never been observed in mid-oceanic ridges. It appears that there is an essential difference in the condition of formation between the mid-oceanic ridge rocks and orogenic ophiolites.

(3) Calcic plagioclase is not so resistant in metabasites of group II. In some group II metabasites of the greenschist facies, epidote and albite are rather abundant, but are not accompanied by amphibole. They may be regarded as having changed toward spilites. In zeolite-facies metabasites (group II), calcic igneous plagioclase is commonly partly replaced by analcime and other zeolites.

Melson *et al.* (1968) and Cann (1969) reported the occurrence of spilitic rocks, i.e. epidote–albite–chlorite metabasalts, from the Mid-Atlantic and Carlsberg Ridges respectively. Probably these rocks correspond or are related to our group II metabasites.

(4) Carbonate minerals are scarce in metabasites as well as in associated serpentinites from the M.A.R. near 24° and 30° N. This, together with development of zeolite-facies rocks, suggests that the chemical potential of CO_2 was low during metamorphic recrystallization and serpentinization in these regions. It is not clear, however, whether such a condition holds in other parts of the M.A.R.

(5) Probably the flow and permeation of a hot aqueous fluid were widespread, resulting in marked migration of Na_2O, CaO and SiO_2. It is noted that the kinds of chemical migration are closely related to metamorphic facies. Introduction of Na_2O is characteristic of the zeolite facies, whereas migration of CaO and SiO_2 of the greenschist facies. SiO_2 was dissolved, moved and re-deposited at least partly in other parts of the crust, whereas CaO does not appear to have been re-deposited and, may have been discharged into ocean water.

(6) Almost all metabasites from the M.A.R. near 24° and 30° N are non-schistose except for the contact metamorphic rocks to be mentioned later, though some of them show a slight degree of preferred orientation. In other parts of the Ridge, schistose metabasites occur in association with non-schistoseones (Melson & van Andel 1966; Aumento & Loncarevic 1969).

Thus, metabasites of the M.A.R. are partly non-schistose and partly schistose. If we are allowed to generalize from the scarce data available at present, the proportion of non-schistose rocks is high, and the schistosity when present is not strong in most cases. We may well use the term burial metamorphism in order to emphasize the poor development of schistosity on a large scale.

7. Contact metamorphism

Dredge haul A 150–RD 6 was made on the top of a crestal mountain adjacent to the junction of the median valley with the Atlantis Fracture Zone. It is composed of serpentinites and metagabbros (Miyashiro *et al.* 1969, p. 124). The metagabbros differ from all other ones in the following respects:

(*a*) Ordinary metagabbros are devoid of parallel structures, whereas the A 150–RD 6 metagabbros are gneissic and banded. The texture suggests granulation followed by metamorphic recrystallization. Big crystals of ortho- and clinopyroxenes and plagioclase in the original gabbros remain as porphyroclasts.

(*b*) Brown hornblende occurs as minute grains produced by recrystallization in interstices between granulated pyroxenes. Hence, these metagabbros are considered to be in a transitional state between the amphibolite and a higher facies (i.e. the granulite or pyroxene-hornfels facies). In other words, they are higher in recrystallization temperature than other metagabbros.

The serpentinite–metagabbro association in this case resembles the association of serpentinized peridotite and contact metamorphic rocks of the Lizard area, England (Green 1964). In the Lizard, the innermost contact aureole is made up of banded ortho- and clinopyroxene gneisses. Therefore, we consider that the metagabbros of A 150–RD 6 were formed by contact metamorphism due to high-temperature peridotite intrusion, which were later hydrated to become serpentinites.

8. Cataclastic metamorphism

Cataclastic metagabbros have been found to occur in a fracture zone (V 25–RD 6) and on a wall in the median valley (V 25–RD 5). The degree of cataclasis in these rocks is variable, but not extreme. The cataclasis postdated metamorphic recrystallization, and is probably due to fault movements.

9. A model for the Mid-Atlantic Ridge

Recent investigations of magnetic lineations in oceanic regions have revealed that the magnetic layer responsible for the anomalies is as thin as about a half to a few kilometres, and that the underlying layer is virtually demagnetized (Vine 1966; Talwani, Windisch, Langseth & Heirtzler 1968; Heirtzler 1968). The depth of demagnetization is too shallow to be ascribed to the Curie point. It is probable that the relatively thin magnetic layer is composed of basalts, dolerites and gabbros, whereas the underlying demagnetized layer is composed of metamorphic derivatives of such rocks (van Andel 1968; Miyashiro *et al.* 1970*a*).

Basalts, dolerites and gabbros commonly have strong thermoremanent magnetism. In metamorphic recrystallization the strong magnetism disappears and instead weak chemical remanent magnetism appears, which is negligible as compared with thermo-remanent magnetism (table 3). Hence, most of the seismological layers 2 and 3 appears to be composed of metamorphosed basalts, dolerites and gabbros. The densities of metabasites are shown in figure 6.

TABLE 3. MAGNETIC PROPERTIES OF ROCKS IN DREDGE HAULS OF *ATLANTIS* CRUISE 150

rock type	intensity of n.r.m., $10^3 M_n$/e.m.u. cm^{-3}	susceptibility, $10^3\chi$/e.m.u. cm^{-3}	$Q'_n = M_n/\chi$
unmetamorphosed basalts	12–36	0.37–1.11	10–81
metabasalts	0.0003–0.01	0.02–0.07	0.004–0.2
metagabbro	0.31	0.15	2.1
amphibolite	0.0003	0.08	0.004
serpentinite	2.3	3.85	0.6

Note: compiled from Opdyke & Hekinian's (1967) data with modification of rock names so as to agree with our classification (Miyashiro *et al.* 1970*a*).

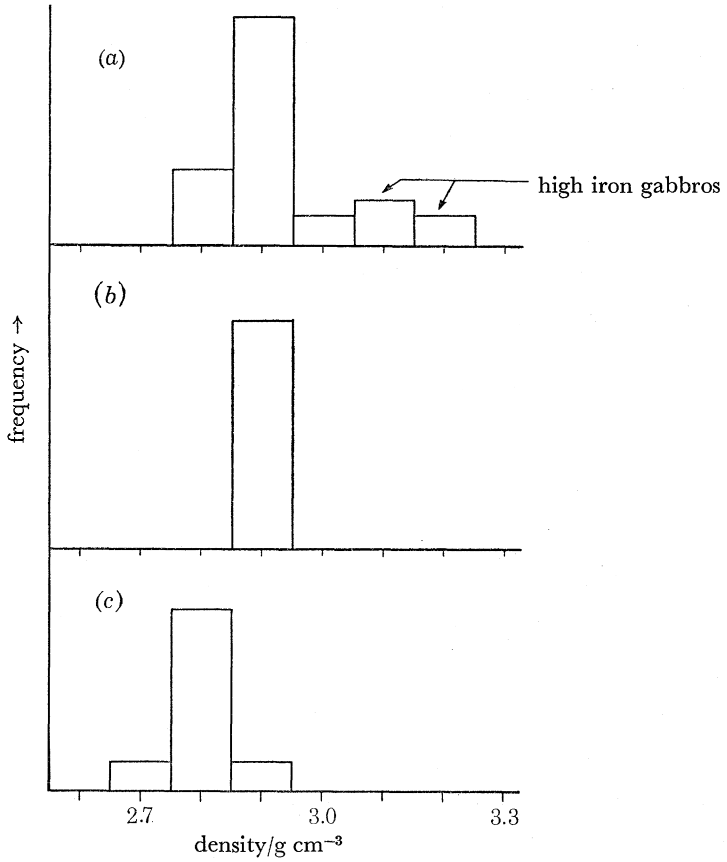

FIGURE 6. Densities of metabasites: (*a*) metagabbros; (*b*) metabasalts (greenschist facies); (*c*) metabasalts (zeolite facies).

The crust beneath normal oceanic basins is about 6 km thick. Assuming a geothermal gradient of 20 or 30 K km^{-1}, the temperature at its base is about 120 to 180 °C. Fissure filling and slight recrystallization would occur there, but the temperature appears to be too low for intense metamorphism.

On the other hand, in the crest of the M.A.R., the crust is thinner, but the heat flow and geothermal gradient are much greater so that extensive metamorphic recrystallization would take place at depth as was first suggested by Cann & Funnell (1967).

However, the heat flow values measured on the crest are not uniform. Values as high as 300 mW m^{-2} (8 μcal cm^{-2} s^{-1}) occur mixed with those as low as 40 to 80 mW m^{-2}(1–2 μcal cm^{-2} s^{-1}) (von Herzen & Uyeda 1963; Langseth 1967). If all these values are accepted, the high values in the crest would depend not only on the general heat conduction but also on some more localized events. Igneous intrusion is a possible event. Flow of a hot aqueous fluid is another. It was mentioned before that some of the greenschist-facies rocks were probably selectively subjected to hydrothermal modification. The aqueous fluid responsible for it would reach the surface of the ocean floor, causing localized high heat flow. If this is the case, the isothermal surfaces beneath the crest must be highly uneven and irregular. As is suggested by the widespread introduction of Na into zeolite-facies metabasites, permeation of a hot aqueous fluid would have been widespread. Even the apparently general increase of heat flow on the crest would be due not only to heat conduction but also to permeation of a fluid.

Thus, the temperature at the base of the crust beneath the crest would be conceivably variable to some extent within a range, say, between 150 and 450 °C. The upper limit would correspond to a transitional state between the greenschist and amphibolite facies. This agrees with the highest metamorphic facies observed in metabasalts. It supports the view that the whole thickness of oceanic crust is mainly composed of basaltic volcanic piles, the bulk of which are metamorphosed to varying degrees to result in demagnetization.

If the temperature in the uppermost mantle may be assumed to be 150 to 500 °C, basaltic magma intruded in small masses there may be chilled to form an ordinary basaltic texture. It is possible that some metabasalts were crystallized and then recrystallized in the uppermost mantle.

Gabbro masses intrusive into the crust should be subjected to metamorphic recrystallization under the same conditions as those prevailing in the surrounding metabasalt complexes. However, a large part of the metagabbros is in the amphibolite facies, that is, higher in metamorphic temperature than metabasalts. This suggests that a considerable part of gabbros was crystallized and recrystallized in the upper mantle as stated before.

The lithosphere would move laterally by ocean-floor spreading. The rocks recrystallized beneath the crest should be gradually cooled with the movement, and would be subjected to retrograde metamorphism. Some metagabbros evidently show such effects.

In our previous paper (Miyashiro *et al.* 1970*a*), we have assumed that the very rugged topography of the crest of the M.A.R. is a surface expression of fracturing within the lithosphere, and that the fracturing causes decrease in seismic velocity. Volcanic piles and their metamorphic derivatives probably have seismic velocities corresponding to layers 2 and 3 respectively. Owing to the fracturing, however, the seismic velocity of the metamorphosed volcanics beneath the crest would have been decreased to a value corresponding to layer 2, with resultant disappearance of layer 3 beneath the Ridge crest.

As the oceanic crust moves laterally away from the axis of the Ridge by ocean-floor spreading, fracturing would gradually wane and stop, while mineral veins would fill the fracture systems in the crust from beneath, to lead to the formation of a coherent plate that represents layer 3. For a more detailed discussion of this problem, refer to Miyashiro *et al.* (1970*a*).

10. Nomenclature

The burial metamorphism beneath the M.A.R. appears to be on a grand scale. However, tc call it by the name of regional metamorphism is undesirable, because this name has been used since the nineteenth century to represent metamorphism taking place in orogenic belts. In many cases, the regional scale of isothermal curves (isograds) and the widespread presence of schistosity also have been considered intrinsic to it (e.g. Harker 1932).

If the mid-oceanic ridge represents the zone where lithospheric plates are created, the orogenic belt would represent a zone related to the disappearance of a plate. Therefore, metamorphism on the ridge differs entirely in geologic setting from regional metamorphism in orogenic belts. Moreover, schistosity is lacking or weak in most of the metamorphic rocks of the ridge. Therefore, the use of the name regional maetamorphism for mid-oceanic ridges will be confusing.

The term burial metamorphism (Coombs 1961) may well be used for ridges as a noncommital name to emphasize the poorness of the development of schistosity. Though this name has been used for zeolite-facies rocks in orogenic belts, there is no rigid historical tradition in its usage.

When we wish to emphasize the geologic setting of the metamorphism in mid-oceanic ridges, it is probably proper to call it by the name of mid-oceanic ridge metamorphism or of ocean-floor metamorphism.

In this paper, the classical names of metamorphic facies adopted by Eskola (1939) have been used with two additional ones by Coombs (1961). It has not been well established to what extent ocean-floor metamorphism resembles regional metamorphism mineralogically. It is regrettable that some authors used such names as the almandine–amphibolite facies or quartz–albite–epidote–almandine subfacies on the assumption that they were dealing with regional metamorphism. These names were originally proposed on the basis of the mineralogical features in regions of Barrovian zones. The burial metamorphism of the Mid-Atlantic Ridge would be of a lower pressure type than that of the Barrovian zones.

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