Geologic Investigations in the Cayman Trough and the Nature of the Plutonic Foundation of the Oceanic Crust

A thesis presented to the Faculty
of the State University of New York
at Albany
in partial fulfillment of the requirements
for the degree of
Master of Science

College of Science and Mathematics
Department of Geological Sciences

Janet B. Stroup
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ABSTRACT

A survey of the literature that deals with the gabbroic rocks believed to comprise the foundation of the oceanic crust indicates that the overwhelming majority of these rocks are recovered from escarpments associated with transform faults. The wide range of mineral and chemical compositions characterizing oceanic gabbroic rocks suggests that the lower oceanic crust is much more heterogeneous in nature than was previously suggested by the results of geophysical investigations. The examination of gabbroic rocks recovered *in situ* from the walls of the Mid-Cayman Rise rift valley by the submersible ALVIN not only supports the notion that oceanic gabbroic rocks are heterogeneous in nature but also that widely varying gabbroic rock types are found distributed heterogeneously on the walls at a scale of tens of meters. Observations that the largest escarpments on the walls of the Rise have only several hundreds of meters of vertical offset, and that gabbroic rocks were recovered to within roughly 100 meters of the tops of the rift valley walls, indicate that the shallow intrusive and extrusive carapace of the oceanic crust here must be anomalously thin. It has been suggested that thin oceanic crust characterizes slowly-slipping ridge-transform intersections elsewhere; the thin crust of the Mid-Cayman Rise may be attributable to the presence of the two long transform faults that bound the 110 km long Rise segment. The two transforms may also have an instantaneous effect on the structural evolution of the Rise creating the well-defined tectonic grain that strikes at a high angle to the axis of the rift valley.

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Acknowledgments

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Chapter I benefitted from the comments of J. Cann, J. Casey, D. Elthon, J. Honnorez and E. Rosencrantz. Chapter II was written while I was a visiting student at the Universite Occidental de Bretagne, Brest, France, and I would like to acknowledge their support and that of the Centre Oceanologique de Bretagne. Chapter II benefitted significantly from the comments of H.D. Needham and A.M.C. Şengör inspired the interpretation presented in Chapter III. Much guidance during the writing of both Chapters II and III was provided by G. White. Drafting support was generously provided by M. Wolters and J. Guichardot-Wirrmann and the patient typist was D. Kelly.

Steven E. DeLong, my advisor, gave me guidance throughout the duration of my research, and made many helpful critical comments on the text of the thesis. The greatest assistance of all, in the realms of both the scientific and the personal, was given me by Paul J. Fox, my husband and coauthor on the published versions of all three chapters. Without Jeff's input this thesis could not have been written.

Preface

At the time of submission of the thesis, Chapter I is in press as the first part of a chapter, coauthored by Paul J. Fox and Janet B. Stroup, in Volume VII of *The Sea*, C. Emiliani, ed., published by John Wiley, New York. Chapter II is in press as a paper, coauthored by Janet B. Stroup and Paul J. Fox, to be published by *The Journal of Geology* in July 1981. Chapter III is in preparation by Stroup and Fox for future publication.

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CHAPTER I

GEOLOGY OF THE PLUTONIC FOUNDATION OF THE OCEANIC CRUST

A. Introduction

The lower oceanic crust, seismic layer 3 or the "oceanic layer," is now believed to be comprised predominantly of plutonic rocks of gabbroic composition that are related to the overlying basaltic and diabasic rocks by crystallization differentiation. Many tons of gabbroic rocks have been recovered from the ocean floor but they have received little attention in the literature relative to the attention received by oceanic basalts. Essentially nothing is known of the lateral and vertical distribution of rocks within the "oceanic layer" other than what may be inferred from studies in ophiolites. The following chapter reviews the petrographic and geochemical data that have been collected on oceanic gabbroic rocks in hopes of establishing the criteria upon which models of lower oceanic crustal evolution may be based.

A very large suite of gabbroic rocks collected by submersible from the Mid-Cayman Rise spreading center, Caribbean, were available to the author for detailed study. Because these rocks appear to be representative of a great proportion of rocks recovered from other oceanic regions, photomicrographs of certain textural features in these samples have been presented as examples within the chapter.

B. Sampling Methods

A diverse range of rock types, presumed to be representative of the lower oceanic crust and upper mantle, has been recovered from the ocean floor. Most of these samples have been recovered by dredging, and dredging surveys have been conducted in all major ocean basins and in a small number of marginal basins. The largest proportion of plutonic rocks recovered by this method has been collected from the Atlantic and Indian Oceans, where the nature of tectonic and petrologic processes operative at slowly accreting plate boundaries lead to the exposure of these rocks. The collection of rocks by dredging has proved effective because the technique is elegantly simple in its implementation and execution, and the method is relatively inexpensive.

Although dredge results provide the framework for our understanding of the plutonic foundation of the oceanic crust, several weaknesses fundamental to the method must be kept in mind. Over several thousands of meters of cable separate the research vessel from the reinforced sampling container located somewhere on the sea floor. In some cases investigators attach pingers to the cable a few tens of meters above the sampling bucket so that it is possible to ascertain the depth of the dredge as it is dragged across the ocean bottom. Recently, dredging surveys have been used in conjunction with moored transponder arrays so that the dredge can be positioned relatively accurately when it is on the bottom. No matter how sophisticated the technique, however, fundamental ambiguities inherent in the indirect dredging method persist: the relative abundances of rock types exposed on the ocean floor are not known; the structure of the outcrop cannot be deciphered; the arrangement of the various rock types in space cannot be ascertained. The coherent nature of most gabbroic outcrops, and the difficulty of sampling directly from these outcrops as documented by submersible investigations, suggests that in the majority of cases dredging recovers talus; therefore, no matter how well navigated the dredge track, it is difficult to reconstruct the actual depth at which a given rock type outcrops. Furthermore, in order to investigate the lower crustal components by dredging, it is necessary to explore those regions of the ocean floor that have been subjected to tectonism that creates structural windows down into the crust. Any textural information obtained from these samples may be biased toward fault-related alteration and deformation. Thus the samples recovered by dredging provide important constraints on the variety of rocks that comprise the oceanic crust, and shed light on the igneous and metamorphic processes occurring during the generation and evolution of these rocks, but tell us nothing about the arrangement of rock types in space or the scale of the processes that create and/or modify them.

The rocks recovered during geologic investigations of the sea floor by accurately-navigated deep-diving submersibles provide more information than those recovered by dredging. The investigator can accurately locate and orient the sample, can ascertain the morpho-tectonic setting from which a given sample is recovered and can, through closely spaced sampling, define the vertical and lateral petrologic associations developed within a given area. Deep-diving submersible technology (diving to depths >3000 m) has only recently been developed, and consequently only two field programs have been implemented that have sampled rocks thought to be representative of the lower oceanic crust. Coarsely crystalline gabbroic and ultramafic rocks have been collected at two localities flanking the Mid-Cayman Rise spreading center, Caribbean (CAYTROUGH, 1979), and in a traverse along the flank of the Azores-Gibralter Ridge in the North Atlantic (contiguous to the location of DSDP drill site 120; Auzende, et al., 1978). Although the potential of submersible technology with respect to elucidating the geology of the oceanic crust has yet to be realized, these two investigations have already made a significant contribution to our understanding of the distribution of rocks within the lower oceanic crust. These studies have shown that plutonic rocks may reside at shallow depths within the crust: analysis of sample recovery along traverses up the submarine slopes indicate that gabbroic rocks outcrop at depths up to a few hundred meters below the top of the escarpments in both field areas. It is apparent from these two studies that the stratigraphy of the oceanic crust does not approximate a layer-cake as our geophysical models have indicated. Furthermore, submersible studies have shown that the plutonic portion of the oceanic crust is profoundly heterogeneous. A complex spatial distribution of gabbroic rocks was suggested previously by Engel and Fisher (1975) as a result of analysis of gabbroic rocks collected in a series of dredge hauls from the Indian Ocean. When it was presented, the significance of their interpretation was compromised by the inherent ambiguities of the dredging method, but recently this interpretation has been documented by studies at the Mid-Cayman Rise which show the distribution of gabbroic rocks within the plutonic complex to be heterogeneous at scales ranging from hundreds to tens of meters (CAYTROUGH 1979; DeLong, et al., 1978). In fact, based upon our sampling results, heterogeneity within the lower oceanic crust is so profound that it is not possible to make generalizations about the distribution of specific types of gabbroic rock within the oceanic crust.

The only serious weakness apparent in submersible experiments is that, like dredging, submersible samples are collected from fault-generated escarpments. These rock faces are often modified by mass-wasting that may remove the actual fault plane; nevertheless it is difficult to ascertain whether the properties exhibited by samples collected from this setting are a function of fault-related processes specific to the outcrop or are an accurate reflection of rock properties on a regional scale.

The ideal way to elucidate the properties of the oceanic crust would be to drill a myriad of continuously cored holes through the oceanic crust in all of the world's ocean basins at localities representative of distinctive tectonic settings. Unfortunately, this approach will never be realized because of the lack of economic incentive and the astronomical expense involved. Nevertheless one of the major themes of the Deep Sea Drilling Project has been to learn more about the composition of the oceanic crust through deep crustal sampling. The investigations are ongoing, but to date the GLOMAR CHALLENGER has recovered coarsely crystalline mafic rocks and/or serpentinized ultramafic rocks at three main ocean basin drill sites, all in the North Atlantic: Leg 13, site 120; Leg 37, site 334; Leg 45, site 395. At all three sites plutonic rocks were encountered at shallow crustal levels: beneath 251.7 meters of sediment in core 8 of site 120; beneath 60.5 meters of aphyric to slightly phyric basalt at site 334; beneath roughly 175 meters of aphyric basalt at site 395. Plutonic rocks from both sites 120 and 395 are badly brecciated and altered, and very small sections were recovered. At site 334 a particularly large suite of gabbroic and serpentinized ultramafic rocks were encountered in a complexly interlayered tectonic and stratigraphic sequence. In some sections of the core rubble or breccia zones separate ultramafic rocks from gabbroic rocks; along other intervals anorthositic gabbro, gabbro, noritic gabbro, olivine gabbro and peridotite are interlayered in apparent stratigraphic continuity (see: Aumento, et al., 1977). At site 447, Leg 59 in the Philippine Sea gabbroic xenoliths and xenocrysts were recovered beneath 113 meters of aphyric and phyric basalt (Kroenke and Scott, 1978). The recovery of plutonic rocks at these shallow levels in both main ocean basins and in the Philippine Sea was unexpected, and, with the exception of site 120, the geophysical data indicated that the sites were located on normal oceanic crust. These drilling data lend support to the notion that the distribution of rocks comprising the oceanic crust may be far more heterogeneous than our models presently suggest.

In the preceding paragraphs we have discussed briefly the tools that provide investigators with samples and the strengths and limitations of these investigative tools. We now address a problem that is common to our total collection of oceanic gabbroic and ultramafic rocks. Almost all of these samples have been recovered from slowly accreting plate boundaries, which we believe represents a sampling bias of considerable magnitude. Dredged gabbroic and ultramafic rocks have been recovered from escarpments associated with either the ridge axis of slowly (<4 cm/yr full rate) accreting plate boundaries, or, most commonly, with transform faults that are associated with slowly accreting ridge segments. All three drill sites recovering plutonic rocks from main ocean basins have been positioned in areas that are assumed to have been created at a slow spreading ridge (the Mid-Atlantic Ridge), and both submersible dive sites are located in environments associated with slow accretion rate. Only a handful of plutonic rocks have been recovered from those accreting plate boundary segments that are spreading at full rates greater than 4 cm/yr (Nishimori and Anderson, 1973; Stakes, 1978). It is therefore not presently possible to assess with any certainty the influence of spreading rate on the primary or secondary processes operating along accreting plate boundaries.

Assessment of the outcrop setting from which dredged or submersible-collected samples are recovered reveals an even more profound problem with the plutonic rock data. Slowly accreting plate boundaries, and the transform faults that truncate the ridge axis, breaking the ridge up into short segments, are characterized by morpho-tectonic elements exhibiting relief on the order of hundreds of meters to several thousand meters. The slopes that define this relief have regional gradients of 15^{o} to 25^{o} and, when investigated with a wide-beam echo sounder, they appear to be continuous and unbroken. It is this kind of terrain that has been repeatedly sampled by dredging. The recovery of large quantities of plutonic rocks, which our geophysical models have suggested underlie one to two thousand meters of shallow intrusive and extrusive basaltic rocks, has led investigators to propose that the escarpments that expose the plutonics represent dip-slip faults characterized by throws with magnitudes of thousands of meters. However, Francheteau *et al*. (1976) have plotted the location of numerous dredge hauls that recovered plutonic rocks and show that these rocks were often recovered from localities so high on the escarpment that "normal" thicknesses of oceanic crust cannot be assumed if large-throw faults are responsible for their exposure. Furthermore, recent SEABEAM sounding results clearly show that the topographic relief of the escarpments on which plutonic rocks are exposed actually is defined by a finite number of small-throw (<500 m) near-vertical faults linked to one another by terraces (D. Needham, pers. comm.). This type of relief also characterizes the rift valley walls of the Mid-Cayman Rise: the escarpments on which the gabbroic and ultramafic rocks occur are only on the order of several tens of meters high and never greater than four hundred meters high (CAYTROUGH, 1979). In light of these data, it is difficult to explain the presence of plutonic rocks at shallow levels in the crust by large-throw faults which have tectonically thinned the crust by removing 1500-2000 m of shallow intrusive and extrusive rocks. Moreover, plutonic rocks recovered at all three DSDP drill sites were found at depths of roughly 175 m or less within the crust. These observations suggest that our present collection of plutonic rock samples is not representative of seismic layer three as commonly conceived (located beneath 1-2 km of shallow intrusive and extrusive rocks). Given the shallow crustal levels from which oceanic plutonic rocks have been collected, we may be examining a suite of samples not truly representative of those rocks that comprise the lowermost portions of the oceanic crust. We believe that the gabbroic rocks that have been recovered from the sea floor are representative of some portion of seismic layer three, but that these rocks, emplaced at shallow levels, may have experienced primary and secondary processes that may be significantly different in type or intensity from processes operating at greater depths.

As suggested above, the lack of available data, the indirect nature of dredge sampling, and the financial and technical limitations on drilling frustrate any attempts to codify vertical and horizontal variations in the petrology of the lower oceanic crust. Observations made in ophiolite suites provide some direct indication of the distribution of oceanic crustal rocks and their structural setting (e.g., Moores and Vine, 1971; Upadhyay, et al., 1971; Williams and Malpas, 1972; Church, 1972; Kidd and Cann, 1974; Dewey and Kidd, 1977; Karson and Dewey, 1978; Elthon and Stern, 1978), but the original tectonic setting of these suites is often ambiguous and structural and metamorphic overprinting due to the emplacement of ophiolites is often difficult to distinguish from structural and metamorphic effects inherited from their original environment. Nevertheless, it has been inferred from investigations in ophiolite complexes (see chapters 9 and 10, this volume) that the lower portion of oceanic seismic layer three (directly overlying residual tectonized harzburgitic upper mantle and cumulate ultramafics) may be comprised of a sequence of intercalated ultramafic and mafic cumulates that are overlain, in turn, by mafic cumulates that grade upward into the isotropic gabbros presumed to comprise the bulk of the plutonic portion of the oceanic crust. Unfortunately, the sampling data available at present for the oceanic crust can in no way substantiate or refute this stratigraphy.

Constraints on the petrogenesis of ocean floor rocks have been accumulating through research on the chemistry of abyssal tholeiitic basalts, but until attempts are made to examine in detail the plutonic equivalents of the basalts, appreciation for the dynamics of accretion of the oceanic crust will remain poor. Keeping in mind the limitations addressed in the preceding paragraphs, the following discussion attempts to define the petrologic, metamorphic and chemical characteristics of rocks of the lower oceanic crust in order for us to arrive at a better understanding of the processes that may be responsible for oceanic crustal genesis.

C. Primary Igneous Textures and Mineralogy: the First Order Geologic Nature of the Lower Oceanic Crust

The most abundant plutonic rock types recovered from the ocean floor and therefore those rock types believed to represent the major proportion of the lower oceanic crust, are the metamorphosed and unmetamorphosed members of the gabbro clan (note the range of rock types in Table 1). Olivine gabbro and two-pyroxene gabbro are greatest in number within this population, followed by "normal" gabbro, troctolite, olivine-hypersthene gabbro, Ti-ferrogabbro, norite and anorthosite (references are given in Table 1). The gabbroic rocks recovered from the ocean floor have a characteristic mineralogy and chemistry that distinguishes them as products of differentiation of a tholeiitic magma; coarsely crystalline late-stage differentiates of this series, principally quartz monzonites, aplites and trondhjemites, have been recovered in minor amounts from the Atlantic and Indian Oceans (Thayer, 1969; Aumento, 1969; Miyashiro, et al., 1970; Engel and Fisher, 1969, 1975).

Serpentinized ultramafic rocks, presumed representatives of hydrated upper mantle, have been dredged from many locations in the oceans and have been recovered by drilling (e.g., Aumento, et al., 1977) and by submersible investigations (Auzende, et al., 1978; CAYTROUGH 1979). Bonatti (1976) has suggested that serpentinite diapirs may intrude the oceanic crust to shallow levels; serpentinite screens are observed to cross-cut gabbroic rocks recovered by submersible from the Mid-Cayman Rise (CAYTROUGH 1979). Serpentinized ultramafic rocks may therefore comprise a volumetrically small but significant portion of the oceanic crust. As ultramafic rocks will be discussed in another chapter in this volume (chapter 7) we will not address the details of their mineralogy and chemistry here.

TABLE 1

Gabbroic Rocks and Their Differentiates Recovered from the Ocean Floor

ROCK TYPE REPORTED	SELECTED REFERENCES
GABBRO	AUMENTO, et al. (1977); AUZENDE, et al. (1978); BONATTI, et al. (1970); CANN (1971); CAYTROUGH (1979); CHERNYSHEVA (1970); ENGEL and FISHER (1969); HEKINIAN (1970); HEKINIAN and AUMENTO (1973); HELMSTAEDT and ALLEN (1977); MELSON and THOMPSON (1970); MIYASHIRO et al. (1970); PERFIT (1977); QUON and EHLERS (1963); THOMPSON (1973)
NORITE	BONATTI et al. (1970); CHERNYSHEVA (1970); ENGEL and FISHER (1975); HELMSTAEDT and ALLEN (1977); MELSON and THOMPSON (1970); PRINZ et al. (1976)
TWO-PYROXENE GABBRO	AUMENTO et al. (1977); CANN (1971); CAYTROUGH (1979); HEKINIAN and AUMENTO (1973); HILL (1977); HODGES and PAPIKE (1976); KAY et al. (1970); MELSON and THOMPSON (1970); PERFIT (1977); QUON and EHLERS (1963); THOMPSON (1973)
OLIVINE-HYPERSTHENE GABBRO	CANN and FUNNELL (1967); CAYTROUGH (1979)
OLIVINE GABBRO	AUMENTO and LOUBAT (1971); AUMENTO et al. (1977); BONATTI et al. (1970); CAYTROUGH (1979); ENGEL and FISHER (1975); HELMSTAEDT and ALLEN (1977); HODGES and PAPIKE (1976); MIYASHIRO et al. (1970); SHAND (1949)
TROCTOLITE	AUMENTO et al. (1977); CAYTROUGH (1979); MIYASHIRO et al. (1970)
TI-FERROGABBRO	EGGLER et al. (1973); ENGEL and FISHER (1975); MIYASHIRO et al. (1970)
ANORTHOSITIC GABBRO	CANN (1971); ENGEL and FISHER (1975); PERFIT (1977); QUON and EHLERS (1963); SHAND (1949)
NEPHELINE GABBRO	BONATTI et al. (1970); HONNOREZ and BONATTI (1970); THOMPSON and MELSON (1972)
HORNBLENDE GABBRO	BOGDANOV and PLOSHKO (1967); ENGEL and FISHER (1975); HILL (1977); SCLATER et al., (1978); SHIBATA (1976); THOMPSON (1973)

QUARTZ GABBRO	BONATTI *et al*. (1970)
* TRONDHJEMITE	AUMENTO, 1969; AUMENTO *et al*. (1971); ENGEL and FISHER (1975)
* ANORTHOSITE	ENGEL and FISHER (1969, 1975); MELSON and THOMPSON (1970)
* QUARTZ MONZONITE	ENGEL and FISHER (1975)
* DIORITE	AUMENTO (1969); AUMENTO *et al*. (1971); BONATTI *et al*. (1970); ENGEL and FISHER (1975); THOMPSON (1973)
* QUARTZ DIORITE	AUMENTO (1969); AUMENTO *et al*. (1971); BONATTI *et al*. (1970)
* APLITE	MIYASHIRO *et al*.(1970); THOMPSON (1973); ENGEL and FISHER (1975)
METAGABBRO	BONATTI *et al*. (1970); BONATTI *et al*. (1975); CANN (1971); CAYTROUGH (1979); CHERNYSHEVA (1970); ENGEL and FISHER (1969); FOX *et al*. (1976); HONNOREZ and KIRST (1975); KIRST (1976); MIYASHIRO *et al*. (1970, 1971); PERFIT (1977); PLOSHKO *et al*. (1970); SHIBATA (1976); STAKES (1978).
AMPHIBOLITE	AUMENTO *et al*. (1971); BOGDANOV and PLOSHKO (1967); BONATTI *et al*. (1970, 1971, 1975); CANN (1971); CANN and FUNNELL (1967); CAYTROUGH (1979); ENGEL and FISHER (1975); KIRST (1976); MIYASHIRO *et al*. (1971); PLOSHKO *et al*. (1970); SHIBATA (1976)

* Rarely recovered

Only a handful of authors have presented detailed descriptions of unmetamorphosed oceanic plutonic rocks. A comparatively large number of general sample descriptions are available for fresh gabbroic rocks collected from the Atlantic and Indian Oceans and the Caribbean Sea; as noted above, a small number of gabbroic rocks have been recovered by dredging from the Pacific Ocean but detailed descriptions are limited to our knowledge to a single reference (Stakes, 1978). The fundamental observation that may be extracted from the available descriptions of fresh oceanic gabbroic rocks* is that there is substantial heterogeneity of textures and mineral associations. This heterogeneity is apparent in the entire world-wide collection of oceanic gabbroic rocks as well as within individual suites of samples recovered by dredging (e.g., individual dredges, such as ANTP 125 and the series of dredges discussed by Engel and Fisher, 1975), within a single 1000 m submersible traverse (CAYTROUGH, 1979) or even within a single DSDP drill core (e.g., site 334; Aumento, et al., 1977). For example, grain size in unaltered oceanic gabbroic rocks varies widely, from relatively fine (<1 mm in diameter) to very coarse (≈2 cm), although most of the freshest and least deformed samples described are medium- to coarse-grained (5 mm to 1 cm; see Figures 1a, 2a, b). The textures of these fresh samples are variously described as equigranular (e.g., olivine and pyroxene gabbros from the Mid-Cayman Rise: CAYTROUGH, 1979), hypidiomorphic (olivine gabbro from the Mid-Atlantic Ridge: Shand, 1949; pyroxene gabbro from the Cayman Trough: Perfit, 1977; hypersthene gabbro from DSDP site 334: Hill, 1977), or panidiomorphic, miarolitic, and

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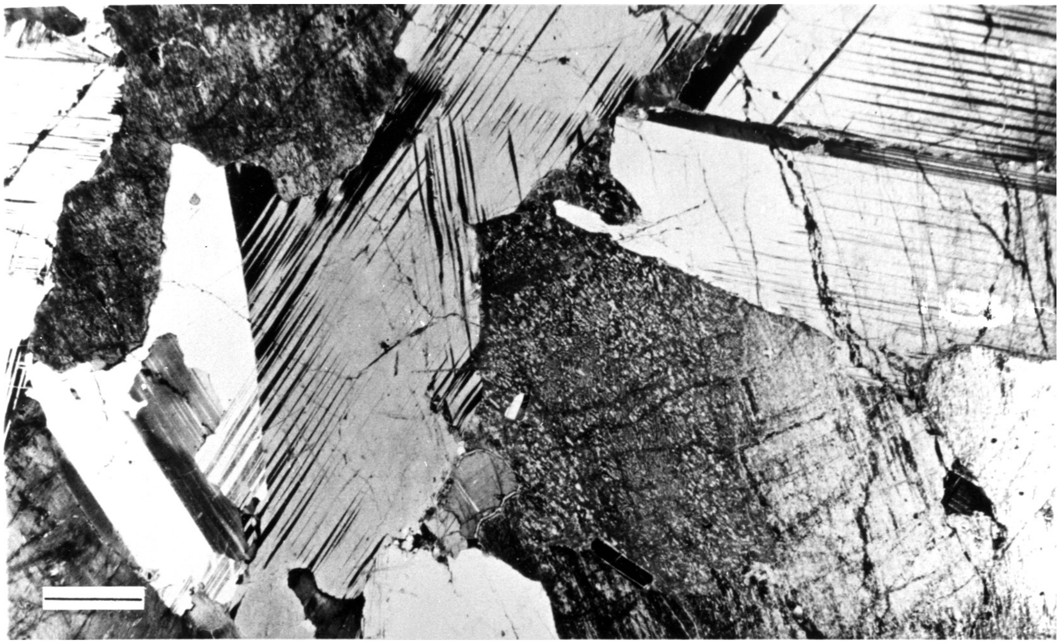
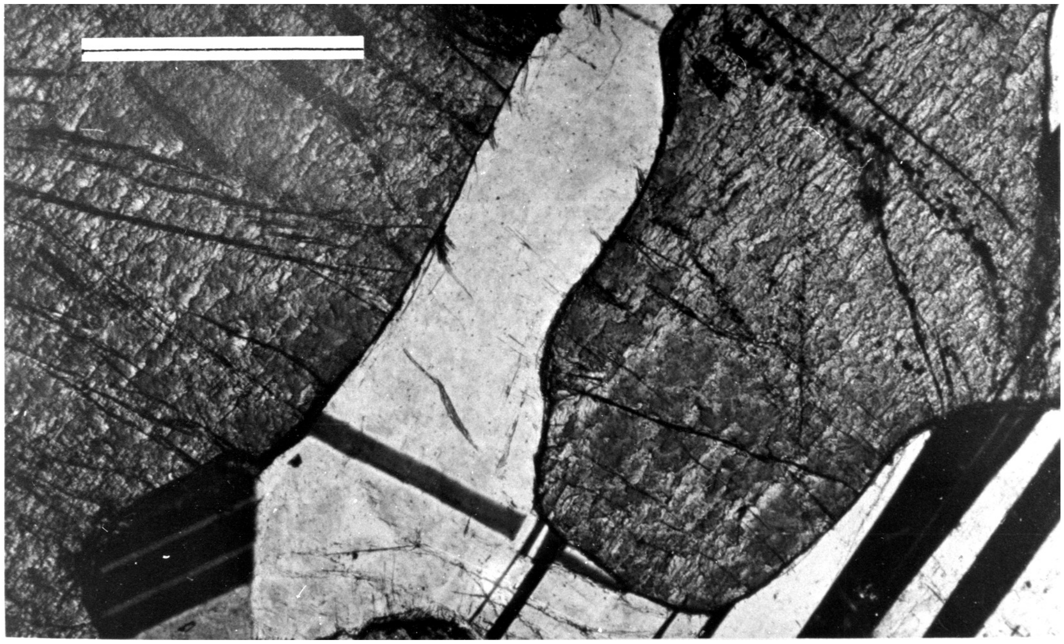
*The term "gabbroic rock" is used in the text to mean rocks that are members of the gabbro clan in general, without reference to their mineralogic or chemical make-up.

<u>Figure 1</u> a. Crossed polar photomicrograph of an essentially undeformed gabbro (sample 615-1-1). Primary phases are plagioclase (white, light grey), clinopyroxene (dark grey), and minor orthopyroxene(?) (mottled mineral at center of picture). Complex exsolution or myrmekitic intergrowth is developed in the orthopyroxene (see Figure 3a). Late-stage microcracks crosscut the slide; plagioclase twins are slightly tapered. Scale bar = 2 mm.

b. Crossed polar photomicrograph of subophitic texture (plagioclase is white, clinopyroxene is dark) in an essentially undeformed gabbro (615-1-1). Scale bar = 0.5 mm.



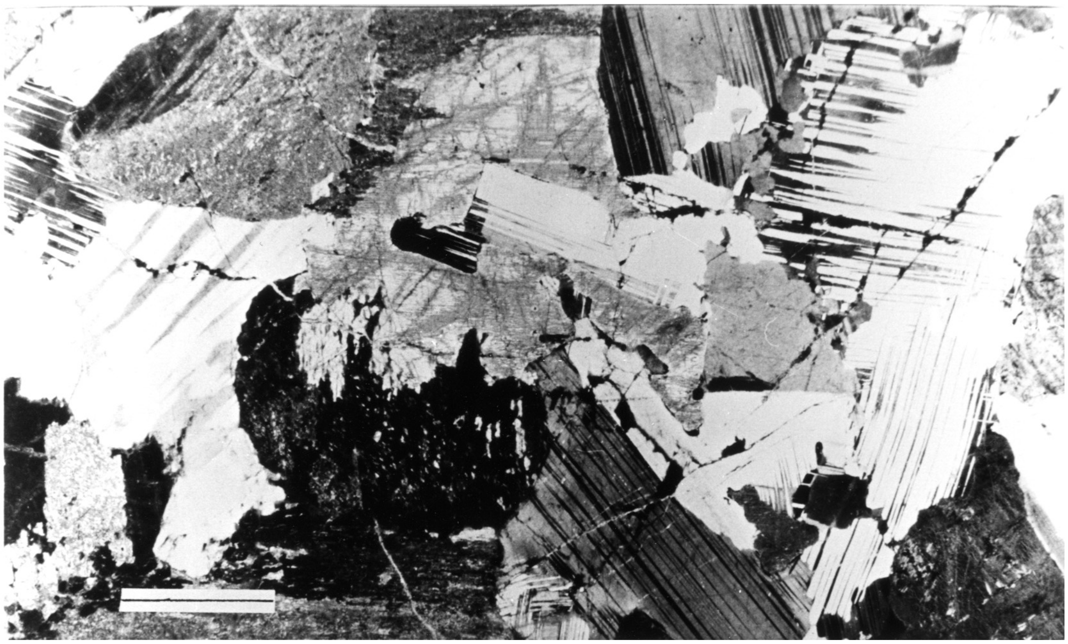
1a



1b

Figure 2 a. Crossed polar photomicrograph of an essentially undeformed gabbro (615-1-1). Note exsolution and intergrowth in clinopyroxenes (e.g., very dark material at the center of the photograph). Incipient metamorphic textures include tapered twins in plagioclase, grain boundary recrystallization of plagioclase, cross-cutting fractures. Scale bar = 3 mm.

b. Crossed polar photomicrograph of an undeformed, incipiently altered olivine gabbro (portion of sample 615-1-1). Olivine (very dark material at lower right) is altering at its margins to opaque oxide + talc + pale green amphibole; the same group of minerals is found in the alteration patch at the center of the photograph. Notice the apparent grain boundary migration of altering fluids from the olivine to pyroxene at upper center of photo. Scale bar = 2 mm.



2a

2b

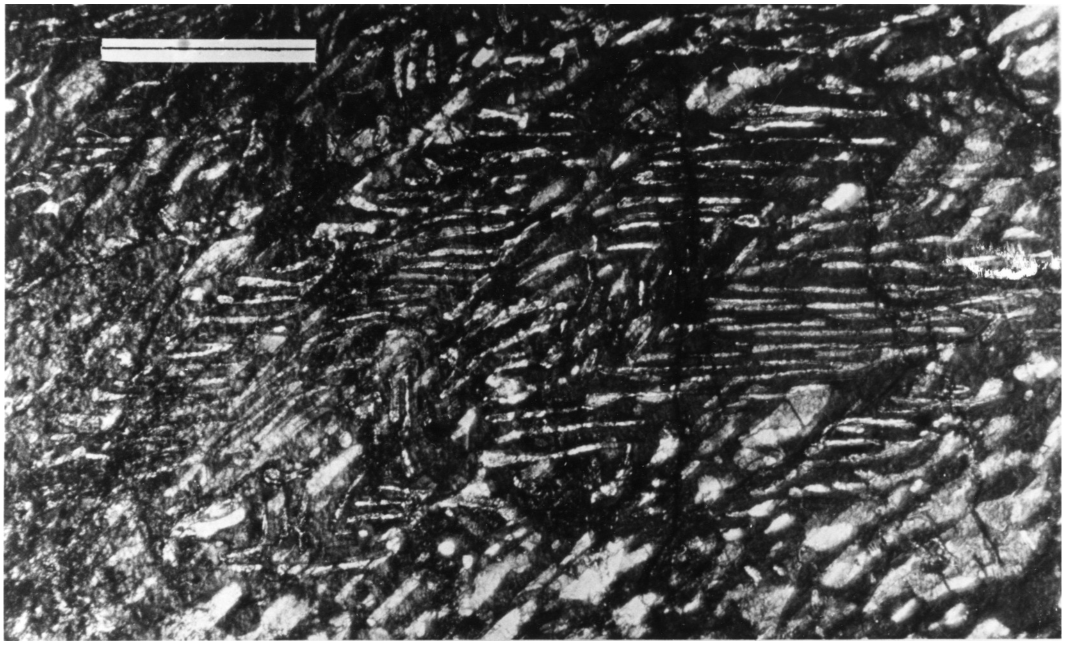
inequigranular (nepheline gabbro from the Mid-Atlantic Ridge: Honnorez and Bonatti, 1970). Ophitic to subophitic textures have been preserved in some of the fresher samples (e.g., Shand, 1949; Fox and Opdyke, 1973; CAYTROUGH, 1979; Figure 1b). Poilikitic texture is common and the minerals involved are extremely variable, such as augite enclosing plagioclase and olivine (e.g., Shand, 1949), or orthopyroxene enclosing olivine, plagioclase and clinopyroxene (Hodges and Papike, 1976).

Based upon examinations of their chemistry (Miyashiro, et al., 1970; Melson and Thompson, 1970; Thompson, 1973), the majority of intrusive rocks recovered from the ocean basins appear to be the product of differentiation of a tholeiitic magma. Many authors have suggested (as we will discuss in the section on chemistry below) that low-pressure fractionation of a tholeiitic liquid in a shallow-level magma chamber involving principally plagioclase, olivine and clinopyroxene (± orthopyroxene ± opaque phases - magnetite, ilmenite, chrome spinel - ± hornblende) can explain the range of plutonic rock types observed in the world's oceans, from the most mafic to the intermediate to the acidic end-members of fractional crystallization. Although the coarsely crystalline samples have observable chemical relationships to the overlying basalts, certain aspects of the nature of magma production and evolution at accreting plate margins are not entirely clear (see chapter 11, this volume; Langmuir, et al., 1977; O'Hara, 1977). For example, one of the more interesting questions to be addressed by petrologists studying oceanic tholeiites is the apparent discrepancy between the relative lack of observed pyroxene phenocrysts in abyssal tholeiitic basalts and the necessity of appealing to low-pressure clinopyroxene fractionation in modelling basalt chemistry. While clinopyroxene is a rare phenocryst phase in the basalts and orthopyroxene phenocrysts are unknown, both clino- and orthopyroxene are extremely common in oceanic gabbroic rocks; indeed, clinopyroxene is almost ubiquitous. Within the population of described gabbroic rocks, the most common clinopyroxene appears to be diallage (augite or diopside with prominent {001} parting) or a clinopyroxene of augitic composition. Hypersthene, bronzite and ferrohypersthene (not common) are reported in oceanic gabbroic rocks; inverted pigeonite has been described by Hodges and Papike (1976) in site 334 two-pyroxene gabbros.

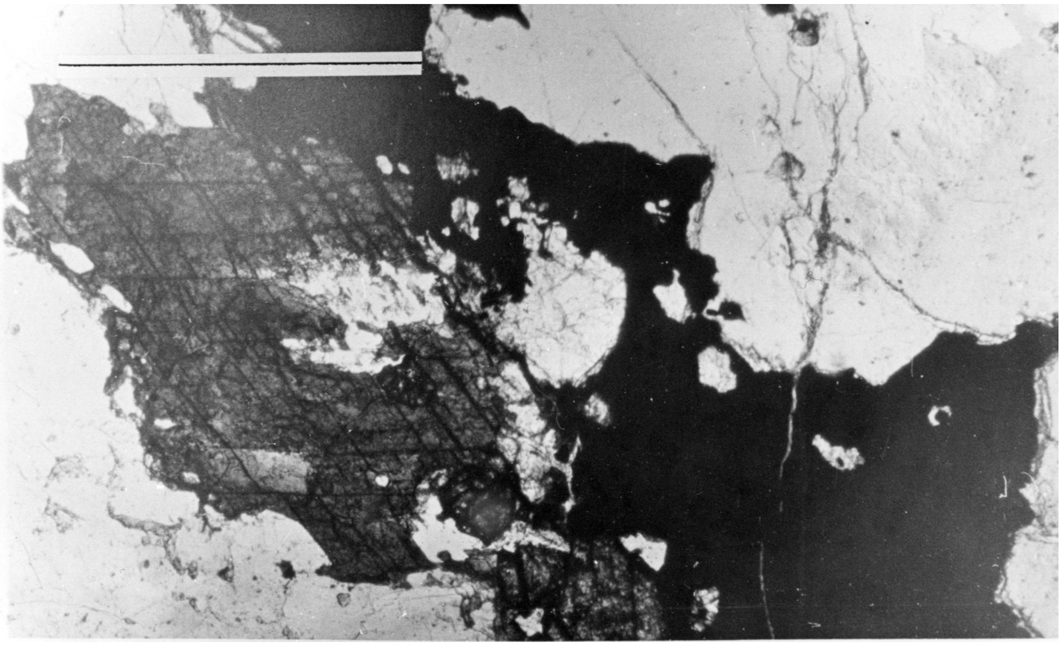
Certain mafic members of the oceanic plutonic suite, notably the two-pyroxene gabbros (both orthopyroxene gabbro and less abundant clinopyroxene norite; all definitions are those of Streckeisen, 1976), are the most abundant within the total population of samples recovered. The two-pyroxene gabbros are comprised of subhedral orthopyroxene, and a subophitic intergrowth of augitic clinopyroxene with calcic plagioclase (often in the range An_{65-75}; however, Hill, 1977, reports normally zoned plagioclase having An_{85-90} in a hypersthene gabbro from site 334). Olivine is often present (Melson and Thompson, 1970; Hekinian and Aumento, 1973). Hodges and Papike (1976) note that their olivine-bearing two-pyroxene gabbros contain trace amounts of primary reddish-brown chrome spinel. Certain interesting intergrowth features have been observed in the pyroxenes in fresh two-pyroxene oceanic gabbros. Exsolution lamellae in pyroxenes, exhibiting a complex variety of patterns and stages of growth, are very common (Figure 3a; exsolution is discussed below as it is of special interest). Vermicular symplectic intergrowths of individual augite crystals that are

Figure 3 a. Crossed polar close-up of complex exsolution lamellae/myrmekitic intergrowth in host orthopyroxene (see Figure 1a). Exsolving and/or intergrown material appears to be principally hornblende. Scale bar = 1 mm.

b. Plain light photomicrograph of a zone, developed in an olivine gabbro (611-2-1A) containing flakes of strongly pleochroic brown hornblende (at left), opaque oxide, apatite (large white patches at center), and zircon (dark grey, high relief material at lower center). The zone is interstitial to recrystallized plagioclase. Scale bar = 0.5 mm.



3a



3b

chemically indistinguishable have been observed in two-pyroxene gabbros from the Palmer Ridge (Cann, 1971), and in our samples from the Mid-Cayman Rise.

Less commonly reported mafic plutonic rocks include olivine gabbro and troctolite, gabbro (*sensu stricto*), and norite (see Table 1). Olivines in two-pyroxene olivine gabbros recovered from DSDP drill site 334 have forsterite contents within the limited range Fo_{86} to Fo_{87} (Hodges and Papike, 1976) and plagioclase with compositions in the range An_{87} to An_{93} (Symes, et al., 1977). Gabbros have been reported quite commonly but are infrequently described. Fragments of a sample recovered from the Ob Trench (Indian Ocean) were described by Hekinian (1970) as comprised of subhedral clinopyroxene, anhedral and strongly optically zoned plagioclase (An_{60-66}), spinel and isolated crystals of brown hornblende. More typically, oceanic gabbros consist principally of augite, occasional olivine and a plagioclase having a somewhat lower anorthite content than is observed in the two-pyroxene or olivine gabbros. Norites and troctolites appear to comprise only a small percentage of the total population of oceanic gabbroic rocks.

Intermediate to acidic end-members of a differentiating tholeiitic magma are also proportionately rare in the population of oceanic plutonic rocks, but their occurrence has suggested to many authors that a fractional crystallization process similar to that observed in the Skaergaard intrusion, east Greenland (Wager and Deer, 1939), is operative within magma chambers at accreting plate boundaries (e.g., Miyashiro, *et al*., 1970). A genetic relationship between certain acid differentiates and spatially associated basalts was confirmed by Aumento (1969), who was able to correlate their ages, major and trace element chemistry and δO^{18} ratios. A Ti-ferrogabbro representative of those recovered elsewhere (i.e., Miyashiro, et al., 1970; Eggler, et al., 1973) was dredged by Engel and Fisher (1975) from the Argo fracture zone and contains large, branching grains of ilmenomagnetite enclosing titaniferous augite, hypersthene and andesine. Two samples of ilmenite norite have been described by Prinz, et al. (1976). Both samples contain plagioclase (An_{37-67} in one, An_{37-41} in the second), orthopyroxene, ilmenite and magnetite, and clinopyroxene occurs in one of the samples. Fragments of highly sodic aplitic rocks, similar to aplites reported from the Mid-Atlantic Ridge (Miyashiro, et al., 1970), and a quartz monzonite dikelet cutting a granophyric diabase were dredged from the Argo fracture zone (Engel and Fisher, 1975). The quartz monzonite is fine-grained, micropegmatitic, and consists primarily of quartz and subhedral zoned oligoclase and orthoclase, with minor biotite, hornblende, apatite, magnetite, sphene and zircon. A representative trondhjemite, recovered from the Mid-Atlantic Ridge, contains plagioclase (An_{20} cores to An_5 rims), hornblende, biotite, quartz and opaques, and 24% of the rock is comprised of an intergrowth of K-feldspar and albite (Aumento, et al., 1971).

Diorites and hornblende gabbros are reported by several authors. Within the site 334 drill core, Hill (1977) describes a hornblende gabbro, in which primary clinopyroxene is mantled by dark green-brown "magmatic" hornblende, which also occurs interstitial to the primary plagioclase and clinopyroxene. A very small number of similar samples have been recovered by us from the Mid-Cayman Rise. Aumento (1969) and Aumento, et al. (1971) have described a selection of rocks recovered from 45° N in the mid-Atlantic as hornblende-rich quartz diorites. These samples contain twinned and zoned crystals of plagioclase (An_{40-45} cores to An_{15} rims) and dark green euhedral crystals of hornblende occasionally replaced by biotite; a single clinopyroxene crystal, which Aumento and coworkers (1971) suggest is a xenocryst; occurs with a rim of green hornblende in one sample. Minor phases in the quartz diorites include sphene, apatite, zircon and opaques (magnetite and chrome spinel). In describing one of the only reported anorthosites recovered from the ocean floor, Engel and Fisher (1969, 1975) note that the sole mafic phase associated with labradorite other than minor magnetite, is a primary red-brown hornblende. The origin of the hornblende in these samples and the source of the water necessary for its production are of interest. Certain hornblendes, as in the two-pyroxene gabbros dredged from the Palmer Ridge, may have been produced by subsolidus reactions, as Cann (1971) suggests based upon his observation that the amphibole reaction rims surround areas of olivine alteration in contact with plagioclase. In general, however, two processes may account for the production of what are interpreted to be primary or magmatic hornblendes: (1) prolonged fractional crystallization, enriching the last-crystallizing liquid in juvenile water necessary for hornblende formation, or (2) admission of seawater to depths in the oceanic crust sufficient to permit seawater interaction with the semi-crystalline material of the still-hot oceanic layer. This discussion will be pursued in the next section in this chapter.

Certain plutonic rocks recovered from the ocean floor are rare enough to be considered anomalous, but have received some attention in the literature. A single nepheline gabbro, recovered from the Romanche fracture zone, was described by Honnorez and Bonatti (1970) as comprised of titaniferous augite which grades into aegirine and has an ophitic relation with zoned plagioclase (An_{20-70}), and they note the presence in this sample of modal nepheline (=9% of the rock made). Minor phases observed in this rock include biotite, sphene and magnetite. This sample was later examined by Prinz, et al. (1976) who, although they could find no modal nepheline in their polished sections (and therefore termed it a teschenite), confirmed the alkalic nature of the rock and the compositions of the other major phases as reported by Honnorez and Bonatti (1970). A second sample described by Honnorez and Bonatti, having normative but not modal nepheline, contains plagioclase (An_{45-55}), and diopside, which appears to have a reaction relationship with rimming hornblende. Minor amounts of primary(?) apatite, zircon and magnetite are also present. The first sample is unique among oceanic plutonics, and as the authors describe it, is a truly silica-undersaturated rock. Rocks having only normative nepheline, however, may not be silica undersaturated, since nepheline-normative compositions might be produced by metasomatic enrichment in alkali elements during alteration (D. Elthon, pers. comm.). A large number of plutonic rocks having nepheline in the norm were also recovered by us from the Mid-Cayman Rise, but none of our samples contain modal nepheline.

The recovery of a fairly large suite of plutonic rocks from widely dispersed regions of the ocean floor is evidence that magma chambers operate at shallow levels in the oceanic crust. Most of these plutonic rocks presumably evolved in magma chambers beneath the axis of spreading of the mid-oceanic ridge system, and there is evidence to suggest that these magma chambers are a part of a complex and dynamic system (see the papers by O'Hara, 1977 and Rhodes, et al., 1979, on magma mixing).

Unfortunately, the nature of magma chamber processes cannot be documented solely by examination of textures in oceanic gabbroic rocks. For example, cumulate textures have been described by a number of authors examining fresh oceanic plutonic rocks. Melson and Thompson (1970) observe a fine-grained (<1 to ≈2 mm) plagioclase cumulate with well-defined parallel orientation of subhedral plagioclase laths enclosed by large poikilitic pyroxenes (augite and less abundant hypersthene) in a sample from the equatorial Atlantic. They also note that some of the coarser-grained gabbros (averaging 1.5 cm) from this area appear to be layered, and they suggest that the concomitant layering and large grain size in their samples are characteristic only of very large, stratiform continental intrusions (i.e., Stillwater or Skaergaard). Eggler, et al. (1973), in a discussion of dredged samples from the Cayman Trough, and Engel and Fisher (1975), in their paper on rocks collected from the western Indian Ocean, have reported Ti-ferrogabbros containing abundant plagioclase and pyroxene and having "pronounced" cumulate textures; in addition, Engel and Fisher observe that other gabbros collected from the Indian Ocean exhibit "faint layering" on the order of 8 to 10 cm in thickness. Perfit (1977) has observed cumulate textures in pyroxene-rich (>50%) and "anorthositic" gabbros (actually leuco-gabbros, with >75% plagioclase) dredged from the Cayman Trough. Aumento, et al. (1977) report that primary magmatic cumulates of plagioclase and olivine (olivine gabbros or troctolites) and of plagioclase and clinopyroxene (olivine-free gabbros) were recovered by the Deep Sea Drilling Project (site 334) from the North Atlantic. Relative to the total population of gabbros collected from the ocean floor, however, (as noted by Melson and Thompson, 1970) distinctive textural cumulates appear to be rare. In fact, the observation of thin-section scale cumulate textures may not be indicative at all of the origin of the rock by cumulate processes. Pike and Schwarzman (1976) have suggested that observation of textures in thin section fitting the cumulate textural classification of Wager, *et al*. (1960) are not sufficient to infer a gravity settling origin for a rock. Outcrop-scale discontinuous layering has been observed in the non-cumulate isotropic gabbros of the Bay of Islands ophiolite complex (E. Rosencrantz, pers. comm.). From submersible observations on the rift valley walls of the Mid-Cayman Rise, CAYTROUGH (1979) note the presence of subtle bands of a few centimeters width on the face of outcrops that prove to be comprised of undeformed gabbro lacking cumulate textures in thin section. Rocks collected from the cumulate gabbro section within the Bay of Islands ophiolite exhibit no evidence in thin section of a cumulate origin, and samples collected from within the isotropic gabbros appear in thin section to be exemplary orthocumulates (J. Casey and E. Rosencrantz, pers. comm.). We suggest that without supportive mesoscopic evidence the inference of a cumulate origin for a rock based only upon thin-section-scale criteria is not necessarily valid, and that assumptions about the size or the shape of the magma chamber or the existence at a large scale of gravity-stratified layered complexes at accreting plate margins may not be justified given only these small-scale criteria. It may be possible, however, to infer the operation of processes that should predict the formation of cumulate rocks given certain chemical criteria (e.g., depletion of the rock in incompatible elements relative to their abundance in associated basalts). Further discussion of this is presented in the section on chemistry, below.

A small number of studies have attempted recently to address the question of temperature and depth of formation of oceanic gabbroic rocks (e.g., Hodges and Papike, 1976; Hill, 1977). These authors have devoted much discussion to the composition and crystallographic orientation of exsolution lamellae observed in clino- and orthopyroxenes in the site 334 gabbroic rocks. Exsolution lamellae in both types of pyroxene are a common feature in oceanic plutonic rocks (see Figures 1a, 2a, 3a). Lamellae of diopside in hypersthene were noted in a two-pyroxene gabbro by Quon and Ehlers (1963), and in an ilmenite norite by Prinz, et al. (1976). Lamellae in clinopyroxenes have been reported in many samples, and the lamellae may be comprised of orthopyroxene (Melson and Thompson, 1970; Hodges and Papike, 1976; Hill, 1977; Perfit, 1977; CAYTROUGH, 1979), iron oxide (Hekinian, 1970; Eggler, et al., 1973; CAYTROUGH, 1979) and/or hornblende (Hodges and Papike, 1976; CAYTROUGH, 1979). Noting that a complex variety of forms are exhibited in the exsolution lamellae even within a single crystal in the site 334 rocks, Hodges and Papike and Hill conclude that their gabbroic rocks have experienced very slow cooling. Crystallization of the pyroxene is suggested by Hodges and Papike to occur at 1200°C, and Hill maintains that subsolidus exsolution occurred down to at least 810°C. The high temperatures required for pyroxene crystallization implied to Hodges and Papike that formation of these gabbroic rocks occurred at depths of 3 to 8 km within the crust. Once again, however, we caution that inference of very large-scale processes from only a few fine-scale criteria may not be completely justifiable. It is difficult to envision a process that could account for fairly deep-level crystallization of rocks recovered from a depth of only 60 m within the oceanic crust. Furthermore, the degree of variability within even the site 334 plutonic suite renders gross comparisons with continental plutonic complexes useless. For example, Hodges and Papike (1976) note that the crystallization sequence inferred for the site 334 two-pyroxene gabbros (early crystallization of plagioclase and late appearance of orthopyroxene) is similar only to Rhum among continental stratiform complexes; yet these authors also note that the exsolution features observed within the site 334 pyroxenes are comparable only to those of the Bushveld and Stillwater continental complexes. Although some authors (e.g., Clarke and Loubat, 1977) suggest that the rocks within the site 334 core comprise a rhythmically layered sequence, this type of interpretation is rendered doubtful, as suggested by Flower, *et al*. (1977), by the presence of numerous breccia zones distributed throughout the sequence.

In view of the heterogeneities observed in oceanic gabbroic rocks, the paucity of field experiments that define the details of the igneous stratigraphy of the plutonic foundation, and the present lack of sufficient petrographic and experimental data, we suggest that it is difficult to infer the operation of a specific set of processes in the formation of the gabbroic rocks comprising the lower oceanic crust. Our present models of accretion, based largely upon observations made in ophiolites, do not explain satisfactorily the recovery of these plutonic rocks from shallow levels in the oceanic crust; we cannot envision a structural solution to resolve the discrepancy between observations in ophiolites and interpretation of the geophysical data and our sampling results. Moreover, it is unlikely that a comparison of the dynamic environment of an accreting plate boundary, characterized by the episodic replenishment of the magma chamber by liquids derived by partial melting of upper mantle sources and characterized by steep thermal gradients produced by convective heat loss, with the relatively short-lived magmatic events producing continental stratiform complexes is valid. Two general observations have emerged from our review of the literature discussing the gabbroic rocks representative of the lower oceanic crust: (1) these rocks are formed and evolved within crustal magma chambers (some of which are apparently quite shallow) present at axis of accretion of the mid-oceanic ridge system, and, as demonstrated by their chemical compositions, are the product of differentiation of a tholeiitic magma; and (2) the heterogeneities observed with respect to primary mineral associations appear on a scale much finer than our geophysical tools can presently resolve.

D. Metamorphic Textures and Mineralogy: Evolution of Rocks Comprising the Lower Oceanic Crust

Metamorphism, defined as "mineralogical and structural changes of rocks" (Miyashiro, 1973), affects to varying degrees almost all of the rocks believed to comprise the lower oceanic crust and that occur in sample collections from all of the world's oceans. A large number of hypotheses have been advanced to explain the processes of ocean floor metamorphism (see Kirst, 1976, for a short review); more detailed treatment of these models is presented in chapter 8 of this volume. In the present chapter we attempt to define, based upon our observations of textures and mineralogic associations, those processes specifically contributing to the alteration and deformation of oceanic plutonic rocks.

As has been stressed by Miyashiro, et al. (1971), metamorphic processes operative within the oceanic crust appear to differ fundamentally from those affecting regionally metamorphosed continental rocks. Relatively few rocks recovered from the ocean floor are texturally schistose or gneissic (although coarse-grained rocks that have been dynamically metamorphosed to mylonites, cataclasites, and tectonic breccias are common: Shand, 1949; Quon and Ehlers, 1963; Miyashiro, et al., 1971; Honnorez and Bonatti, 1975; Perfit, 1977). At the largest scale, metamorphic grade appears to increase with increasing depth in the oceanic crust: most metabasalts are found in the zeolite to greenschist facies, while metagabbros are metamorphosed principally to the greenschist to amphibolite facies (Miyashiro, et al., 1971; Aumento, et al., 1971; Cann, 1971; Miyashiro, 1973; Bonatti, et al., 1975; Kent, et al., 1978; Cann, 1978). Metamorphism in the metagabbros, however, appears to be retrograde, resulting in the superposition of increasingly lower facies mineral assemblages on the antecedent metamorphic mineralogy (e.g., Elthon and Stern, 1978; Cann, 1978) and therefore the coexistence of greenschist facies mineral assemblages with minerals characteristic of the amphibolite facies.

Current discussions on metamorphism of the oceanic crust use the terms derived from studies of continental terrains, based upon metamorphic facies names established by Eskola (1939) and Coombs (1961) and adopted for use by most authors discussing ocean floor metamorphism (see Miyashiro, et al., 1971; Miyashiro, 1973). In the assimilation of the following observations, it has become apparent to us that equilibrium assemblages of minerals typical of any one of these facies are exceedingly rare in oceanic plutonic rocks. It may be that a closer examination of the apparent equilibrium metamorphic mineral assemblages present in oceanic plutonic rocks could render fruitful results (see, for example, Elthon and Stern, 1978). Miyashiro, et al. (1971) noted in some of their samples the persistence of calcic plagioclase throughout the alteration of coexisting mafic phases to low-temperature metamorphic minerals (actinolite and chlorite); these authors suggest that the association of calcic plagioclase + actinolite + chlorite may represent a new low-pressure metamorphic facies. This assemblage has been recognized by other authors examining metamorphosed oceanic plutonic rocks (e.g. Shibata, 1976; Helmstaedt and Allen, 1977). Epidote, present in many finer-grained oceanic rocks, is rare in oceanic metagabbros; this is interpreted by Elthon and Stern (1978), who observe a decrease in the amount of epidote present with an increase in depth in the Sarmiento ophiolite complex, to indicate a reduction in P_{O_2} with depth in the oceanic crust. An interesting discussion of apparent paragenetic sequences in oceanic metagabbroic rocks has been presented by Kirst (1976), but we believe that more work is necessary before it will be possible to understand metamorphic mineral paragenesis in oceanic metagabbros.

The lack of truly fresh oceanic gabbroic rocks relative to altered oceanic gabbroic rocks is remarkable and has led some authors to refer to only the most severely altered plutonic rocks as "metagabbros." For the purposes of simplification, we will refer to metamorphosed oceanic gabbroic rocks, regardless of the degree of such metamorphism, as "metagabbros" when we are discussing general observations or inferences (see also Table 1). The reader should be wary of the usage of this term here and in general, however, and should keep in mind that both truly fresh oceanic plutonic rocks and true oceanic metagabbros (those most severely altered) are rare in the total population of oceanic plutonic rocks.

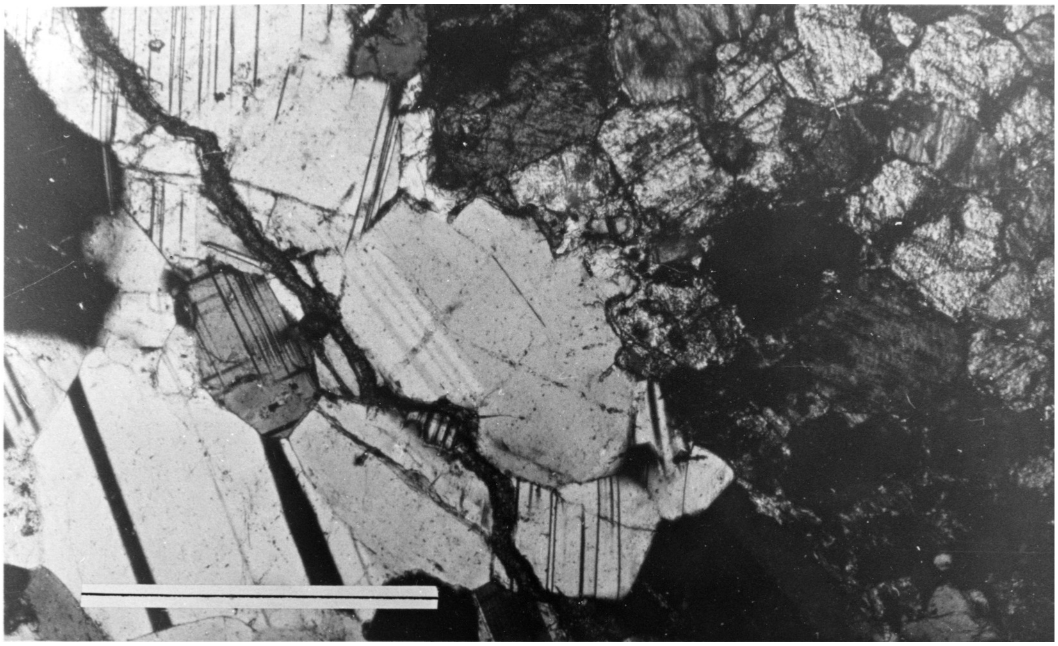
In most of the literature discussing oceanic metagabbros, the technique used for mineral identification is principally that of optics, and only rarely are microprobe analyses or x-ray diffraction analyses of individual minerals available. The type of identification technique used is crucial for discussions of the amphibole(s) present in a metagabbro. It can be demonstrated that, on the basis of optical properties alone, it may not be possible to distinguish between an actinolite, actinolitic hornblende or a hornblende (J. Honnorez and F. Malcolm, pers. comm.). Furthermore, microprobe analyses of fibrous blue-green amphiboles identified optically as "actinolites" give identical chemical compositions as those of some blocky brown amphiboles identified optically as "hornblendes" (D. Elthon and F. Malcolm, pers. comm.). Since the proper identification of the amphibole present in a metamorphic rock is essential for estimation of the temperature regime of amphibole formation, the lack of microprobe or x-ray diffraction data makes interpretation of temperatures of metamorphism difficult. During our discussion of brown hornblende formation, we will use observations that are substantiated by chemical analysis; however, during our discussion of general petrographic features we must rely on amphibole identification made largely by optical methods.

The first minerals in oceanic metagabbros that appear to be affected by metamorphism, as noted by Cann and Funnell (1967) and Cann (1971), are olivine and orthopyroxene. The principal replacement minerals after olivine are iddingsite, talc and magnetite (Kent, et al., 1978; CAYTROUGH, 1979; Figure 2b), flaky pale green actinolite (Cann, 1971; Kirst, 1976), and occasional calcite (Kirst, 1976). Kirst (1976) observes that cores of olivine are rimmed successively by talc + magnetite, pale green actinolite and chlorite, and that the cores themselves are crosscut by fractures infilled with iddingsite; further alteration reduces the olivine cores to actinolite + magnetite. Hodges and Papike (1977) observe that the degree of alteration of samples from DSDP site 334 is a direct function of the amount of olivine present. Orthopyroxene is principally replaced by pale green bladed (Kirst, 1976; CAYTROUGH, 1979) or flaky (Cann, 1971) actinolite, although Kirst (1976) identifies an interior zone comprised of possible tremolite in one orthopyroxene. Kirst notes that other replacements of orthopyroxene include talc and magnetite, and a brown actinolitic hornblende replaces the actinolite surrounding orthopyroxenes in several of his samples when the orthopyroxene is in contact with a primary opaque phase. Clinopyroxenes in oceanic metagabbros tend to be relatively stable throughout metamorphism, although the high-temperature recrystallization that often appears to be concomitant with granulation or brecciation of the rock affects clinopyroxenes (see Figure 4a), and recrystallized aggregates may be intergrown with biotite and/or brown hornblende (Chernysheva, 1970; CAYTROUGH, 1979). Alteration of clinopyroxenes produces principally actinolite or uralite, or green to blue-green hornblende (Cann, 1971; Chernysheva, 1970; Ploshko, et al., 1970; Kirst, 1976; Helmstaedt and Allen, 1977; CAYTROUGH, 1979); brown hornblende is often found in a rimming relationship with clinopyroxene, but its chemistry and occurrence frequently indicate that it may be a primary phase (this is discussed further below).

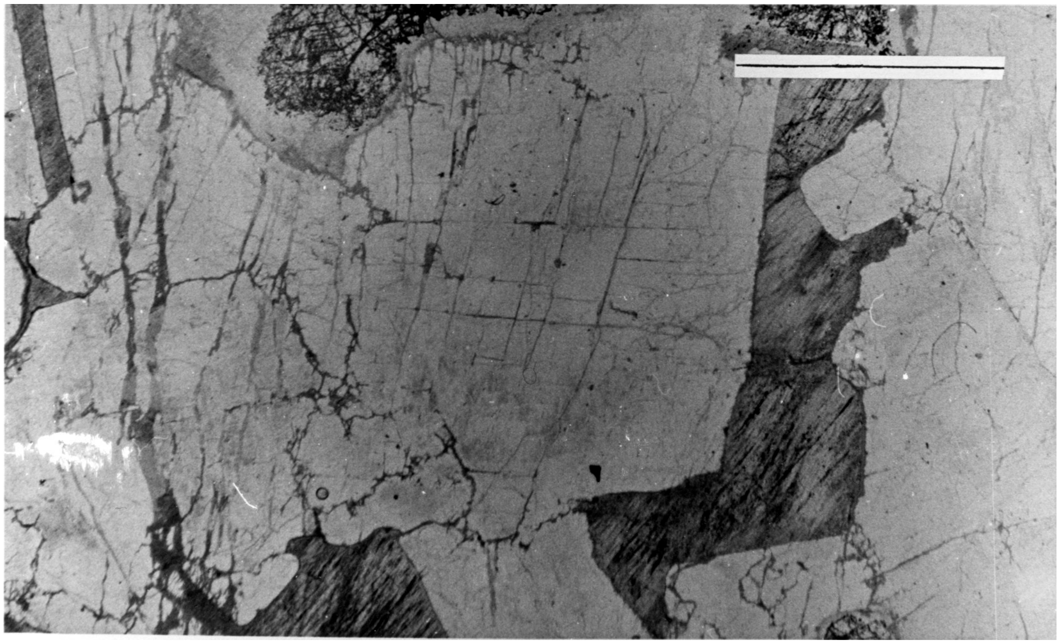
Plagioclase appears to be the mineral in the plutonics that is most resistant to alteration, retaining a subhedral shape and calcic

Figure 4 a. Crossed polar photomicrograph of recrystallized plagioclase (white and light grey at left) and recrystallized clino- and (minor) orthopyroxene (dark grey at right) in a gabbro (613-1-2). Cross-cutting fracture is infilled with chlorite. Scale bar = 0.5 mm.

b. Plain light photomicrograph of chlorite-filled cracks crosscutting plagioclase and "feeding" marginal alteration of the mafic phases olivine (top of picture) and clinopyroxene (light grey material). Scale bar = 5 mm; sample number 741-4-1.



4a

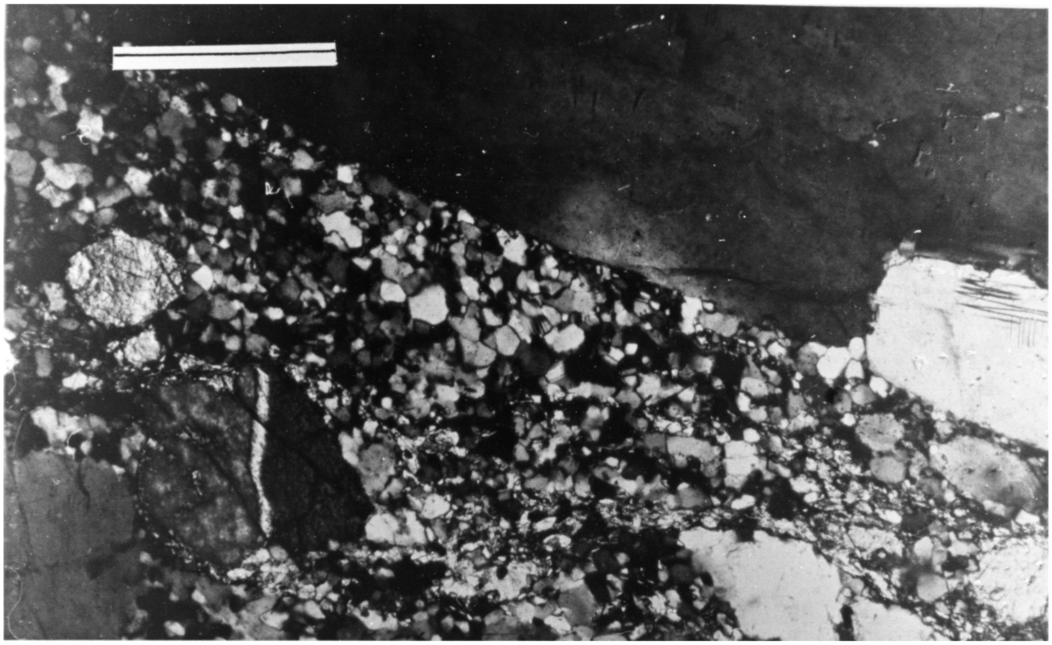


4b

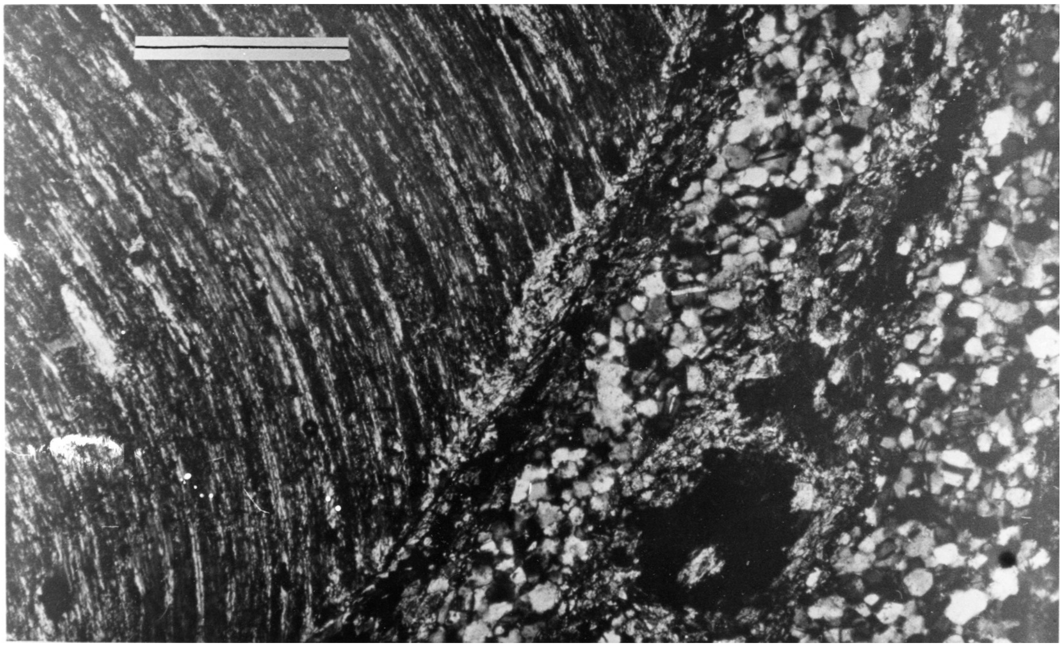
composition long after primary mafic phases have been partially to completely replaced by secondary phases. Plagioclase is recrystallized in many samples but large calcic plagioclase porphyroclasts are almost always preserved in a matrix of recrystallized fragments; in contrast, where clinopyroxenes appear to be preserved as porphyroclasts in more altered and deformed rocks close examination reveals them to have been totally pseudomorphed by green to brown amphibole (for example, Figures 5b, 6b). Shibata (1976) observed in his samples that, while pyroxene and hornblende are susceptible to recrystallization and are replaced by actinolite and chlorite, the behavior of plagioclase appears to be brittle (grains are "strained, bent, ruptured and brecciated"). Cann and Funnell (1967) observed zeolites replacing plagioclase in their more altered samples, and Chernysheva (1970) observed the appearance of saussurite after plagioclase in his more altered samples. Chemical compositions of remnant and recrystallized plagioclases have been discussed by many authors. Reduction of An content in the plagioclases from high-An composition of relict primary plagioclase to low-An composition of recrystallized aggregates is commonly noted, together with an apparent compositional hiatus between the two generations. For example, Ploshko, et al. (1970) observed plagioclase porphyroclasts of untwinned labradorite (An_{60-65}) with resorbed edges and with cross-cutting cracks infilled with a more sodic plagioclase; recrystallized aggregates surrounding the porphyroclasts are oligoclase - andesine (An_{28-35}) that occasionally show polysynthetic albite twinning. Similar observations were made by Bonatti, et al. (1975) who describe An_{20} plagioclase in fractures cross-cutting large, rounded and zoned remnant plagioclase (An_{60} cores to An_{20} rims).

Figure 5 a. Crossed polar photomicrograph of a portion of a zone of deformation in an otherwise undeformed gabbro (sample 739-6-1; zone comprises roughly one-third of the thin section). Material at top portion of photograph is essentially undeformed plagioclase; material at lower portion of photograph is recrystallized and brecciated plagioclase matrix with small clinopyroxene porphyroclasts. Within deformed zone incipient fluxion structure is the result of alignment of slightly elongated clinopyroxenes and subparallelism of fibrous-amphibole-filled veins. Scale bar = 0.5 mm.

b. Crossed polar photomicrograph of deformed clinopyroxene (largely psuedomorphed by green-brown amphibole). Altered margin of the pyroxene contains small flakes of green amphibole + opaque oxide. Matrix material is recrystallized plagioclase; altered zone at right is comprised of flaky green amphibole + opaque oxide. Scale bar = 0.5 mm; sample number 737-1-1.



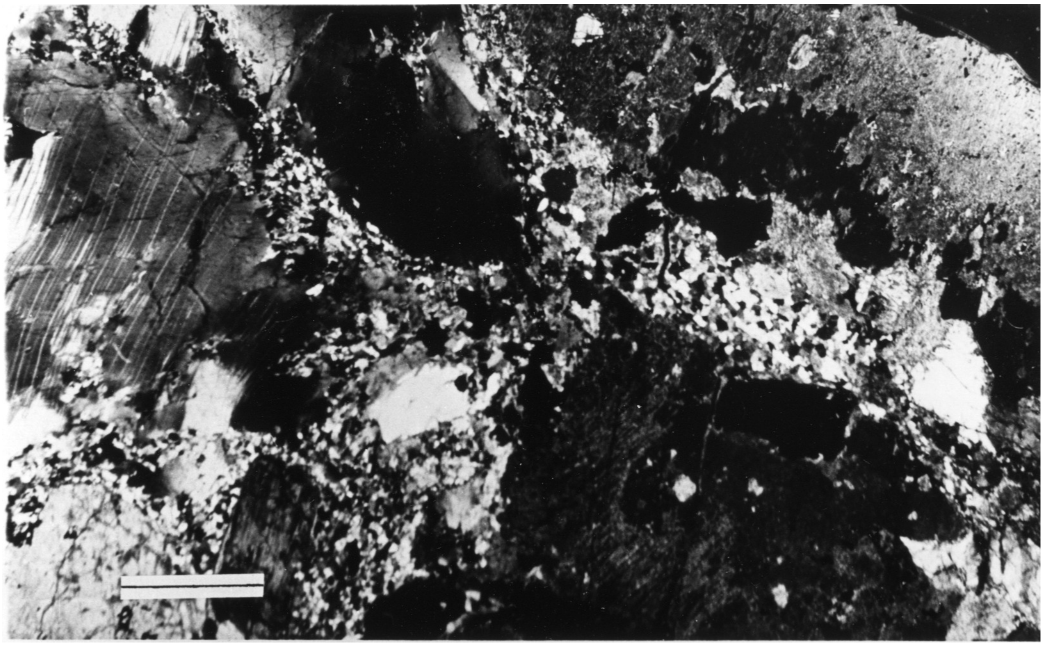
5a



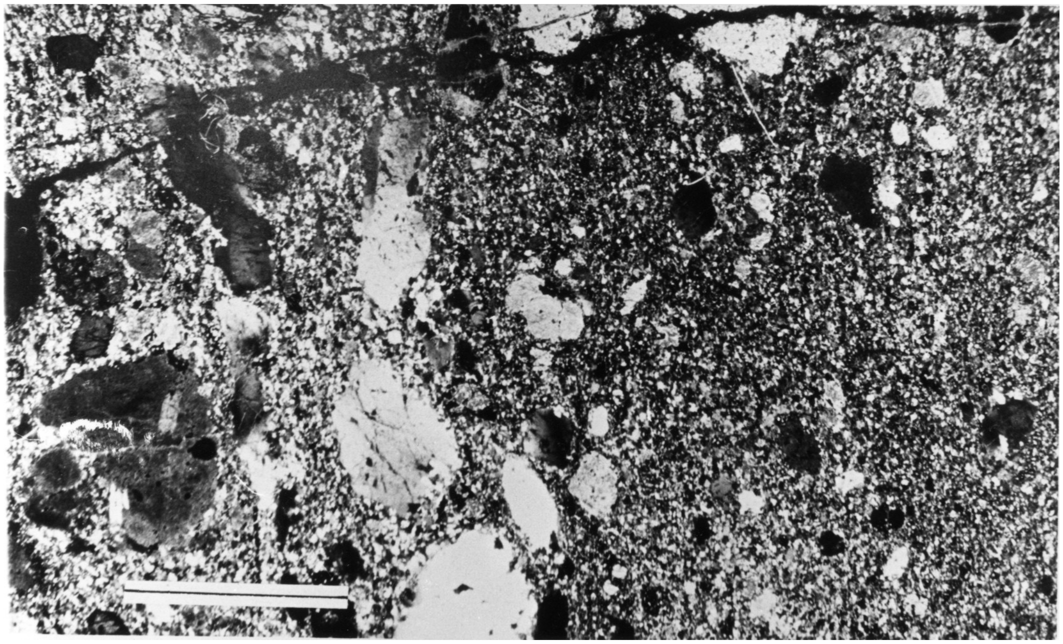
5b

Figure 6 a. Crossed polar photomicrograph of metamorphosed orthopyroxene gabbro (739-4-2). Porphyroclasts of plagioclase, clinopyroxene and orthopyroxene are surrounded by fine-grained recrystallized plagioclase. Large plagioclase porphyroclast at left has bent and tapered twin lamellae. Scale bar = 5 mm.

b. Crossed polar photomicrograph of deformed gabbro (611-4-1A). Slight fluxion structure, perpendicular to length of photograph, is apparent. Porphyroclasts are plagioclase and clinopyroxene, matrix is plagioclase. Scale bar = 4 mm.



6a



6b

Chernysheva (1970) noted two generations of plagioclase in his metagabbros: in the first, large tabular grains of bytownite (An$_{75-78}$) have albite-pericline twins; in the second, smaller grains of andesine-labradorite (An$_{45-50}$) grade inward to labradorite and have albite and combined twins.

Helmstaedt and Allen (1977) examined the compositions of relict primary and recrystallized clino- and orthopyroxenes and plagioclase in a site 334 gabbronorite. They found that primary clinopyroxenes are replaced by amphibole and by recrystallized clinopyroxene having slightly higher FeO and TiO_2 and lower CaO contents than observed in the remnant phases. Hypersthene is totally disaggregated, with both generations exhibiting nearly identical chemistries. Unzoned primary plagioclase crystals (An$_{85-90}$) have albite and pericline twins, and recrystallized grains (An$_{65-80}$) are strongly zoned and have albite twins.

The mineral hornblende is recognized commonly in oceanic metagabbros, and the nature of its formation has been discussed by a number of authors. Brown hornblende has been recognized as "primary" phase in fresh to slightly altered oceanic gabbroic rocks by Miyashiro et al. (1970), Chernysheva (1970), Thompson (1973), Kirst (1976), Hill (1977) and CAYTROUGH (1979), and has been recognized in greenschist to amphibolite facies metagabbros containing plagioclase and remnant augite in which the hornblende is of questionable origin (Shibata, 1976). The common hornblende reported by Shibata (1976) pseudomorphs or rims augite, and is optically zoned with a pronounced change in color from a brown interior to a rim of green or blue-green. Despite the high degree of alteration that has apparently affected his samples, Shibata notes that the association of hornblende and augite is not necessarily indicative of the metamorphic production of hornblende; the same association would result if augite were to react with the hydrous magma during crystallization. Furthermore, he suggests that without strong internal deformation it would be difficult to distinguish amphibolite facies metagabbro from a pure igneous hornblende gabbro. Shibata concludes that the production of the plagioclase - hornblende gabbros that he observes (and which, according to him, have been reported by other authors as amphibolites; see: Bogdanov and Ploshko, 1967; Ploshko, et al., 1970; Bonatti, et al., 1970, 1971, 1975; Miyashiro, et al., 1971; Aumento, et al., 1971; Cann, 1971) may be accounted for by either magmatic crystallization in the presence of water, burial metamorphism, or contact metamorphism.

Kirst (1976) believes that most of the brown hornblende in his greenschist to amphibolite facies metagabbros is metamorphic in origin, since it poikiloblastically encloses plagioclase fragments. Within the lower grade metagabbroic rocks and unmetamorphosed gabbros identified by Kirst and in relatively fresh gabbros examined by CAYTROUGH (1979), however, brown, strongly pleochroic hornblende occurs in small irregular patches interstitial to plagioclase and clinopyroxene megacrysts or in a matrix of recrystallized plagioclase (CAYTROUGH, 1979; Figure 3b) and as an apparent alteration product rimming clinopyroxene, and both authors report that clino- and orthopyroxenes frequently contain small internal patches, often elongated and oriented parallel to crystal parting planes, of chestnut brown pleochroic hornblende. Interstitial patches of red brown hornblende have been observed by Stakes (1978) in gabbroic rocks dredged from the Pacific and Atlantic Oceans; in her samples the hornblende is associated with other hydrous phases, including smectite, apatite and a phlogopitic mica, and with the anhydrous phases pigeonite and titanomagnetite. Stakes notes, in addition, that the minerals of this mesostasis have a skeletal morphology, suggesting that they were quenched relatively rapidly. We will discuss aspects of the formation of the brown hornblendes and the other late-crystallizing primary hydrous phases observed by these authors later in this section.

Plutonic rocks partially or completely altered to rodingites are infrequently recovered from the ocean floor, but are interesting examples of alteration by metasomatic processes. Rodingites have been described by Ploshko, et al. (1970), Aumento and Loubat (1971) and Honnorez and Kirst (1975), and a few partially rodingitized gabbros have been recovered by us from the Mid-Cayman Rise. A summary of the petrography, associations and significance of rodingites dredged from the Atlantic Ocean has been presented by Honnorez and Kirst (1975). These authors note that the rodingitized gabbros are invariably associated with serpentinized ultramafic rocks; in addition, no rodingitization ever appears to affect the shallow intrusive or extrusive carapace of the oceanic crust. They also note that in several rodingite samples mineralogic alteration takes place along fractures penetrating the rock; further penetration of altering solutions appears to take place along grain boundaries (see Figure 2b for an example of this texture), and mortar texture apparently predating the alteration (and resulting in an increase in the abundance of grain boundaries) provides an excellent permeable pathway for these solutions. The spatial proximity of the serpentinized ultramafics and the rodingites suggested to Honnorez and Kirst that the processes forming the rodingites must be associated with the intrusion of the serpentinites or with the serpentinization of pre-existing ultramafic rocks, and with the mobilization of Ca into solution to form Ca-bearing silicates in the rodingites by alteration of surrounding and overlying basic rocks. Our in situ collection of a small number of partially rodingitized gabbros on the rift valley walls of the Mid-Cayman Rise suggests two further points bearing upon their formation: (1) the occurrence of rodingitized gabbro is not confined solely to the walls of fracture zones as was previously supposed (Honnorez and Kirst, 1975); (2) the scale at which the gabbroic country rock appears to be affected by the metasomatic processes accompanying intrusion of thin (a few meters to a few tens of meters) serpentinized ultramafic screens is much finer than previously envisioned.

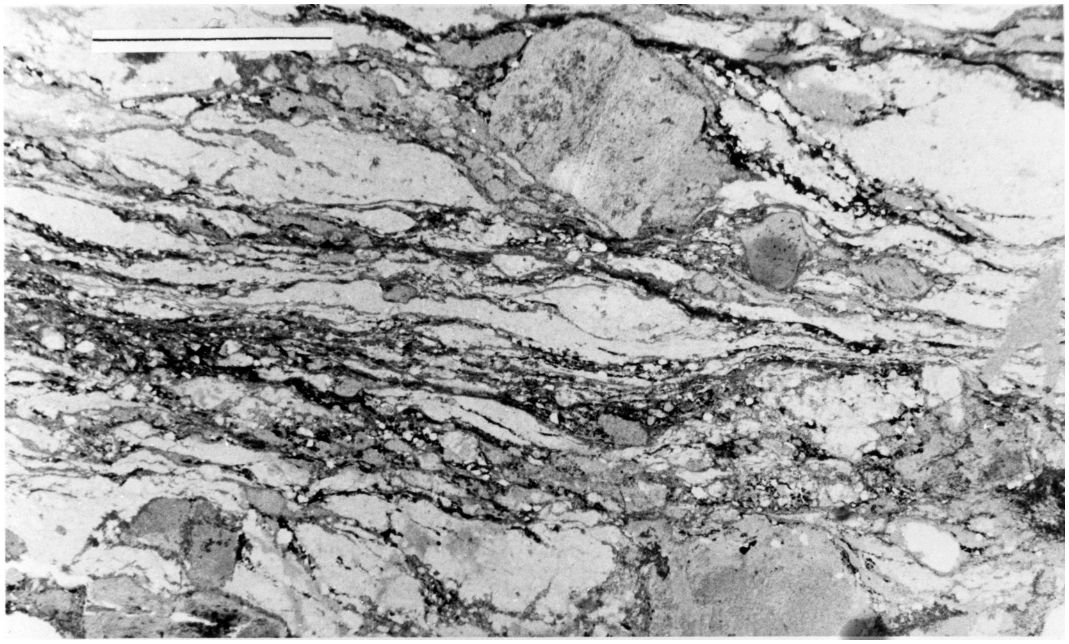
Deformation effects in oceanic metagabbros have been discussed by a number of authors. Helmstaedt and Allen (1977) assessed the effects of deformation in a gabbronorite, recovered at DSDP site 334, that exhibits a strong planar fabric due to the presence of pressure shadows of augen-shaped porphyroclasts of plagioclase, clinopyroxene and orthopyroxene in a matrix of anhydrous and hydrous recrystallized fragments. Two observations made by these authors are particularly significant: (a) the zone of penetrative strain, transecting core 334, that is represented by this sample appears to be of very limited width, grading abruptly into zones of relatively undeformed rock above and below; (b) recrystallization concomitant with alteration and deformation (mylonitization) of the mineral phases observed in this rock implied to Helmstaedt and Allen that metamorphism was initiated at high temperatures (~800^{o}C), which then dropped rapidly enough to produce successively lower temperature mineral phases (e.g., separate patchy intergrowths of tremolite and actinolite, and late-stage smectite, sericite, chlorite and calcite).

Gneissic metagabbros have been described by Miyashiro, et al. (1971) and by Chernysheva (1970). These authors interpret the textures in their samples to imply granulation followed by metamorphic recrystallization, which they suggest may reflect contact metamorphism induced by high-temperature intrusion of serpentinites dredged simultaneously with the metagabbros. Dynamic metamorphism over a wide range of temperatures and pressures is suggested by Engel and Fisher (1975) to have produced the varying types of deformation observed in their oceanic metagabbros (from recrystallization and ductile deformation resulting in bent plagioclase twins, to mylonitization to brecciation; see Figures 5a, 5b, 6a, 6b, 7a, 7b). Based upon intensity of deformation, Bonatti, et al. (1975) distinguish two types of metagabbros in a collection dredged from the Mid-Atlantic Ridge: (1) granular and (2) banded amphibolitic metagabbro. The two are characterized by nearly identical chemical and mineralogic compositions; the banding of the second group is produced by an alternation of amphibole-rich and plagioclase-rich layers. Banded metagabbros from the Romanche fracture zone having similar characteristics are observed by Ploshko, et al. (1970).

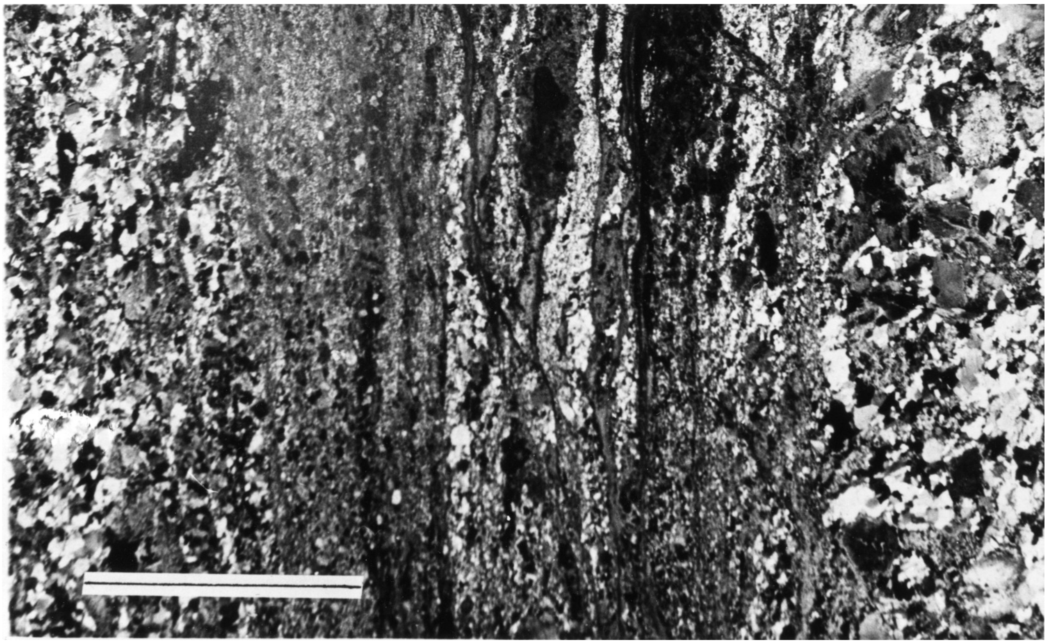
Brittle deformation textures in oceanic gabbroic rocks have been described by Quon and Ehlers (1963), Engel and Fisher (1969, 1975), Honnorez and Bonatti (1975), Kirst (1976), Shibata (1976), Perfit (1977), Helmstaedt and Allen (1977) and CAYTROUGH (1979). All of these authors observe samples that have experienced some degree of

<u>Figure 7</u> a. Plain light photomicrograph of protomylonite (741-6-1). Porphyroclasts are clinopyroxene, partially psuedomorphed by green amphibole, and plagioclase. Stringers of material are green amphibole + opaque oxide. Scale bar = 5 mm.

b. Crossed polar photomicrograph of mylonite zone in gabbro (612-3-1B). Zone is roughly 2 cm wide, and contains green to brown amphibole + plagioclase + opaque oxide. Host gabbro is partially brecciated and recrystallized but unfoliated. Chlorite-filled fractures are apparent at oblique angles to the mylonite zone in the upper right of the photograph. Scale bar = 10 mm.



7a

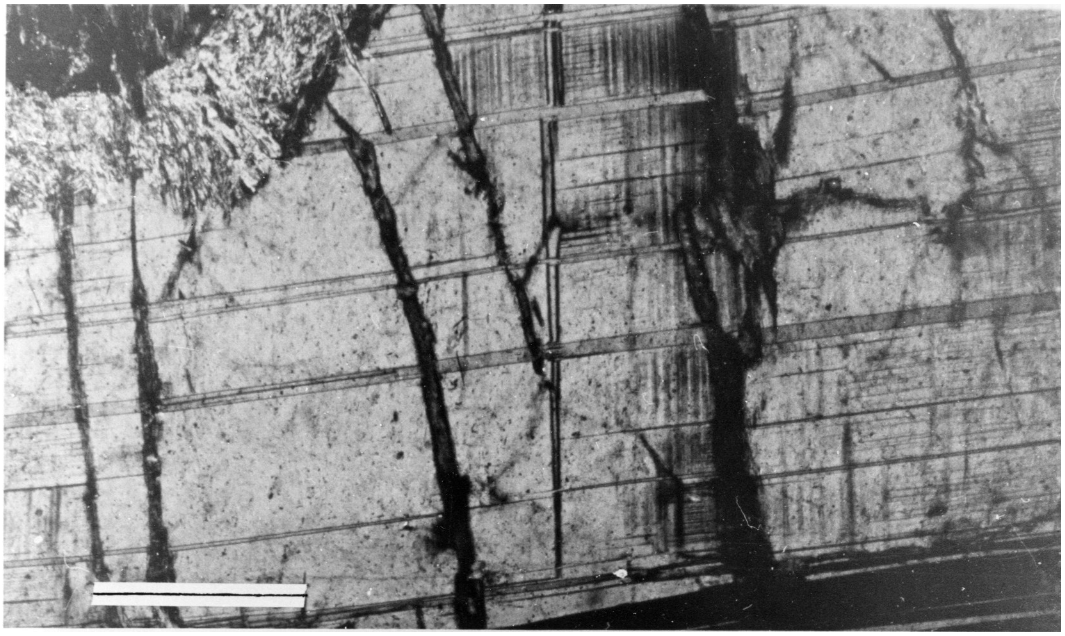


7b

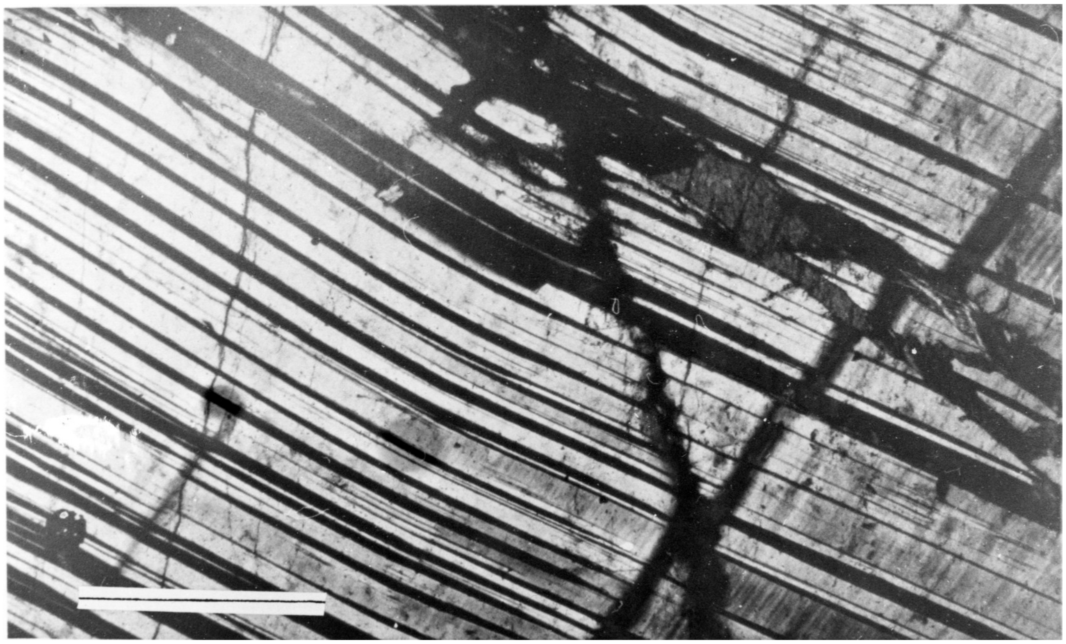
cataclasis, resulting in granulation or brecciation and breaking or kinking of parting planes in pyroxene and twin lamellae in plagioclase (Figures 8a, 8b). Mylonites, cataclasites and tectonic breccias are widely reported from the oceans (e.g., Honnorez and Bonatti, 1975; Figures 6b, 7a, 7b) and Honnorez and Bonatti suggest that the variety of textures observed in many of their samples indicate that they experienced a complex polymetamorphic history. CAYTROUGH (1979) identify late-stage fractures that cross-cut earlier high-temperature deformation features (such as recrystallization, and bent plagioclase twin lamellae); these late-stage fractures are infilled with minerals (i.e., actinolite, chlorite, serpentine, calcite) that appear to be related to the introduction of water (Figures 4b, 8a). The observation of gabbro-peridotite breccia zones within cores recovered from DSDP sites 334 and 395 suggests that brittle deformation occurring at temperatures below ~300°C may represent faulting which accounts for the recovery of the plutonic rocks from shallow levels in the crust (Aumento, et al., 1977; Helmstaedt and Allen, 1977). Hekinian (1970) suggests that the brittle deformation features (e.g., kinked or broken plagioclase twin lamellae and pyroxene parting planes) observed in gabbroic rocks from the Indian Ocean reflect dynamic metamorphism due to faulting, possibly during uplift of these rocks to their present level of exposure. Helmstaedt and Allen (1977), in their discussion of deformation of the plutonic rocks from site 334, conclude that these gabbros experienced a complex deformation history that was initiated at elevated temperatures, producing ductile deformation in narrow zones of shear, and that terminated with the brittle faulting possibly responsible for uplifting the complex.

Figure 8 a. Crossed polar photomicrograph of offset and tapered plagioclase twin lamellae. Offsetting microcracks are infilled with chlorite. Microcracks appear to be feeding altering fluids to produce olivine alteration (colorless fibrous amphibole + chlorite + opaque) at upper left. Scale bar = 0.5 mm; sample number 741-4-1.

b. Crossed polar photomicrograph of deformed plagioclase twin lamellae. Lamellae are bent and tapered; cross-cutting fractures are filled with chlorite. Scale bar = 0.5 mm; sample number 741-4-1.



8a



8b

Based upon his examination of a suite of oceanic metagabbroic rocks, Kirst (1976) suggests that metamorphic grade and intensity of deformation appear to be linearly related. Those rocks within Kirst's suite exhibiting the highest degree of granulation also contain the greatest amount of metamorphic hornblende; this observation accords with the suggestion that hornblende formation is favored over actinolite in the event that the rock experiences shear (Kirst, 1976). An intergrowth of green actinolitic hornblende and brown ferro-hornblende observed by Kirst in his samples is interpreted to be not an equilibrium pair but a partial replacement of actinolitic hornblende by hornblende under directional stress.

Similar to the characteristics observed with respect to primary petrographic features, textural and mineralogic heterogeneity of oceanic metagabbros is apparent in the descriptions of almost all authors. This observed heterogeneity is a first-order function of the nature of ocean-floor metamorphism, at least as expressed in the shallow-level plutonics, and may reflect the nature of the environment of the upper portion of Layer 3. The textures and mineralogic associations presently recognized in oceanic metagabbros appear to indicate that metamorphism of the lower oceanic crust is controlled by hydrothermal activity due to seawater circulation within the crust, concomitantly with dynamic metamorphism resulting from movement along the faults that permit seawater penetration and that exist at the axis of accretion and along fracture zone lineaments. Some authors describe textures that they believe are produced by contact metamorphism (Miyashiro, et al., 1971; Bonatti, et al., 1975), but samples with these textures are relatively few in number, and it appears that contact metamorphism may be a local phenomenon.

Large-scale hydrothermal circulation at mid-ocean ridges has been postulated to account for a great number of observations, including the distribution of metalliferous sediments, compositional variations in basalts and anomalies in values of heat flow at accreting plate margins (Lister, 1972; Spooner and Fyfe, 1973; Williams, et al., 1974). The discovery of local hydrothermal vents at the sea floor in the eastern equatorial Pacific (Edmond, et al., 1977; Corliss, et al., 1979) lends unequivocal support to this hypothesis. Oxygen isotope data obtained for a variety of oceanic rocks, including gabbroic rocks (Muehlenbachs and Clayton, 1972; Muehlenbachs, 1977), and oxygen and hydrogen isotope analyses of serpentinized ultramafic rocks (Wenner and Taylor, 1973) indicate that most, if not all, of the circulating fluid in the oceanic crust is seawater. Seawater circulation along faults and fractures to the depth of emplacement of plutonic rocks within the oceanic crust is indicated by four general petrographic features, all of them interrelated, that are observed within oceanic metagabbros: (1) the apparent retrograde sequence of metamorphic reactions; (2) discontinuity of metamorphism, resulting in partial reactions and in disequilibrium mineral assemblages; (3) variability of alteration effects at all scales; (4) the variety and extent of deformation effects.

A retrograde metamorphic sequence is observed by most authors describing oceanic metagabbros (e.g., Miyashiro, et al., 1971), and is described in detail for a suite of oceanic gabbroic rocks by Kirst (1976) and for a suite of ophiolitic rocks by Elthon and Stern (1978, 1979). Retrograde effects might result if the permeable pathways circulating water through the crust are sealed in time, as a function of either their closure by growth of mineral phases (e.g., smectite, calcite, zeolites; Schreiber and Fox, 1976; Honnorez, 1978) or their effective closure by increasing accumulations of pelagic sediment onto the overlying accreted crust (Sclater, et al., 1974; Anderson, et al., 1977). Disequilibrium textures within the mineral assemblages observed by Elthon and Stern (1978) have also been observed by Kirst (1976), and they include the preservation of relict primary igneous minerals, and the partial replacement of one apparent metamorphic mineral assemblage by another. These textures are produced if the metamorphic reactions occurring in oceanic crustal rocks cannot proceed to completion, which, as noted by Elthon and Stern (1978), is a function of the irregular availability and distribution of hydrothermal fluids within the crust. Kirst (1976) suggests that the presence of a number of zeolites, having very diverse chemical compositions and temperature stability ranges, within vein fillings in a single sample may also indicate significant variability in the composition and temperature of fluids passing through fractures only centimeters apart. The microscopic variability observed by Kirst and by Elthon and Stern has also been observed by CAYTROUGH (1979), who note that the degree of alteration in their samples is heterogeneous on the smallest of scales: zones of extensive alteration, in which primary phases are completely replaced, are adjacent to (within 2 to 3 cm of) areas in which the primary phases are pristine. Permeable pathways open to altering fluids range in size from faults and shear zones at the scale of one to several meters (as our in situ observations in the Mid-Cayman Rise indicate), to narrow shear zones several millimeters to centimeters in width (Bonnati, et al., 1975; CAYTROUGH 1979; Figure 7b), to grain boundaries in rocks with mortar texture such as those described by Honnorez and Kirst (1975) or in rocks with a large percentage of readily altered olivine (Hodges and Papike, 1977). Even at the largest scales, variability of alteration effects that is expected to result from combined hydrothermal and dynamic metamorphism has been observed: Elthon and Stern (1978) maintain that their individual metamorphic facies are distributed heterogeneously throughout each stratigraphic level of the Chilean ophiolites, and DeLong, et al. (1978) have shown that no psuedo-stratigraphic correlation of intensity or type of metamorphism exists for their samples collected in situ in the Mid-Cayman Rise.

The linear relationship between metamorphic grade and intensity of deformation as suggested by Kirst (1976), may indicate the interaction and inter-dependence of faulting (i.e., dynamic metamorphism) and the introduction of water along fault planes (hydrothermal metamorphism). The penetration of fractures, formed by contraction and extension in the cooled basaltic carapace, into the still-hot gabbroic complex could result in the ductile deformation that is implied by the presence of shear zones at a variety of scales and by high-temperature recrystallization of the primary phases. The late brittle deformation of oceanic metagabbros noted by many authors could be the result of faulting of the cooled gabbroic complex during its translation away from the active zone of gabbro accretion. Contact metamorphism has been suggested by Miyashiro, et al. (1971), Bonatti, et al. (1975), Shibata (1976) and Elthon and Stern (1978) to account for some features in oceanic metagabbros. For example, Bonatti, et al. (1975) suggest that contact metamorphism can explain the heterogeneity of metamorphic intensity within samples recovered from a small area; Elthon and Stern (1978) propose that contact metamorphism will account in part for the decrease in intensity of metamorphism observed with increased distance away from the axis of spreading in the Sarmiento ophiolite complex. We believe that contact metamorphism has a very minor effect on the rocks of the lower oceanic crust. The suggestion of Bonatti, et al., is explained equally well by hydrothermal metamorphism that is confined to a series of heterogeneously distributed permeable pathways. Contact metamorphism cannot account for (a) recrystallization under directional stress (banding and mylonitization), (b) the mobility of elements along micro-cracks and fissures and, within them, the production of hydrous secondary minerals, nor (c) the observed linear relationship between metamorphic grade and intensity of deformation (Krist, 1976).

The observation of brown hornblende, in association with other hydrous phases in late-crystallizing interstitial patches, and as an apparent late magmatic phase in a reaction relationship with pyroxene, suggests that the last-crystallizing liquid is preferentially enriched in sufficient water to produce these phases. None of the authors cited above (Kirst, 1976; Shibata, 1976; Stakes, 1978; CAYTROUGH, 1979) feel that the textural evidence can support production of at least some of the hornblende that they observe by subsolidus interaction (nor can chemical evidence, as noted by Stakes, 1978; see below). Based upon the following evidence, Kirst (1976) suggests that the brown hornblende that he observes is a product of "deuteric" alteration: (1) the brown hornblende in his samples is always associated with pyroxene, either in a rimming or an exsolution relationship; (2) the hornblende is commonly associated with minerals (e.g., apatite, zircon) that crystallize from a liquid rich in residual volatiles; and (3) the Ti content and Na/Na+Ca ratio of his hornblendes shows them to be chemically distinct from amphiboles of metamorphic origin. Deuteric alteration*, however, implies that the hydrous minerals in question were produced during the last stages of consolidation of the liquid as a result of enrichment of juvenile or magmatic water in the remaining liquid. We suggest that the term deuteric is somewhat misleading, since Kirst (1976) and Stakes (1978) both believe, although they use this term, that the water involved in the formation of the brown hornblende and other late-crystallizing primary hydrous phases that they observe may, in fact, be seawater.

$\delta^{18}O/^{16}O$ studies on metagabbros from the Mid-Atlantic Ridge by Muehlenbachs and Clayton (1972) indicate a lack of equilibrium of coexisting plagioclase and pyroxene produced by the ability of plagioclase to exchange oxygen atoms with hot water more readily than pyroxene. The isotopically light nature of the water ($\delta^{18}O$ of -2 to +2 o/oo) interacting with the plagioclase suggests that it must be seawater ($\delta^{18}O$ of 0.0 o/oo) rather than juvenile water ($\delta^{18}O$ of 7 to 9 o/oo). Furthermore, many authors analyzing tholeiitic basalt glasses find little or no water present suggesting that the source for abyssal tholeiitic magmas is essentially dry (Moore, 1970; Moore and Schilling, 1973; Bryan and Moore, 1977; Delaney, et al., 1977; Delaney and Mathez, 1978); even the preferential enrichment of juvenile water in the late-crystallizing liquid would not concentrate water of the low quantities

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*The AGI Glossary of Geology (1972) defines "deuteric" as: "said of a process or of an effect in an igneous rock that takes place in the later stages and as a direct result of consolidation of a magma." "Autometamorphism," often cited as a synonym for deuteric, is defined as: "(a) a process of chemical adjustment of an igneous mineral assemblage to falling temperature attributed to the action of its own volatiles . . . (b) the alteration of an igneous rock by its own residual liquors (Tyrrell, 1926). This process should rather be called deuteric because it is not considered to be metamorphic."

found in the basalts sufficiently to produce the brown hornblende and other hydrous phases observed in the gabbros. Given the textural and mineralogic data available for oceanic plutonic rocks, we infer that circulating hydrothermal fluids comprised predominantly of seawater may penetrate locally the uppermost portions of the magma chamber beneath the ridge axis, and may be responsible for the production of the late-crystallizing primary hydrous phases described by Kirst (1976), Shibata (1976), Stakes (1978) and CAYTROUGH (1979). This assumption implies that seawater must be interacting with very hot and mostly crystalline intrusive rocks, a process invoked by Stakes (1978) to explain the textures, chemistries and mineralogic associations in her metagabbros. As the basaltic carapace fractures during the combined processes of cooling and lateral transport, it may be possible for seawater to penetrate along cracks and fissures into isolated regions at the periphery of the magma chamber characterized by aggregates of crystals and interstitial melt. It should be noted that confirmation of the origin of these interstitial hydrous phases by local seawater invasion of the magma chamber can only be made by direct examination (i.e., $\delta^{18}O$ ratios) of the phases, and the present lack of such data renders this argument speculative.

Wolery and Sleep (1976), in their examination of geochemical flux and hydrothermal circulation of seawater, conclude that the bulk composition of the oceanic crust appears to be only slightly modified by seawater interaction, and that the alteration of the crust is therefore dependent upon a restricted system of permeable pathways. This observation is compatible with a scheme in which seawater invades the lower crust along a system of faults that may diminish in number with depth, or along the few dykes that penetrate the gabbroic layer. This scheme is suggested by D. Elthon and C. Stern (pers. comm.) to account for the textural and mineralogic heterogeneity, and the termination of metamorphism with depth, observed in the gabbros of the Tortuga ophiolite complex. Cannibalization of overlying previously altered oceanic crust by stoping into the magma chamber could introduce water secondarily into the magma, although the effects of such a process are likely to be far less local than the introduction of small amounts of water along permeable pathways. As we have suggested above, it appears that hydrothermal metamorphism by seawater that invades the lower oceanic crust along a system of fractures or faults ranging in size from a few millimeters to several meters in width best explains almost all of the observed metamorphic textures and mineralogic relationships in oceanic plutonic rocks.

Early workers examining metagabbros from the oceans were inclined to infer that the processes producing them might be similar to those producing some continental metamorphic rocks. For example, Miyashiro et al. (1971) distinguish two groups of unfoliated metamorphic rocks in a selection of gabbroic samples from the Mid-Atlantic Ridge: those that have roughly preserved their original igneous composition (Group I), and those that have experienced intense chemical migration through contact with percolating, hot aqueous fluids (Group II). Most of the metagabbros that they examined belonged to Group I, suggesting to Miyashiro and coworkers that these samples experienced burial metamorphism subsequent to their differentiation and accretion at the ridge crest. This hypothesis has also been advanced by other authors (e.g., Melson and van Andel, 1966). Given what we believe to be the relatively steady-state accretionary processes operative at mid-oceanic ridges, burial metamorphism, particularly to the depths required to induce the high grades of metamorphism observed in some gabbros, does not appear to be a viable mechanism for alteration of the lower oceanic crust. Hydrothermal alteration effects at depth within the crust would be limited to the decreasing number of permeable pathways open at depth, and extensive metasomatic changes would not be expected to occur except very locally within the gabbroic pile (thus accounting for the small number of Group II metagabbros). Burial metamorphism should produce uniform alteration of the rocks from any given pseudo-stratigraphic horizon. Widely variable degrees of alteration, however, are observed at any given depth in (a) positioned dredges on fracture zone walls (Bonatti, et al., 1975), (b) submersible collections from the Mid-Cayman Rise (DeLong, et al., 1978; CAYTROUGH, 1979) and (c) the Sarmiento ophiolite complex (Elthon and Stern, 1978). The most important factor governing the alteration of the oceanic crust is the water/rock mass ratio (Hajash, 1977; Mottl and Seyfried, 1977); at depth within the crust the water/rock ratio is regionally low enough that metasomatic changes are not extensive (Ito, 1979), but locally (along microcracks and fissures, or along grain boundaries) high enough to produce hydrous phases or to rim primary phases with late-stage alteration products. In the presence of excess water only low lithostatic pressures are required to develop the mineralogy of the highest metamorphic grades that are observed in oceanic plutonic rocks, depending upon the temperature of metamorphism. Temperatures of circulating hydrothermal fluid would be expected to vary locally, as a function of depth, or of interaction of percolating fluids with overlying cold basaltic cover or hot basaltic flows, or with hot semi-crystalline magma. We infer that temperatures of metamorphism vary heterogeneously from the maximum indicated by late-stage primary brown hornblende formation (~600 to 800°C) to a minimum indicated by the chlorite and zeolites infilling the cross-cutting brittle fractures that are observed in almost all oceanic gabbroic rocks.

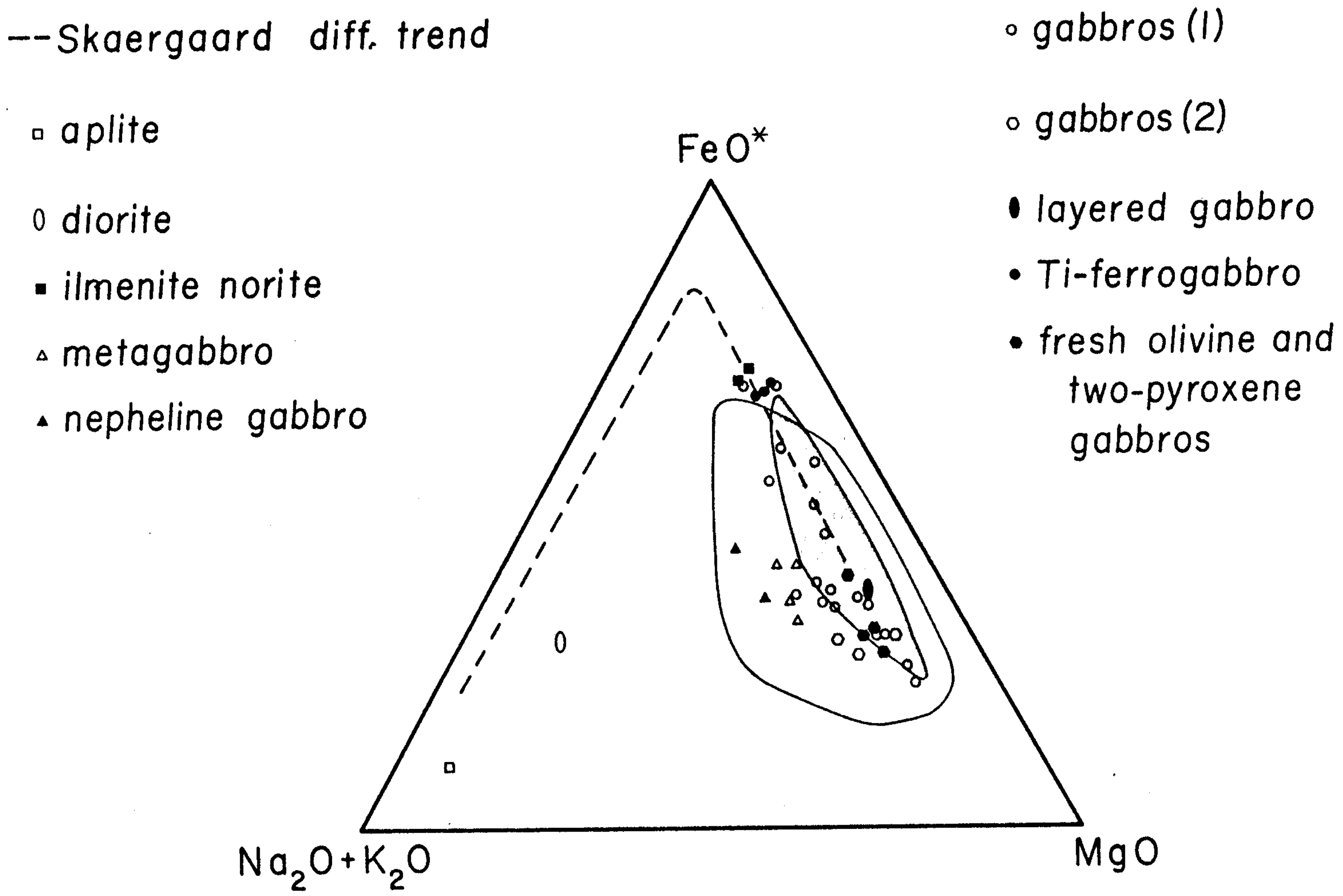
One cautionary statement should be made. We have noted previously that the plutonic rocks recovered from the ocean floor are exposed or drilled from shallow levels within the oceanic crust, which implies that we have recovered only those rocks that are representative of the uppermost portion of layer three. Furthermore, lower crustal rocks exposed at the sea floor must have been subjected to faulting of some magnitude, since we presently find no evidence for the large-scale tectonic mass-wasting required to remove most or all of the shallow intrusive and extrusive basaltic carapace that is emplaced near or at the crust-seawater interface. Therefore we contend that inferences that are based on studies of alteration and deformation relationships as exhibited in oceanic gabbros are valid for shallow-level processes (<500 m) and are not likely to be valid for processes operative at depths thought to be representative of the depth of gabbro emplacement (deeper than 2000 m).

E. Whole-rock Chemistry of Rocks of the Lower Oceanic Crust

The body of literature directed toward understanding the variations in major and trace element chemistry of oceanic tholeiitic basalts is large; papers that attempt to address the problem of the petrogenesis of oceanic gabbros and other rocks presumed to comprise the lower oceanic crust are relatively few (see: Aumento, 1969; Kay, et al., 1970; Miyashiro, et al., 1970; Aumento, et al., 1971; Thompson, 1973; Engel and Fisher, 1969, 1975; Hodges and Papike, 1976; Kirst, 1976; Perfit, 1977; CAYTROUGH, 1979). Published whole-rock analyses indicate that the range of compositional variation in oceanic gabbros is much greater than than in analyzed oceanic tholeiitic basalts (Miyashiro, et al., 1970; Bonatti, et al., 1971; Thompson, 1973). It is of primary importance to identify: (a) the degree to which the plutonic rocks from a given area of the oceanic crust are genetically related to the overlying basalts; (b) the petrogenetic processes responsible for formation of oceanic gabbroic rocks; and (c) the extent to which alteration acts to modify initial rock chemistry.

Present interpretation of the chemistry of unaltered oceanic gabbroic rocks suggests that for the most part they follow a fractional crystallization sequence similar to that observed for the Skaergaard layered intrusion, East Greenland (Wager and Deer, 1939). When plotted on an $FeO^*/MgO/Na_2O+K_2O$ ternary diagram (Figure 9), plutonic rocks from throughout the world's oceans follow the tholeiitic differentiation trend defined by Wager and Deer (see also: Miyashiro, et al., 1970; Bonatti, et al., 1971, 1975; Thompson, 1973; Perfit, 1977; CAYTROUGH, 1979). The world-wide recovery of high-iron / high-titanium gabbros, and of aplites, quartz monaonites and trondhjemites, all presumed late-stage to extreme differentiates of a crystallizing tholeiitic magma, has provided support for this interpretation. Miyashiro, et al. (1970) have suggested that the inverse correlation of An content of modal plagioclase with FeO^*/MgO in the bulk rock also lends credence to the view that the chemical variations observed in oceanic gabbros are

Figure 9 FeO^*-MgO-Na_2O+K_2O ternary diagram showing the distribution of gabbroic rocks collected from the ocean floor. The open field is the compositional range of gabbroic rocks from the Mid-Cayman Rise spreading center (CAYTROUGH, 1979); the shaded field is the range of gabbroic rocks from the Mid-Atlantic Ridge (Miyashiro, et al., 1970). References for other points are as follows: Skaergaard differentiation trend (Wager and Deer, 1939); aplite (Miyashiro, et al., 1970); diorite (Thompson, 1973); ilmenite norite (Prinz et al., 1976); metagabbro (Bonatti, 1970); gabbros (1) (Honnorez and Bonatti, 1970); gabbros (2) (Perfit, 1977); layered gabbros (Thompson, 1973); Ti-ferrogabbro (Engel and Fisher, 1975); fresh olivine and two-pyroxene gabbros (Engel and Fisher, 1975).


--Skaergaard diff. trend
□ aplite
0 diorite
■ ilmenite norite
△ metagabbro
▲ nepheline gabbro
○ gabbros (I)
○ gabbros (2)
● layered gabbro
● Ti-ferrogabbro
● fresh olivine and two-pyroxene gabbros
FeO*
Na_2O+K_2O
MgO
0

controlled by fractional crystallization. A few authors have suggested that two distinct differentiation trends may be recognized (Bonatti, et al., 1971), but support for this conjecture is yet to appear; alkali enrichment that might be inferred to represent a distinct differentiation trend may well be produced by metasomatic activity (Stakes, 1978).

A summary of the major and trace element analyses of unaltered oceanic gabbros and their differentiates made by a number of investigators is presented in Tables 2 and 3. The principal generalization that can be made with respect to the less differentiated samples is that the abundance of K_2O is uniformly low ($\lesssim$ 0.30% in individual analyses). Silica contents in individual analyses of unmetamorphosed gabbroic rocks are generally 49 to 50 percent, but decrease to roughly 40% in high-iron gabbros. The percentage of Al_2O_3 in individual analyzed oceanic gabbroic rocks varies from a low of 11% to a high of 26%.

Thompson, et al. (1972) and Thompson (1973) have shown that Cr, Ni and Co contents decrease with increasing fractional crystallization in samples from the Mid-Atlantic Ridge; they suggest that early precipitation of olivine and chromite are responsible for the Cr and Ni variations observed in their samples, a suggestion also made by Engel and Fisher (1975) for variations observed in gabbros from the western Indian Ocean. Prinz, et al. (1976), conclude that the chemistry and textural relationships observed in their samples from the Mid-Atlantic Ridge may indicate early crystallization and subsequent differentiation of opaque oxides and olivine. A two-pyroxene gabbro recovered from the Romanche Fracture Zone and analyzed by Melson and Thompson (1970) is enriched in Mg, Cr and Ni and depleted in Na, K, Ti, P, Fe, V and Zr, which these authors believe reflects its formation during the

TABLE 2

WHOLE-ROCK MAJOR ELEMENT COMPOSITIONS OF SELECTED OCEANIC GABBROIC ROCKS. VALUES GIVEN IN WEIGHT PERCENT.

	1	2	3	4	5	6
Rock Type:	Gabbro	Troctolite	Olivine Gabbro	Olivine Gabbro	Olivine Gabbro	Two-pyroxene Gabbro
Number of analyses:	1	1	9	2	2	1
SiO_2	48.56	46.42	49.22	50.60	49.94	50.88
TiO_2	0.24	0.05	0.33	0.36	0.13	1.09
Al_2O_3	18.69	23.68	17.01	16.29	16.84	14.48
Fe_2O_3	2.27	0.52	1.28	1.87	1.96	6.16
FeO	4.30	3.22	4.34	4.12	4.86	4.36
MnO	0.11	0.06	0.14	0.09	0.15	0.17
MgO	9.26	11.49	10.53	9.59	10.87	7.42
CaO	12.67	11.47	12.73	14.33	14.16	11.95
Na_2O	1.88	1.81	2.20	2.15	1.07	2.16
K_2O	0.07	0.03	0.06	0.07	0.02	0.30
P_2O_5	0.02	0.01	0.02	0.04	----	----
H_2O^+	1.72	1.02	2.06	0.52	nd	0.44
H_2O^-	0.17	0.13	0.23	0.15	nd	0.17
Total:	99.96	99.91	100.15	100.18	100.00	99.58
Locality:	Romanche Fracture Zone	Mid-Atlantic Ridge	Mid-Atlantic Ridge	Western Indian Ocean	Site 334, N. Atlantic	Site 334, N. Atlantic
Source(s):	Melson & Thompson, 1970	Miyashiro et al., 1970	Miyashiro et al., 1970	Engel and Fisher, 1969, 1975	Flower et al., 1977	Aumento et al., 1977

TABLE 2 (continued)

	7	8	9	10	11	12
Rock Type:	Gabbro	Clinopyroxene-hornblendegabbro	Clinopyroxene-hornblende-titano-magnetite gabbro	Plagioclase-rich gabbro	Anorthosite	Norite
Number of analyses:	1	3	1	2	1	1
SiO_2	52.00	51.53	41.83	48.35	56.43	43.38
TiO_2	0.44	0.65	7.05	0.15	0.18	4.00
Al_2O_3	17.20	15.17	11.94	21.55	26.10	11.89
Fe_2O_3	1.92	1.64	7.05	4.29	0.51	9.09
FeO	3.08	5.75	12.04	2.05	0.63	10.02
MnO	0.03	0.14	0.21	0.11	0.01	0.28
MgO	8.77	8.65	6.47	11.99	0.92	5.41
CaO	13.12	10.85	9.88	8.87	8.34	9.97
Na_2O	3.09	3.17	2.43	2.53	6.36	3.00
K_2O	0.12	0.10	0.10	0.09	0.07	0.14
P_2O_5	0.02	0.03	0.01	0.01	trace	1.25
H_2O^+	nd	2.14	1.04	nd	0.23	1.25
H_2O^-	nd	0.33	0.08	nd	0.01	0.27
Total:	99.75	100.15	100.13	99.9	99.79	99.95
Locality:	Cayman Trough	Mid-Atlantic Ridge	Mid-Atlantic Ridge	(corrected total) Cayman Trough	Western Indian Ocean	Mid-Atlantic Ridge
Source(s):	Perfit, 1977	Miyashiro et al. 1970	Miyashiro et al., 1970	Perfit, 1977	Engel and Fisher, 1969, 1975	Bonatti et al., 1971

TABLE 2 (continued)

	13	14	15	16	17	18	19
Rock Type:	Ilmenite Norite	Diorite	Aplite	Quartz monzonite (dyklet)	Nepheline gabbro	Granular amphibolitic metagabbro	Rodingite
Number of analyses:	2	2	1	1	1	2	1
SiO_2	43.44	67.22	78.39	75.07	46.32	52.27	35.25
TiO_2	4.94	0.64	0.09	0.15	1.35	0.34	3.88
Al_2O_3	11.76	15.09	12.68	13.18	16.84	16.74	8.07
Fe_2O_3	6.79	2.54	0.38	0.76	5.79	0.98	3.83
FeO	11.63	2.38	0.41	1.15	3.73	5.83	8.40
MnO	0.30	0.09	0.01	0.03	0.14	0.11	0.21
MgO	5.20	1.91	0.54	0.23	6.48	7.29	10.38
CaO	9.92	2.36	0.55	1.10	7.68	9.14	17.83
Na_2O	3.08	5.55	6.66	4.55	4.36	4.03	0.34
K_2O	0.16	0.50	0.06	3.27	1.01	0.08	0.05
P_2O_5	0.66	0.14	0.01	0.12	0.21	0.09	3.38
H_2O^+	2.14		0.38	0.20	4.50	1.79	7.94
	1.09						
H_2O^-	0.27		0.03	0.08	1.30	0.90	nd
Total	100.13	99.49	100.19	99.89	99.92	99.58	99.56
Locality:	Mid-Atlantic Ridge	Mid-Atlantic Ridge	Mid-Atlantic Ridge	Western Indian Ocean	Romanche Fracture Zone	Mid-Atlantic Ridge	Mid-Atlantic Ridge
Source(s):	Prinz *et al.*, 1976	Aumento, 1969	Miyashiro, *et al.*, 1970	Engel and Fisher, 1969, 1975	Honnorez and Bonatti, 1970	Bonatti *et al.*, 1975	Kirst, 1976

TABLE 3

Whole-rock Trace Element Compositions of Oceanic Gabbroic Rocks from Table 2.

Values given in ppm.

B	<10	nd	nd	70	9	nd	2.0	<5	nd	nd
Ba	10	10	18	<7	<5	37	230	55	120	nd
Co	nd	34	nd	45	50	<2	<20	10	<10	65
Cr	900	670	732	570	15	370	<20	<5	8	180
Cu	85	60	90	73	20	4	27	9	5	<10
Ga	11	11	nd	nd	17	13	36	24	20	nd
Li	6	nd	nd	70	6	nd	nd	5	nd	nd
Mo	nd	nd	nd	nd	35	nd	nd	<5	nd	nd
Nb	nd	<20	nd	nd	nd	<20	nd	nd	29	nd
Ni	200	240	225	230	50	34	34	6	<10	215
Pb	2	nd	nd	nd	nd	nd	2	nd	nd	nd
Rb	nd	nd	0.3	nd	nd	nd	<30	nd	nd	nd
Sc	nd	40	nd	36	nd	15	<10	nd	<10	29
Sr	110	130	30	26	95	320	114.5	40	18	nd
V	110	160	nd	100	500	39	30	35	5	315
Y	25	<10	5.3	<1	39	<20	nd	95	150	135
Yb	nd	<2	nd	0.57	nd	<2	nd	nd	13	nd
Zn	45	nd	nd	nd	nd	nd	39.5	nd	nd	nd
Zr	<10	19	6.9	<1	85	~20	480	150	250	63
Column from Table 2	1	4	5	6	9	11	14	15	16	19

earliest stages of fractional crystallization. Yttrium and Zr, which tend to concentrate in late-stage differentiating liquids, show the expected gradually increasing concentrations with increase in degree of fractionation; V and Mo are greatly enriched in high-iron oceanic gabbroic rocks (Thompson, 1973) probably due to their partition into opaque phases. Increased concentrations of Ba and Sr were observed by Engel and Fisher (1975) in anorthosites, which they believe are cumulates resulting from crystal fractionation. The lower Fe, Ti, K, Ba, Y, Yb and Zr concentrations of gabbros dredged from the Indian Ocean than those observed in the associated basalts suggested to Engel and Fisher (1969) that either a slow rate of diffusion or stratiform differentiation may have depleted the gabbros in these elements.

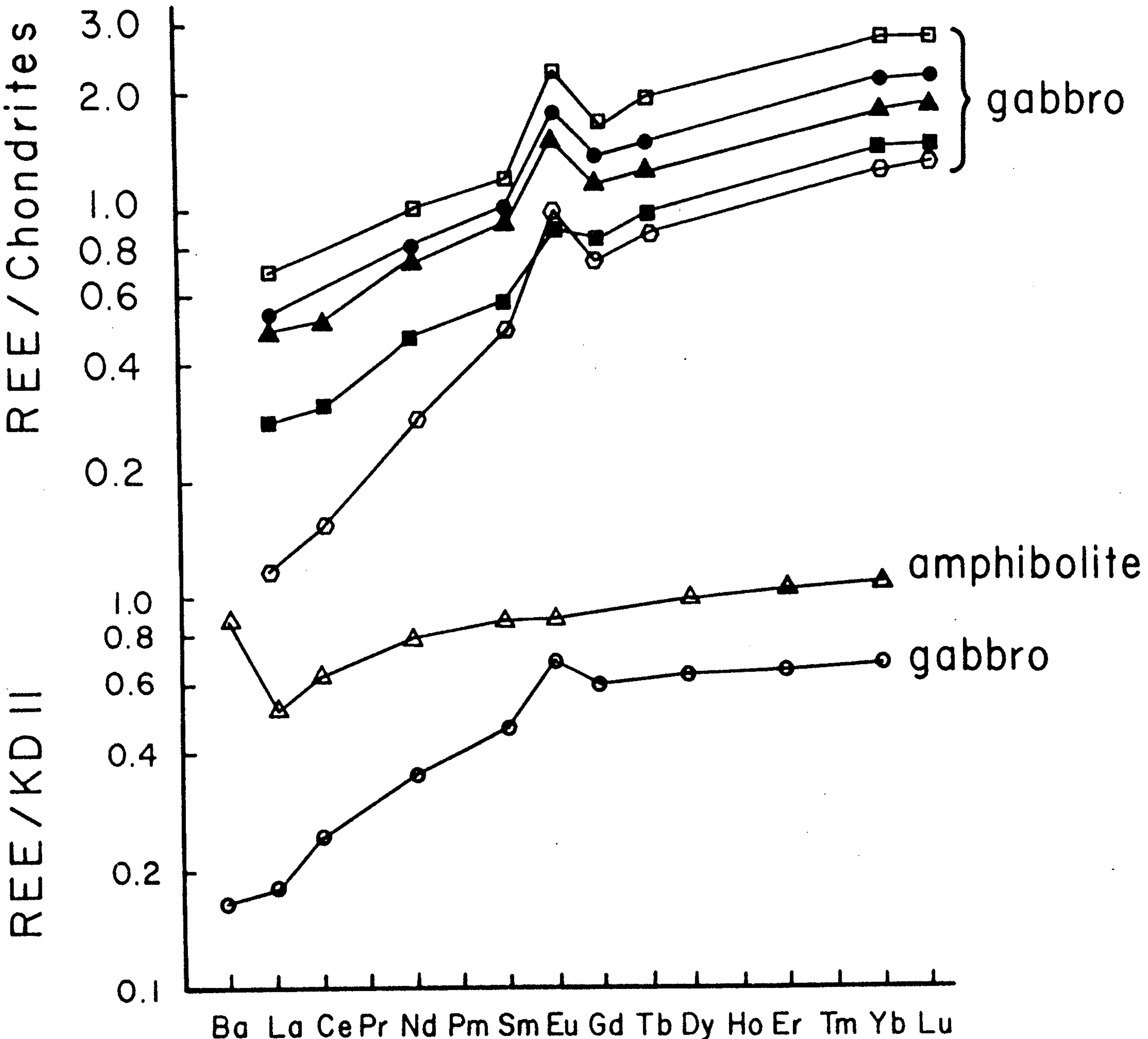
Rare earth element analyses of oceanic gabbros have been discussed by Kay, et al. (1970), Shih and Gast (1971), Masuda, et al. (1971), Schubert (1972), Masuda and Jibiki (1973), and Dostal and Muecke (1977, 1978). The fresh gabbro samples have consistently similar patterns, with light REE (La/Sm) depletion and positive Eu anomalies, the latter attributable to early accumulation of plagioclase during differentiation (Kay, et al., 1970; Shih and Gast, 1971; Schubert, 1972; Dostal and Muecke, 1977, 1978; Figure 10).The fresh plutonics also have more fractionated REE and lower total concentrations than similarly analyzed abyssal tholeiitic basalts associated with the gabbros. The REE pattern of the site 334 population exhibits a differentiation trend similar to that observed for Skaergaard, as REE contents in the gabbros increase with increasing bulk rock FeO*/MgO ratio (Dostal and Muecke, 1977, 1978). Both Kay and coworkers and Dostal and Muecke suggest that the slope of the REE patterns observed in the gabbroic rocks indicates fractionation of the rare earths

Figure 10 Rare earth element patterns for oceanic gabbroic and metagabbroic rocks. The uppermost five patterns are from Dostal and Muecke (1978) and represent cumulate gabbros collected by DSDP leg 37 (site 334) with the following numbers:

□—□ 23-1
●—● 21-1
▲—▲ 24-1
■—■ 24-3
○—○ 24-4

The lower two patterns, normalized to oceanic basalt KD 11, are from Kay, et al. (1970) and have the following sample numbers:

△—△ A150 8C
○—○ A150 20 4C


REE / Chondrites
3.0
2.0
1.0
0.8
0.6
0.4
0.2
gabbro
amphibolite
gabbro
REE / KD II
1.0
0.8
0.6
0.4
0.2
0.1
Ba La Ce Pr Nd Pm Sm Eu Gd Tb Dy Ho Er Tm Yb Lu

between cumulate pyroxenes and their parent liquid.

Thompson (1973) suggests that chemical variations observed in gabbros from the Mid-Atlantic Ridge are compatible with differentiation in large, shallow-level magma chambers. His calculations indicate that initial fractionation involves plagioclase and/or olivine (depending upon the composition of the parent liquid) and may be followed by low-pressure fractionation involving pyroxene, hornblende and Fe-Ti oxide. The chemical composition of gabbroic rocks dredged from the Mid-Cayman Rise and described by Eggler, et al. (1973) suggests that they were formed by crystal settling in a shallow-level magma chamber. Within the suite of samples collected from the Mid-Cayman Rise (CAYTROUGH, 1979) variability of Al_2O_3 versus FeO*/MgO in some gabbroic samples appears to reflect accumulation or removal of plagioclase from an initial liquid having the composition of the least differentiated crystalline basalt collected from the same area. Shido, et al. (1971) point out that the formation of most oceanic gabbroic rocks by crystal accumulation may be responsible for the low P_2O_5 values of fresh gabbros (0.01-0.03%) as opposed to those of the basalts (0.20-0.30%) examined by these authors. This observation is in agreement with that of Shih and Gast (1971), who suggest that rare earth patterns in 8 Mid-Atlantic Ridge gabbros indicates their accumulation origin. Hodges and Papike (1977) infer a crystallization path for site 334 gabbroic rocks that involves first olivine plus chrome spinel, followed successively by plagioclase, clinopyroxene and orthopyroxene or pigeonite.

It is therefore the consensus of most investigators that the chemical variations observed in oceanic gabbroic rocks can be explained by crystal fractionation in shallow-level magma chambers. One further constraint on the evolution of oceanic gabbroic rocks is the observation that the range of their chemical compositions is much greater than the range of chemistries observed in oceanic basalts (Miyashiro, et al., 1971; CAYTROUGH, 1979). This observation is compatible with the inferred evolution of oceanic plutonics in a shallow crustal magma chamber: LIL-depleted compositions and high Mg/Mg+Fe bulk ratios may be produced by accumulation of early-crystallizing mafic phases on the magma chamber floor; extreme differentiates - trondhjemites, diorites, Ti-ferrogabbros - may be produced by continued fractionation in isolated pockets of the magma chamber which cannot interact with the less-fractionated basaltic magma that we believe episodically must enter the main body of the magma chamber in a steady-state system (O'Hara, 1977; Cann, this volume).

Chemical compositions of metagabbroic rocks have been discussed by only a small number of authors (Bonatti, et al., 1971, 1975; Miyashiro, et al., 1971; Masuda, et al., 1971; Honnorez and Kirst, 1975; Kirst, 1976; Stakes, 1978; CAYTROUGH, 1979). As Kirst (1976) and CAYTROUGH (1979) point out, it is more difficult to assess changes in chemistry in oceanic metagabbros than in metabasalts due to the wide range in chemical variation reflecting primary differentiation of the parental gabbroic suite. Some of the most recent contributions (e.g., Stakes, 1978) indicate that there may be a need to reevaluate the work of earlier investigators.

Retrograde metamorphism of oceanic gabbroic rocks in the zeolite facies appears to result in enrichment of the rock in Na (Miyashiro, et al., 1971). Kirst (1976) observes that metagabbros in the greenschist and greenschist-amphibolite transitional facies appear to have experienced a gain in Si and a loss of Ca and Fe. He also notes that Cu is depleted and that Cr and V are low in his suite of metagabbroic rocks; he suggests that leaching by circulating hydrothermal fluids results in a loss of Cu and Cr, while V may be excluded during recrystallization in the amphibolite facies. Rare earth element patterns for metagabbros from the Mid-Atlantic Ridge presented by Masuda, et al. (1971) are generally similar to patterns for unmetamorphosed gabbroic rocks, but they do differ in that they are greatly enriched in total concentrations of REEs.

As noted above, Miyashiro, et al. (1971) distinguish two groups of unfoliated metamorphic rocks in a selection of dredged samples from the Mid-Atlantic Ridge. A small number of their metagabbros in the greenschist facies appear to belong to Group II (those experiencing intense metasomatic alteration). The Group II samples have been depleted in CaO and enriched in H_2O relative to their assumed primary compositions. Silica has been strongly affected by this metasomatism and is redistributed heterogeneously, resulting in variation of SiO_2 contents in individual analyses from 25 to 85 percent.

Stakes (1978) has recently suggested that the enrichment of certain elements, notably Mn, Fe, K, Ti, Si and the LREE, in late-crystallizing mesostasis of some metagabbros may be a function of seawater leaching reactions rather than of magmatic processes. Her suggestion is substantiated by the following observations: (1) these elements appear to be mobilized into hot seawater solutions that percolate to depth based upon their overall depletion in altered holocrystalline rocks relative to fresh glass; (2) the elements are enriched preferentially in the mesostasis interstitial to large (slowly-cooled) crystals of plagioclase and clinopyroxene; (3) the phases occurring in the mesostasis include hydrous phases (amphibole); (4) the mesostasis minerals (actinolite, chlorite, vermiculite, apatite, titanomagnetite, and rarely, K-feldspar and quartz) are skeletal suggesting that they were rapidly quenched due to an abrupt change in cooling rate that cannot be explained by gradual enrichment of late-crystallizing fluids in juvenile water Stakes condludes that redistribution of these elements by seawater interaction is responsible for the chemistries she observes in the metagabbroic rocks that she examined. If she is correct, then the chemical variations produced by seawater leaching reactions may mimic the chemical signature of fractionation processes, which may have profound implications for the modelling schemes outlined above.

The chemical signature of seawater interaction with oceanic plutonic rocks has been discussed by several other authors. Bonatti et al. (1971, 1975) and Kirst (1976) observe an increase in the $^{87}Sr/^{86}Sr$ ratio of oceanic metagabbros relative to fresh gabbros and they suggest that some radiogenic Sr (most probably from seawater) is added to, or exchanged with, the metagabbros that they analyzed. This suggestion has been confirmed by the observation that Cl contents of amphiboles in some of their samples is roughly 0.08% higher than would be expected in amphiboles formed by fluids of magmatic origin (Kirst, 1976). In addition, $\delta^{18}O$ data obtained on two metagabbros dredged from the Mid-Atlantic Ridge are compatible with the interpretation that these rocks had equilibrated with seawater at the time of their formation (Muehlenbachs and Clayton, 1972). Further oxygen isotope work on the site 334 gabbros confirms this interpretation and indicates that large volumes of seawater interacted with still hot but crystalline lower crustal rocks (Muehlenbachs, 1977). In view of the observed association of rodingitized gabbro and serpentinized ultramafic mentioned above (section on metamorphism), it is interesting to note that strontium isotope analyses by Hart (1973) of mineral separates from a rodingitized gabbro dredged from the western Indian Ocean are also consistent with interaction of the rock with seawater during metasomatism. Seawater interaction with rocks of the lower oceanic crust appears to have effected significant migration of certain chemical elements. We believe that it is essential for present workers to examine the magnitude of this interaction, which has implications for the observation of primary magmatic processes, and for the chemical balance of ocean water (see: Wolery and Sleep, 1976).

Small-scale differences in chemical composition in oceanic gabbroic rocks cannot yet be correlated with tectonic setting. For example, CAYTROUGH (1979) have recently demonstrated that a single group of gabbroic rocks from a very small area of the Mid-Cayman Rise show chemical variations that encompass those seen in all oceanic gabbroic rocks. Clearly the complexity of processes that create the oceanic crust is becoming more apparent as the quantity of data increases and as controls on sampling (with the use of submersibles) become more rigorous. Unfortunately, enough data are not yet available that would permit us to compare chemistries of plutonic rocks from fast versus slow accreting plate margins, so that large-scale variations can only be inferred indirectly (see Chapter 9).

F. Summary

(1) The gabbroic rocks presumed to comprise the lower oceanic crust, appear, based upon chemical and supportive petrographic evidence, to be produced during differentiation of basaltic magmas ascending

from the asthenosphere at accreting plate boundaries. Preliminary chemical modeling of oceanic gabbroic rocks suggests that they are formed in shallow crustal magma chambers by fractionation principally of the observed major phases olivine, plagioclase and clinopyroxene. The passive emplacement of basaltic magma at the locus of accretion along a spreading ridge implies that shallow level reservoirs or magma chambers steadily feed basaltic material to the surface; these reservoirs or chambers must, therefore, be continually supplied with new batches of liquid from the upper mantle. This "open" system is compatible with the observations made on the site 334 gabbros and with chemical modeling on some oceanic basalts (Rhodes, et al., 1979). The degree of chemical evolution within a magma chamber will be a function of its replenishment rate, implying that more evolved plutonic rocks could be recovered preferentially at slowly accreting, infrequently replenished plate boundaries, and less evolved rocks should be recovered preferentially from rapidly accreting plate boundaries. Unfortunately, our current data bias (toward slowly accreting plate boundaries) does not permit us to confirm this suggestion.

(2) There appear to be both chemical and mineralogic data indicating that seawater may penetrate along a restricted system of permeable pathways to the magma chamber and interact with still-hot crystal mush. This process may occur at the periphery of the magma chamber, where the overlying basaltic carapace is sufficiently brittle to effectively propagate fractures and the underlying gabbro is not yet completely crystalline. In addition, individual dykes penetrating the gabbroic complex may act as local conduits for seawater, a suggestion supported by field and chemical evidence from the Sarmiento

ophiolite complex (Elthon and Stern, 1978).

(3) Deformation and alteration at accreting plate boundaries appear to occur in a continuum that ranges from high-temperature recrystallization and ductile deformation to low-temperature brittle deformation and the formation of low-temperature minerals in cracks and veins. The inter-dependence of dynamic metamorphism and hydrothermal metamorphism is suggested by the observation that both zones of mylonitization and brittle faults appear to act as conduits for altering fluids.

(4) All of the petrographic observations discussed in this section, and the above model of ocean floor metamorphism, imply that the lower oceanic crust is characterized by a complex distribution of rock type and metamorphic effects. It has been demonstrated that a marked heterogeneity of textures observed at both outcrop and microscopic scales exists within a single submersible traverse on the bounding walls of the Mid-Cayman Rise rift valley, which expose a portion of Layer 3 (DeLong et al., 1978; CAYTROUGH, 1979). This observed range of variability appears on all scales in rocks collected from all of the world's oceans (Engel and Fisher, 1975). In addition to these thin section and hand specimen observations, many authors note that the lower oceanic crust appears to be heterogeneous with respect to the distribution of rocks. For example, serpentinized ultramafic rocks had been believed to occur principally as random diapiric upwellings within the highly faulted fracture zone regime. The recovery of serpentinites in regions far removed from fracture zones and the random pattern of their distribution in these regions, has, however, also been documented (Aumento and Loubat, 1971). Thompson and Melson

(1972) and Bonatti and Honnorez (1976), in agreement with Aumento and Loubat, suggest that throughout the oceanic crust layer 3 may be a complex intercalation of mafic and ultramafic rocks. Screens of serpentinized ultramafic material appear to intrude the gabbroic unit observed by submersible at the Mid-Cayman Rise (CAYTROUGH, 1979). CAYTROUGH, in fact, have noted that these screens are often associated with rodingitized gabbro, suggesting that intrusion of the serpentinite is accompanied by extensive metasomatism (rodingitization). A realistic model for the lower oceanic crust must take into account this heterogeneous distribution of igneous textures, mineralogy and chemistry and of metamorphic effects.

(5) Our models may reflect our interpretation of the igneous and metamorphic character of only the shallowest portion of seismic layer three. As we observed in the first section of this paper, all of the gabbroic samples recovered from the sea floor have been emplaced, either dynamically or through igneous processes, at very shallow levels in the oceanic crust.

(6) In addition to the complexities demonstrated to be inherent in the distribution of rocks within the lower oceanic crust, transform faults may further perturb the accretionary and metamorphic processes and thereby have an effect on the formation and evolution of "normal" oceanic crust. The complexities invoked by the presence of a transform are discussed at length by Fox, et al. (in press) and will be discussed in the summary of this chapter.

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CHAPTER II

GEOLOGIC INVESTIGATIONS IN THE CAYMAN TROUGH: EVIDENCE FOR THIN OCEANIC CRUST ALONG THE MID-CAYMAN RISE

A. Abstract

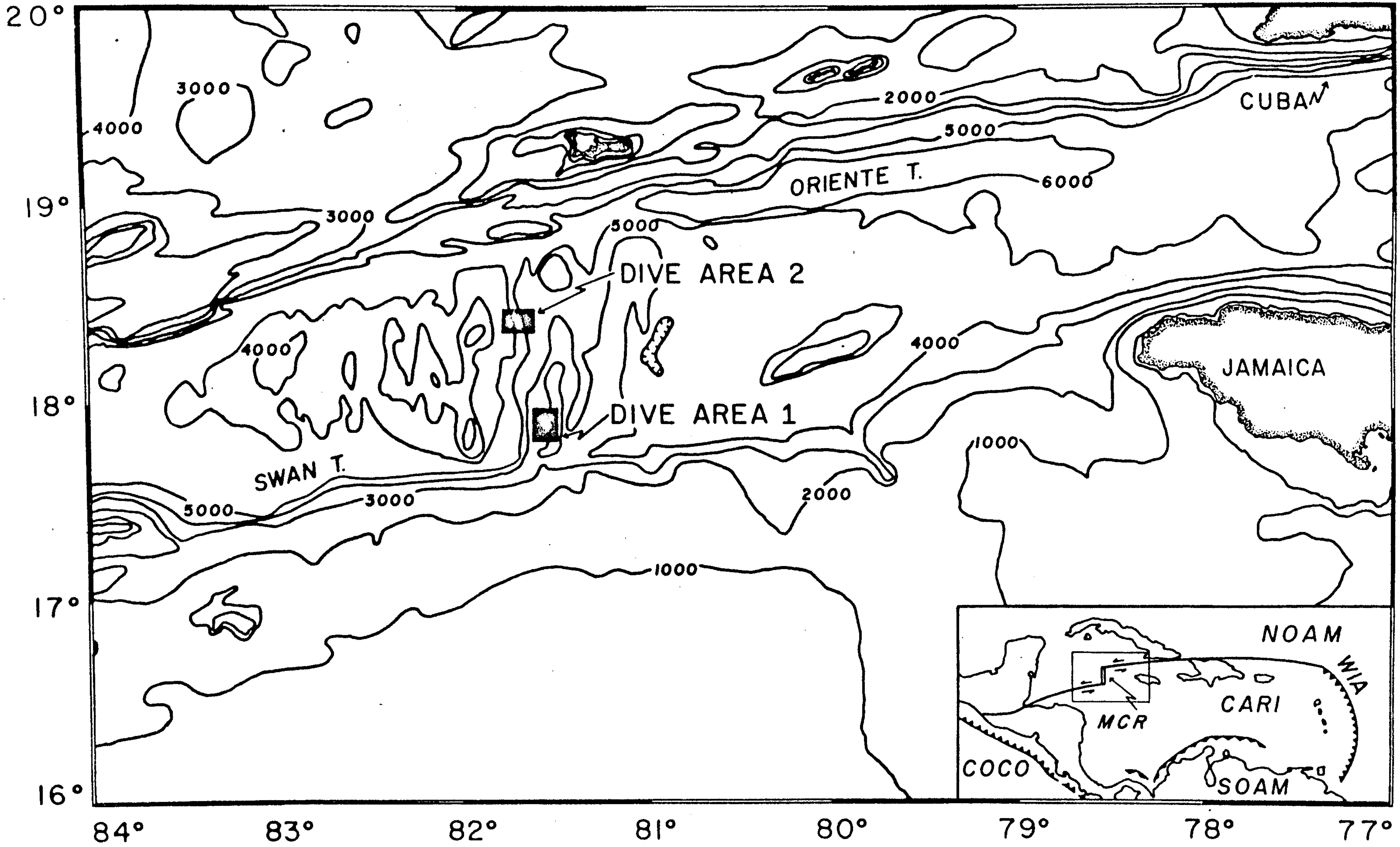
The Mid-Cayman Rise is a 110 km long accreting plate boundary (~2 cm/yr, full rate) characterized by a deep rift valley. Eighteen transponder-navigated dives were made by the submersible ALVIN along the rift valley walls in two areas on opposite sides of the rift valley. The relief of the walls is produced by a large number of inward facing small-throw fault escarpments with vertical displacements ranging from a few tens of meters to perhaps as much as 400 meters. From these escarpments 142 samples were collected, and gabbroic rocks (116 samples), characterized by a wide range of compositions and a complex metamorphic history, predominate in number over other rock types (basalt, serpentinized ultramafic). We interpret the assemblage of rocks exposed on the escarpments to indicate that a shallow level magma reservoir exists beneath the axis of accretion at the Mid-Cayman Rise and creates anomalously thin oceanic crust with a carapace of only several hundreds of meters of diabase and basalt. This carapace is underlain by a plutonic assemblage, possibly of only 1 to 2 km thickness, composed of gabbroic rocks intruded by screens of serpentinized ultramafic. The crust created along the axis of the Rise may be thin as a result of the juxtaposition of the short, slowly accreting Rise segment and two long transform faults. The closely spaced transforms act as heat sinks for the asthenosphere wedge rising beneath the axis of accretion, resulting in a decrease in the volume of melt segregated from the asthenosphere

and, hence, a thinner than normal oceanic crust. Although the Mid–Cayman Rise probably represents an end-member example of this effect, we suggest that thin oceanic crust and the existence of a heterogeneous assemblage of gabbroic rocks at shallow levels is a characteristic of ridge/transform intersections at slowly accreting plate boundaries.

B. Introduction

The northern Caribbean plate boundary is defined by an east–west trending morphologic feature known as the Cayman Trough (e.g., Molnar and Sykes, 1969; fig. 1). The margins of the 110 km wide Trough are delineated by two deeps, the Oriente on the north and the Swan on the south. Based upon an analysis of sedimentalogic, bathymetric and seismic data, Holcombe et al. (1973) identified a north–south trending ridge with a deep axial valley within the central portion of the Trough (at 81°40'W) that they interpreted to be the locus of active sea–floor spreading, and they named this spreading center the Mid–Cayman Rise. The northeastern and southwestern portions of the latitudinal deeps are transform faults with left–lateral relative motion: Jordan (1975) has shown from a study of epicenter and first-motion data that the Oriente Transform extends eastward from the Mid–Cayman Rise into the Puerto Rico Trench (also a left–lateral transform) and abuts the West Indies Arc subduction zone, and that the Swan Transform projects westward from the Rise into the Polochic-Motagua fault zone of Central America (fig. 1 inset). The interpretations of these authors are supported by or consistent with other marine geological and geophysical data, summarized by Perfit and Heezen (1978) and CAYTROUGH (1979); most notably, Macdonald and Holcombe

Figure 1 Generalized bathymetric map of the central portion of the Cayman Trough, showing the location of the two ALVIN dive areas on the Mid-Cayman Rise. Depths are in meters. Inset (after Jordan 1975) is a schematic representation of the first-order tectonic configuration of the Caribbean area. MCR = Mid-Cayman Rise; NOAM = North American Plate; CARI = Caribbean Plate; COCO = Cocos Plate; SOAM = South American Plate; WIA = West Indies Arc.


20°
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83°
82°
81°
80°
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78°
77°
CUBA
ORIENTE T.
JAMAICA
DIVE AREA 2
DIVE AREA 1
SWAN T.
2000
5000
6000
3000
4000
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5000
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4000
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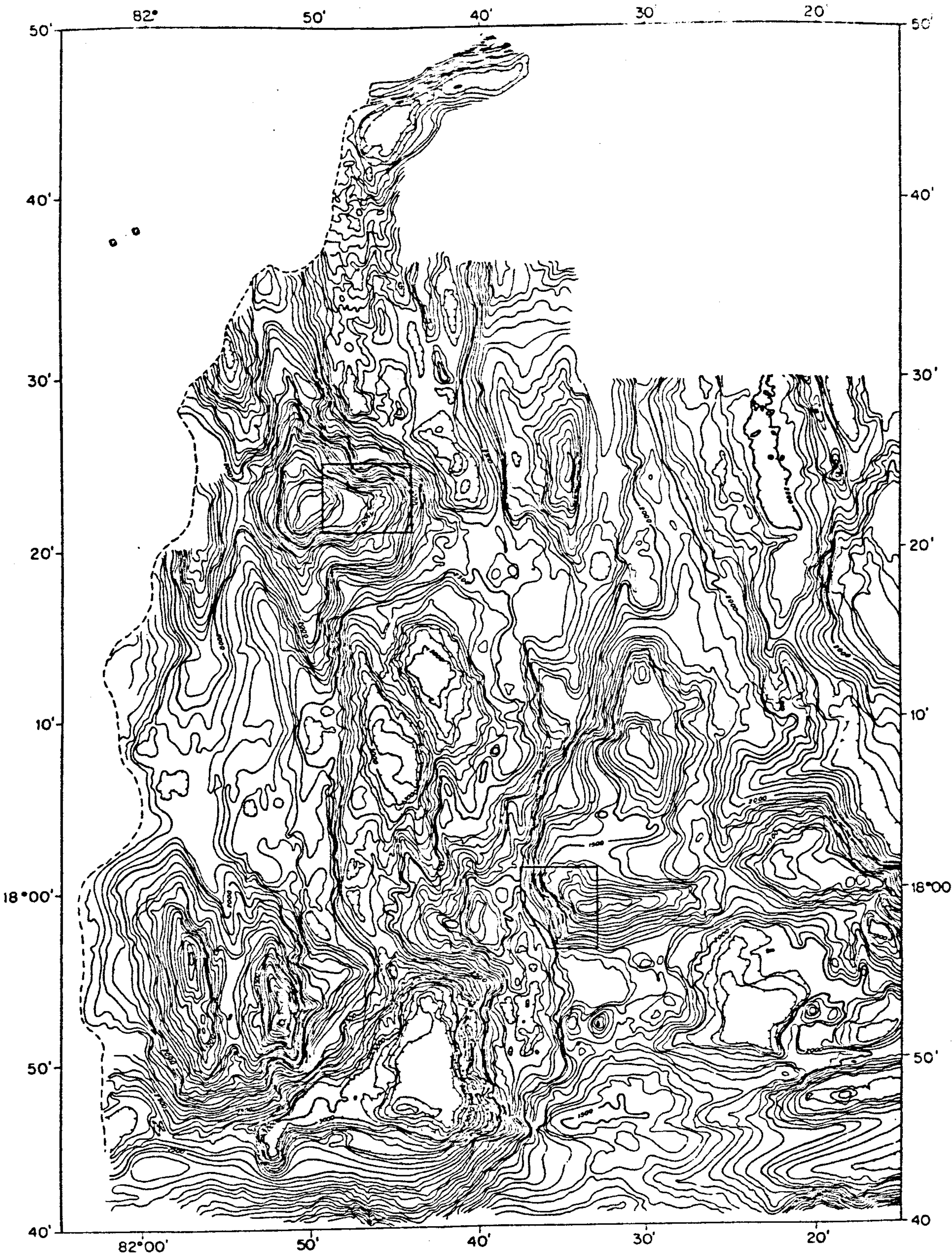
3000
1000
NOAM
WIA
CARI
MCR
COCO
SOAM

(1978) have presented marine magnetic anomaly data indicating that the Rise is presently opening with a full rate of 2.0 cm/yr, and that it has been spreading for at least the last 8.3 m.y.

In January 1976 the Cayman Trough Project began a series of field programs designed to explore the Mid–Cayman Rise, and the preliminary results of these programs have been reviewed by CAYTROUGH (1979). The data that will be examined in this paper were collected during a submersible survey that employed the DSRV ALVIN in two consecutive field seasons (January-March 1976 and April 1977). The survey, which recovered rock samples and utilized video–tape and high repetition–rate still cameras, was conducted in two dive areas located on the steep rift valley walls flanking the axis of spreading (figs. 1 and 2). The samples were obtained by ALVIN from small–relief inward facing escarpments, similar to those shown to characterize rift valley wall morphology in the FAMOUS region of the Mid–Atlantic (e.g., Macdonald and Luyendyk 1977); but, unlike the suite of basaltic rocks recovered from the FAMOUS area, the Mid–Cayman Rise collection is comprised predominantly of coarse-grained gabbroic rocks. Petrographically and chemically identical gabbroic rocks have been recovered routinely from the bounding escarpments of oceanic fracture zones (e.g., Engel and Fisher, 1969, 1975; Bonatti et al., 1971; Miyashiro et al., 1971). In only two other sampling programs, however, have gabbroic rocks been collected from escarpments thought to be generated at an accreting ridge segment (Bonatti et al., 1975; Tiezzi and Scott 1976), and the interpretation of the significance of these latter samples is compromised by the ambiguities inherent in their recovery by dredging. Thus, while the Mid–Cayman Rise is a ridge segment with all of the features thought to

<u>Figure 2</u> Detailed bathymetric map of the Mid-Cayman Rise; the data used to construct this map were compiled during the Cayman Trough Project using the U.S. Navy multinarrow beam echo sounding system (CAYTROUGH 1979). Boxes show the locations of the two ALVIN dive areas. Depths are in uncorrected fathoms.


82°
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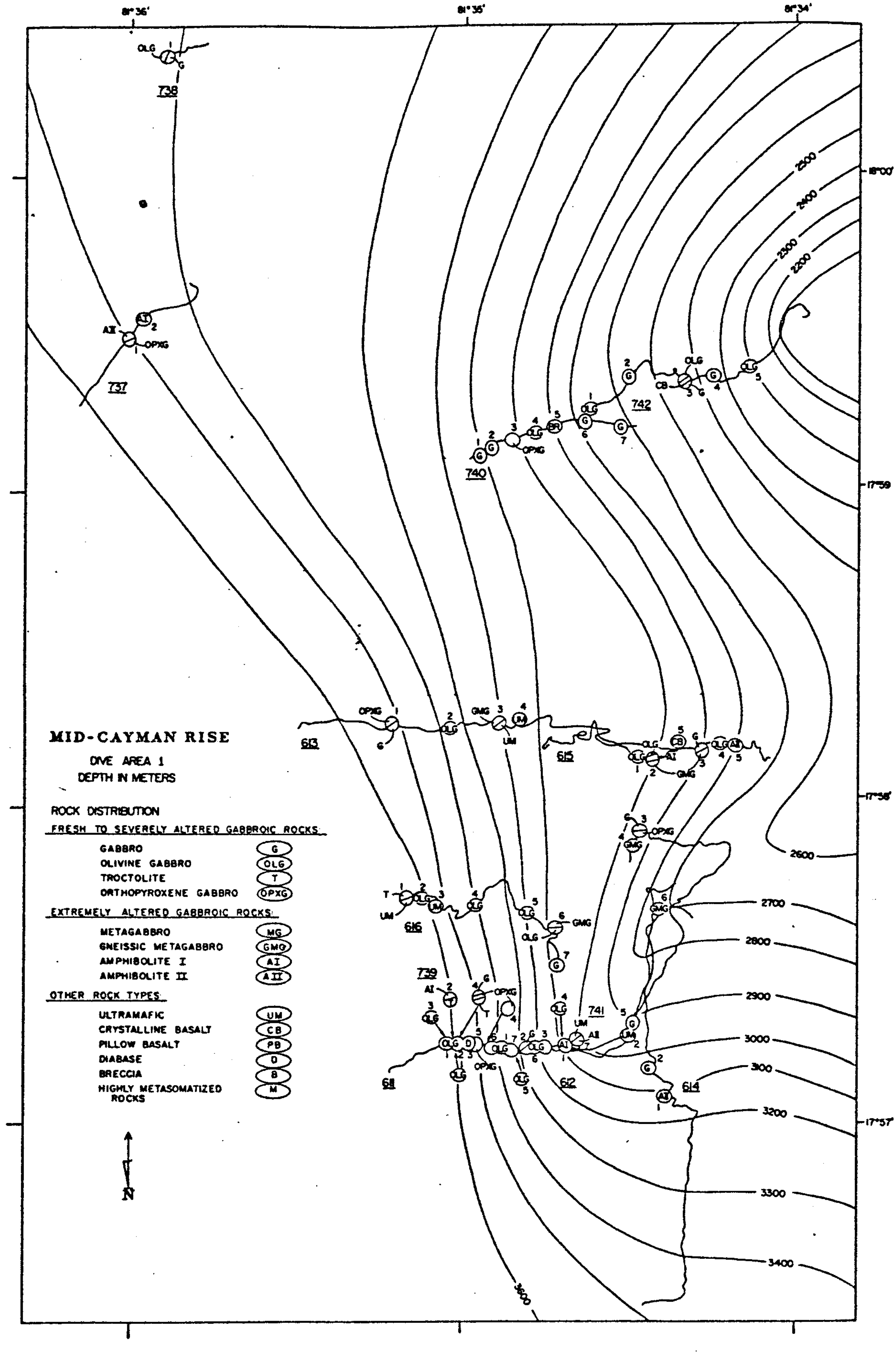
40'
30'
20'
2000
1500
1000

be characteristic of slowly accreting plate boundaries, the exposure of gabbroic rocks on rift valley walls is not common, suggesting that the tectonic processes operating at the Rise contrast in some fundamental way with those thought to be operating at most ridge segments. Furthermore, if the exposure of these gabbroic rocks is an exposure of the upper portions of the plutonic foundation of the oceanic crust, then we have a singular opportunity to examine the vertical and lateral distribution of the rocks of the lower oceanic crust.

C. Submersible Observations

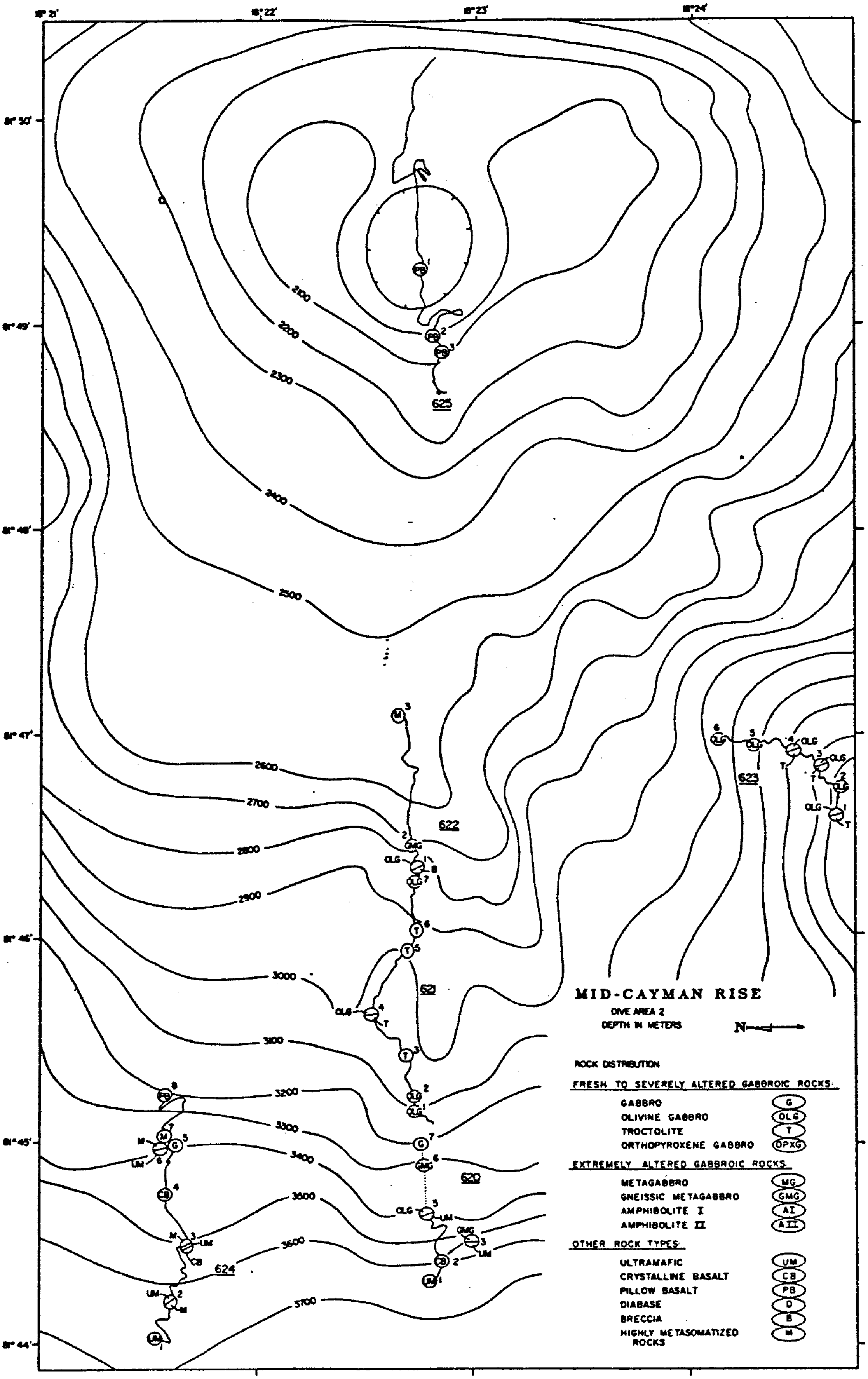
The eighteen dives conducted by ALVIN were navigated by its acoustical transponder system (ALNAV), which is capable of ±10 m positioning accuracy. In the first field season (1976), twelve dives were conducted to ALVIN's maximum depth capability (~3600 m), with six dives located on the east wall of the rift valley (Dive Area 1, dives 611–616) and six dives located on the west wall (Dive Area 2, dives 620–625) 60 km to the north of Dive Area 1 (figs. 2, 3 and 4). In 1977 we returned with ALVIN to Dive Area 1 and completed six additional dives (dives 737–742). In 1976 we did not anticipate a return to Cayman in 1977; hence, no transponders were left on the sea floor and the dives of the second field season could only be fixed relative to those of the first by matching satellite and bathymetric data. However, we have, since the publication of two preliminary Cayman Trough Project papers (CAYTROUGH 1979; White and Stroup 1979), made positive photographic verification of total overlap of the southernmost two dives of each field season (fig. 3) allowing us to fix precisely the two sets of dives relative to each other. The sampling interval along most of our

Figure 3 Generalized bathymetry and dive tracks of Dive Area 1 with distribution of rock types collected at numbered stations. All dives in both areas were initiated at greater depths and proceeded to shallower depths.



MID-CAYMAN RISE
DIVE AREA 1
DEPTH IN METERS
ROCK DISTRIBUTION
FRESH TO SEVERELY ALTERED GABBROIC ROCKS:
GABBRO G
OLIVINE GABBRO OLG
TROCTOLITE T
ORTHOPYROXENE GABBRO OPXG
EXTREMELY ALTERED GABBROIC ROCKS:
METAGABBRO MG
GNEISSIC METAGABBRO GMG
AMPHIBOLITE I AI
AMPHIBOLITE II AII
OTHER ROCK TYPES:
ULTRAMAFIC UM
CRYSTALLINE BASALT CB
PILLOW BASALT PB
DIABASE D
BRECCIA B
HIGHLY METASOMATIZED ROCKS M
N
81°36'
81°35'
81°34'
18°00'
17°59'
17°58'
17°57'
2200
2300
2400
2500
2600
2700
2800
2900
3000
3100
3200
3300
3400
3600
737
738
739
740
741
742
611
612
613
614
615
616

Figure 4 Generalized bathymetric map, dive tracks and rock distribution of Dive Area 2.

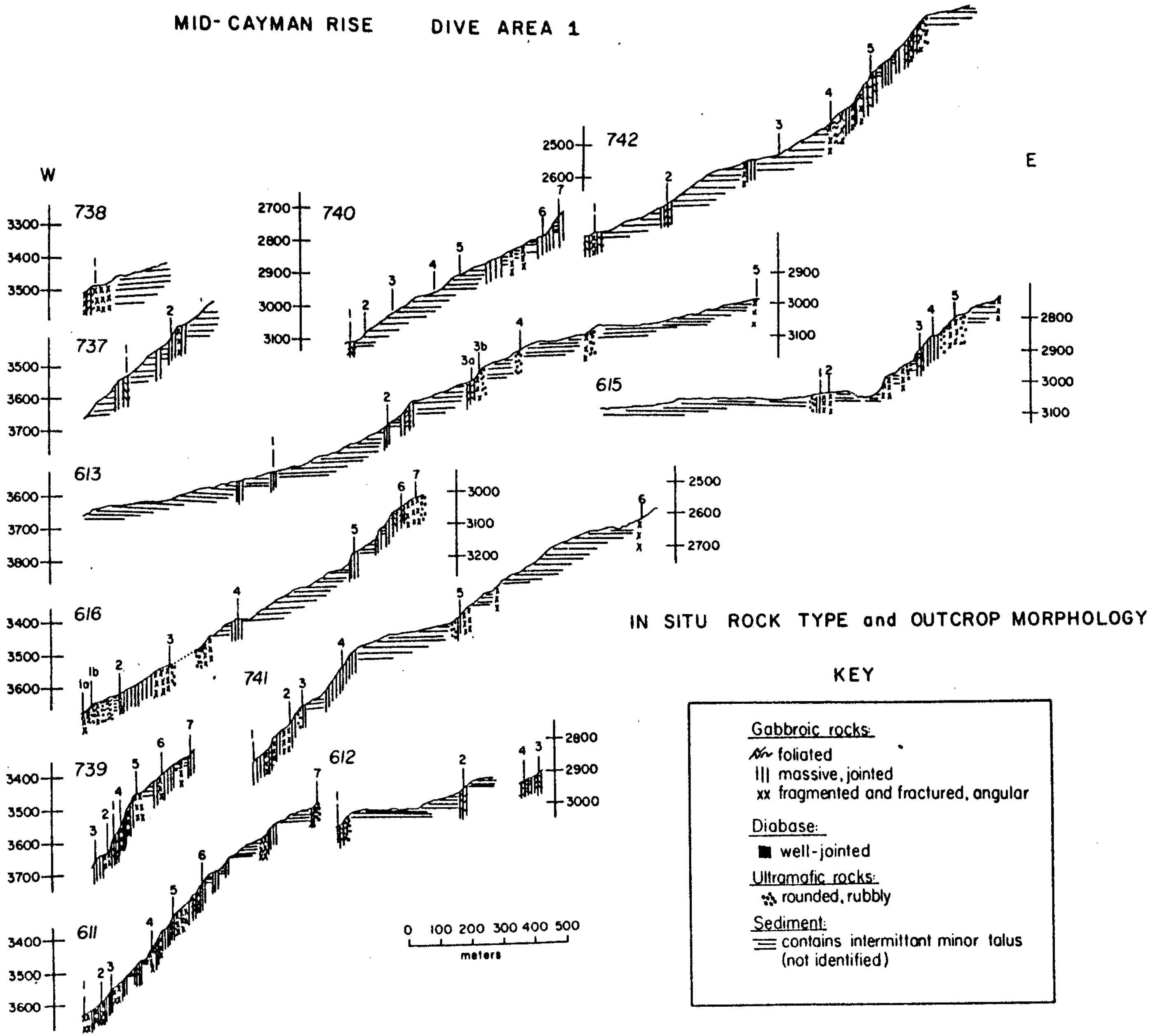

MID-CAYMAN RISE
DIVE AREA 2
DEPTH IN METERS
N
18°21'
18°22'
18°23'
18°24'
81°50'
81°49'
81°48'
81°47'
81°46'
81°45'
81°44'
2100
2200
2300
2400
2500
2600
2700
2800
2900
3000
3100
3200
3300
3400
3600
3600
3700
625
622
621
620
624
623
ROCK DISTRIBUTION
FRESH TO SEVERELY ALTERED GABBROIC ROCKS:
GABBRO G
OLIVINE GABBRO OLG
TROCTOLITE T
ORTHOPYROXENE GABBRO OPXG
EXTREMELY ALTERED GABBROIC ROCKS
METAGABBRO MG
GNEISSIC METAGABBRO GMG
AMPHIBOLITE I AI
AMPHIBOLITE II AII
OTHER ROCK TYPES:
ULTRAMAFIC UM
CRYSTALLINE BASALT CB
PILLOW BASALT PB
DIABASE D
BRECCIA B
HIGHLY METASOMATIZED ROCKS M

traverses is 50 to 100 m, and between traverses is ~1000 m; the sampling interval along the southernmost, overlapping dives of Dive Area 1 averages ~30 m. Vertical and lateral variability of rock distribution and of morphologic features can be determined with great accuracy given this sampling interval and the continuous photographic coverage of our traverses.

(a) Rift valley wall topography and outcrop morphology. The rift valley floor of the Mid-Cayman Rise is extremely deep, residing between 5 and 6 km below the sea surface and 3.5 km below the tops of the flanking rift valley walls. The walls, which appeared on earlier surface ship surveys (e.g., Holcombe et al., 1973) to be essentially continuous, and sloping at angles of 20^0 to 30^0 toward the valley floor, are actually characterized by a large number of inward facing steps (figs. 5 and 6). The steps are comprised of a series of escarpments, with relief varying from several meters to roughly 100 meters and with dips at angles of 60^0 or greater toward the valley floor, and of intervening pelagic carbonate-covered platforms that dip at angles of 10^0 to 60^0 toward the valley floor and that vary from a few meters to several hundreds of meters in width. The integrated topography of the steps is irregular, which is the result of significant variability of the dimensions of the steps: inspection of the dive cross-sections (figs. 5 and 6) shows that the relief of escarpments and the width of sediment platforms change both vertically and laterally. For example, in the southern portion of Dive Area 1 the sediment platforms are very narrow and the combined relief of the escarpments is large over short distances on a single profile; in the northern portion of the area escarpment frequency diminishes and relief on a given escarpment is small, and the sediment platforms here are considerably broader than

Figure 5 Surficial morphology and major rock types represented as profiles for traverses conducted in Dive Area 1 (not meant to be representative of subsurface geology).

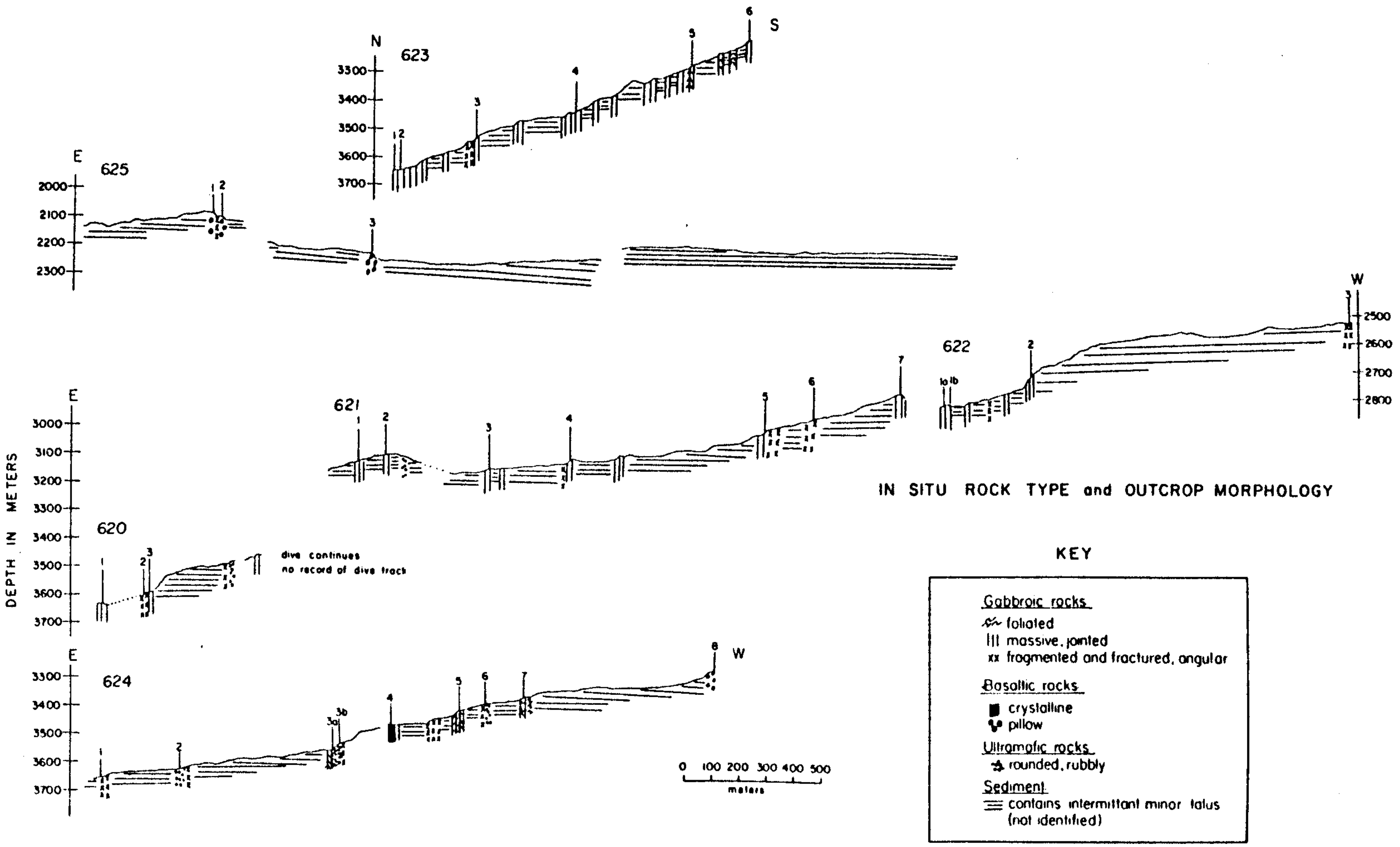
MID-CAYMAN RISE DIVE AREA 1



IN SITU ROCK TYPE and OUTCROP MORPHOLOGY

Figure 6 Surficial morphology and major rock type profiles for Dive Area 2 traverses.

MID-CAYMAN RISE DIVE AREA 2


IN SITU ROCK TYPE and OUTCROP MORPHOLOGY

they are to the south.

The general trend of the inward facing escarpments is north–south. These escarpments, however, are not continuous along their strike but are offset or interrupted at frequent intervals (50 to a few hundred meters) by a set of east–west trending near–vertical escarpments. The east–west escarpments are neither vertically nor laterally as large as the north–south escarpments but have from ten to several tens of meters of relief, and from a few meters to several tens of meters of horizontal extent. The offset of the predominant north–south topographic grain by these east-west escarpments creates a distinctive saw–tooth morphology characterized by blocky rock promontories with steep north–south faces, and re–entrants that generally serve as conduits for talus (fig. 7a) but that may expose a steep north–south trending rear wall.

Many of the escarpments have been modified by submarine mass wasting. The tops of outcrops are often comprised of bedrock fragments loosened by fracturing, and large planar cracks parallel with the vertical faces of some escarpments appear to represent planes of weakness for future episodes of spalling. The sediment–covered platforms are characterized by intermittant but abundant talus fans made up of material ranging from gravel–sized fragments to large blocks up to a meter or more in diameter; talus accumulations range in size from isolated fragments strewn on the slope to ramps of talus several meters in width to large piles at the base of a steeply dipping escarpment. In spite of this evidence of submarine erosion, however, scour marks in sediment (the trails of falling debris) are only rarely observed. Very few escarpments are completely sediment–free, and most exposed rock surfaces are manganese encrusted with manganese coatings that vary from .5 mm to 1.5 cm in thickness. Talus piles are welded by

Figure 7 a. North-south trending, granular-textured massive escarpment offset by small east-west trending scarp which has created a chute for sediment and talus (at right). Width of photo ~2 m (dive 739, ~3640 m).

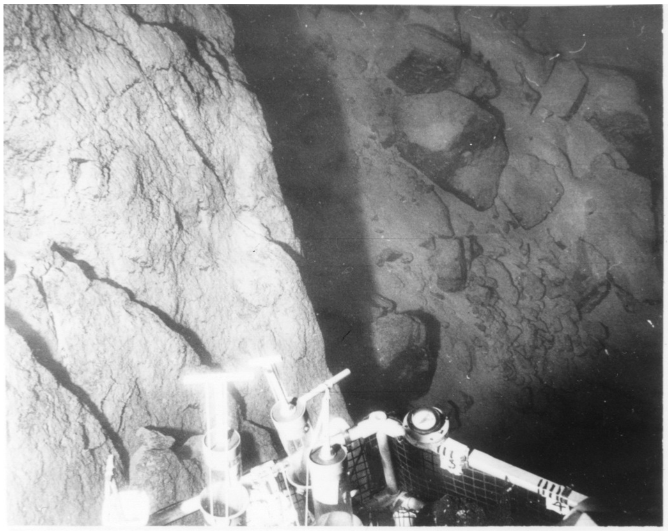
b. Downslope slickensides on granular-textured massive north-south scarp (vertical field of view at left ~2 m; dive 739, ~3630 m).

c. Fairly massive north-south scarp broken by east-west trending near-vertical joints. Width of photo ~5 m (dive 739, ~3460 m).

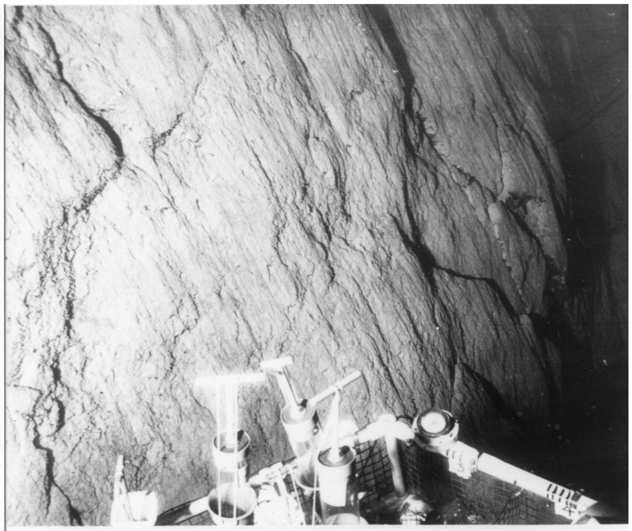
d. Small (~3 m vertical) "fruitcake" outcrop exposed at right on steeply dipping sediment ramp (dive 741, ~2830 m).

e. Typical "shark's tooth" textured terrain of fractured, moderately sediment-covered gabbroic outcrop. Vertical field of view ~2 m (dive 739, ~3530 m).

f. Contact between north-south trending diabase dike (in foreground) and vertical north-south face of strongly banded rock (at rear). Width of photo ~3 m (dive 739, ~3520 m).



a



b

c

d

e

f

sediment and manganese. We observed no sediment scarplets or sediment disruption (by faulting, for example), and talus and sediment platforms or ramps abut, with no gap or discontinuity, the bases of the bedrock escarpments.

Both north—south and east-west trending escarpments expose bedrock that can be characterized most frequently as blocky or massive in appearance (i.e., fig. 7b, c), and much of this massive material can be observed, where not too heavily masked by sediment and/or manganese, to have a roughly textured, grainy or pockmarked surface character. Sampling indicates that these massive outcrops are composed of gabbroic rocks, and their granular surface texture may reflect coarse grain size. We observed two other, less common outcrop morphologies on the rift valley walls: (1) an outcrop type that was described by CAYTROUGH (1979) as having the appearance of a fruitcake with large ovoid and smaller, more angular fragments set in a fine matrix (fig. 7d); (2) basalt. The "fruitcake" outcrop type is intercalated heterogeneously with the massive outcrops; the size of fruitcake outcrops varies from very small (a pod or lens of material < 1 to 2 m in length, $\leq$ 1 m in width) to moderate (5 m of vertical exposure). Fruitcake outcrops appear to suffer erosional degradation readily, and the distinctive ovoid—shaped clasts occur frequently as debris scattering sediment—covered slopes. Fruitcake outcrops are composed, at least in part, of serpentinized ultramafic rocks. On recent dives on the walls of the Oceanographer Transform we observed morphologically similar outcrops of serpentinized ultramafic material that there appear to be semiconsolidated debris flows (unpublished data). Several pillow basalt outcrops were observed. The pillows, moderately sediment—covered and manganese—encrusted, are easily recognizable: in one dive they appear as isolated, broken outcrops of only ~7 to 10 m in vertical extent, and in another we observed a single near—vertical escarpment made up entirely of pillows, many of which are truncated at the face of the escarpment. A massive basalt sheet flow or sill, having a smooth or fine-grained surface appearance, was also observed.

The north-south and east—west trending escarpments represent the most obvious, first—order morphotectonic feature of the rift valley walls, but a range of second—order features disrupts the integrity of the rocks exposed on the escarpments. The most prominent of these second—order features is jointing (fig. 7c). Two principal intersecting joint sets are present, one trending roughly north—south and one trending roughly east—west. The joint planes strike generally parallel with the north—south and one trending roughly east—west. The joint planes strike generally parallel with the north—south and east—west trending escarpments; dips of joint surfaces are observed to vary from vertical to almost horizontal. The intensity of jointing is widely variable from outcrop to outcrop and even appears to increase or decrease gradually over several tens of meters in continuous outcrop. Almost as prevalent as the joints are randomly oriented fractures that cut through the outcrops. The most pervasively fractured outcrops have a distinctive texture resembling shark's teeth embedded in sediment (fig. 7e). The width of zones of fracturing is variable, and rubble zones (with "shark's tooth" texture) only a few meters wide are observed to be intercalated with less fractured rock. A third feature observed on the rift valley walls is the apparent planar banding, either layering or foliation, of outcrops. Large outcrops of banded rock are common (i.e., fig. 7f) and the range in orientation of the planes defining the banding is large. Rarely we observed narrow zones (<1 to 2 m wide) apparently composed of either very finely layered or highly foliated rock that transect coherent and unbanded rock.

Changes in outcrop appearance, as a function of changes in outcrop morphology or of changes in the nature and extent of tectonic modification of outcrops, occur in random order and at random intervals on the rift valley walls. This heterogeneity is reflected in random distribution of the intensity of jointing and/or fracturing, small rubble zones within unfractured material, narrow zones of banded rock within non-banded rock, and the intercalation of massive with fruitcake and basalt outcrops. In some areas the changes in outcrop appearance take place gradually over continuous exposures (i.e., steeply dipping, massive escarpments become progressively more fragmented by joints and/or fractures over vertical or horizontal distances of 10 to 30 m). In other areas, however, transitions between outcrop characteristics are extremely sharp. Sharp contacts may be either intrusive or fault contacts; apparent fault contacts are observed in the abrupt juxtaposition of large outcrops of fractured against unfractured material or banded against unbanded material (fig. 7f).

The prominent set of steeply dipping north—south trending escarpments is presumed to be analogous to the set of small—throw faults that is observed on the rift valley walls at the slowly accreting ridge segments of the FAMOUS area (e.g., Needham and Francheteau 1974; Ballard and van Andel 1977; Macdonald and Luyendyk 1977) and that are linked by a series of more gently sloping sediment—covered terraces. The sense of relative motion on these north—south faults should be largely dip-slip in order to create their observed relief, and, compatible with this assumption, slickensides that trend downslope are observed on many north-south striking faces (fig. 7b). The secondary set of east-west trending near-vertical escarpments also appears to represent a set of small-throw faults, but the sense of relative motion on the east-west fault planes cannot be readily determined (for further discussion, see Stroup 1981).

The observed relief of the inward facing escarpments varies from only a few meters to approximately 100 meters. However, due to the effects of mass-wasting and the obscuring nature of the sediment/talus accumulations, this relief must represent the minimum offset along inward facing fault planes. Moreover, we assume that, as suggested for the rift valley walls in the FAMOUS area (e.g., Needham and Francheteau 1974; Macdonald and Luyendyk 1977), the rift valley walls of the Mid-Cayman Rise are made up of a number of upfaulted blocks whose inner faces are the inward facing escarpments. Given that some modification of the escarpments by mass wasting may have occurred along joint surfaces paralleling the strike of the escarpments, it is probable that not all of the escarpments represent fault planes defining the faces of fault blocks suggesting that the actual number of fault blocks may be smaller than it appears. For example, there is approximately 400 m of almost continuous outcrop exposure on the lower part of the slope in Dive Area 1 (figs. 3 and 5) where the escarpments are interrupted by narrow, steeply dipping sediment/talus ramps; these outcrops may represent a single fault block whose face has been modified by mass wasting.

The vertical and lateral variability of slope morphology suggests that the fault blocks of the walls are not continuous along the strike of the rift valley, and that there is probably significant irregularity to the size of the fault blocks. This may be a result of relay or scizzor faulting such as is observed on the Mid-Atlantic Ridge rift valley walls (Macdonald and Luyendyk 1977). The lateral discontinuity of the block morphology on the Mid-Cayman Rise may also reflect the effects of mass wasting of the slope and the displacement of the blocks on east-west trending fault surfaces.

The abundance of talus and the apparent degradation of many of the steeply dipping bedrock escarpments suggests that the role of mass wasting in modifying the morphology of the slopes is pronounced. Yet, in spite of the evidence of mass wasting, and in spite of evidence indicating that the escarpments are generated by faulting, we observe that very little of the mass wasting and apparently none of the faulting are recent. There is no structural disruption of sediment slopes or of talus, and faces of bedrock outcrops and the fractures and joints that transect them are dusted or infilled by sediment. It appears that the processes that led originally to the development of the observed morphotectonic features, and to the random juxtaposition of outcrops having different morphotectonic imprint or morphologic character, are not appreciably active on the upper portions of the rift valley walls.

(b) Properties and distribution of rocks recovered. During our 18 dives with ALVIN we occupied 94 sampling stations and recovered 142 samples (Table 1; CAYTROUGH 1979). Gabbroic rocks are the most abundant rock type in our collection (116 samples); detailed descriptions of these rocks are provided by Malcolm (1979), whole-rock major and trace element analyses have been made on most samples (Stroup unpublished data), and mineral chemistry analyses have been made on a

TABLE 1

Samples collected by ALVIN from the rift valley walls of the Mid-Cayman Rise.

Rock Types	Sample Numbers Dive Area 1	Sample Numbers Dive Area 2
Serpentinized Ultramafics		
Spinel harzburgite	612-2-1^b, 612-2-2^b, 613-3-2, 613-4-1, 613-4-3, 613-4-4, 616-3-1	624-1-1^b, 624-2-1^b, 624-3-3,
Spinel lherzolite	611-7-1, 613-4-2, 616-1-1	624-6-2
Spinel-plagioclase dunite		620-1-1, 620-3B
Plagioclase wehrlite		620-5-2, 624-2-3^b
Fine-grained Rocks		
Diabase	611-3-1	
Crystalline basalt	613-5-1^b, 742-3-2	620-2-1, 624-3-1, 624-4-1
Pillow basalt		624-8-1, 624-8-2, 625-1-1, 625-2-1, 625-3-1
Gabbroic Rocks^a		
Gabbro	612-3-1, 613-1-2, 614-2-1, 615-3-1, 616-7-1, 616-7-2, 738,1-2, 739-4-1, 740-1-1^b, 740-2-1^b, 740-6-1, 740-7-1 741-2-1, 741-5-1, 742-2-1, 742-3-3^b, 742-4-1, 742-4-2	620-7-1, 624-5-1
Olivine gabbro	611-1-1, 611-2-1, 611-5-1, 611-5-2, 611-6-1, 613-2-1, 615-1-1, 615-2-1, 615-4-1, 616-2-1, 616-2-2, 616-3-2 616-4-1, 616-5-1, 616-5-2, 616-6-2 738-1-1, 739-1-1^b, 739-3-1^b, 739-6-1 739-7-1, 740-4-1^b, 741-1-1, 741-1-2, 741-2-2, 741-3-1, 741-4-1, 742-1-1, 742-3-1^b, 742-5-1, 742-5-2	620-5-1, 621-1-, 621-2, 621-4-1, 621-4-2, 621-7-1, 622-1-1, 622-1-2, 623-1-1, 623-2-1, 623-3, 623-4-1, 623-4-2, 623-5-1, 623-6-1
Troctolite	616-1-2, 739-2-2, 739-4-3, 739-4-4	621-3-1, 621-3-2, 621-4-3, 621-5-1, 621-6-1, 623-1-2, 623-1-3, 623-1-4, 623-3-2, 623-4-3

Orthopyroxene gabbro	611-4-1, 612-3-2, 613-1-1, 613-1-3, 737-1-2[b], 739-4-2, 739-5-1, 740-3-1	
Miscellaneous		
Amphibolite I (brecciated but not foliated hornblende-plagioclase rock)	612-1-1, 612-1-2, 615-2-2, 737-2-1[b]	
Amphibolite II (foliated hornblende-plagioclase rock)	611-7-2, 614-1-1, 615-5-1, 737-1-1[b]	
Metagabbro (original igneous minerals only partially preserved)	739-2-1	
Gneissis metagabbro (foliated metagabbro)	612-4-1, 612-4-2, 613-3-1, 615-2-3, 615-3-2, 616-6-1, 741-6-1	620-3A, C, 620-6-1, 622-2-1, 622-2-2
Highly metasomatized rocks		622-3-1, 624-2-2[b], 624-3-2, 624-6-1, 624-7-1
Breccia	740-5-1[b]	622-1-3

[a] Classification of fresh gabbroic rocks after Streckeisen (1976)

[b] Samples recovered as talus far from or not visibly associated with outcrop

subset of the samples (Ito 1979; Malcolm 1979). The range of primary gabbroic rock types, and the primary igneous textures preserved within the least altered gabbroic rocks, are comparable to the range of rock types and textures of rocks collected previously from other oceanic regions (Fox and Stroup 1981).

Olivine gabbro comprises the largest proportion of the gabbroic population; troctolite, gabbro (sensu stricto) and orthopyroxene gabbro were also recovered (Table 1; primary gabbroic rock type classification is that of Streckeisen 1976). In rocks where they are well preserved, olivines are subhedral to anhedral; in most samples olivines are surrounded by alteration coronas and cross-cut by veinlets infilled with alteration minerals. Olivine compositions range from Fo_{88} to Fo_{72}, the more magnesian olivines are found in troctolites, and none of the olivines appear to be compositionally zoned (Ito 1979; Malcolm 1979). Plagioclase is a ubiquitous phase in our samples. Many of the more calcic plagioclases are very large (up to 2 cm in length) and idiomorphic, and a number of these are both optically and chemically zoned. The range of plagioclase compositions, An_{84} to An_6, is extreme, and is found even within a single sample (Ito 1979; Malcolm 1979); the most calcic plagioclases occur in troctolites. Clinopyroxene is present in almost all samples, and crystals are euhedral to anhedral. Diopside and diopsidic augite are the most common clinopyroxenes and their compositions are within the field Wo_{40-50} En_{40-50} Fs_{5-10} (Malcolm 1979). Many of the clinopyroxenes contain chromium in abundances of .5% to 1% Cr_2O_3 (Ito 1979; Malcolm 1979), and TiO_2 contents of .5% to 1.5% characterize a few grains (Malcolm 1979), but no apparent correlation exists between rock type and clinopyroxene composition. Orthopyroxenes, apparently all of hypersthene composition, are rare in our samples. Rocks containing orthopyroxene are the most iron-rich members of the suite (Malcolm 1979); in addition to occurring as megacrysts orthopyroxenes are present as coronas around olivine and as exsolution lamellae in clinopyroxene. Calcic amphibole is common to almost all our rocks, and except for nearly constant Ca content, varies widely in composition and exhibits rare optical and chemical zoning (Ito 1979; Malcolm 1979). Hornblende rims clinopyroxene and olivine, appears rarely as exsolution lamellae in clinopyroxene, and is found in zones of granulation and veining; Ito (1979) observes hornblende projecting into vugs in a few samples. Actinolite is very common in veins and alteration patches, and cummingtonite and anthophyllite rim orthopyroxene (Ito 1979). Minor mineral phases include magnetite, ilmenite, iddingsite, chrysotile, talc, phlogopite, chlorite, biotite, prehnite, hydrogrossular and certain sulphides; trace amounts of apatite, zircon and sphene are quite common, and epidote and zoisite are rare (Ito 1979; Malcolm 1979).

Original igneous textures are preserved in many samples. Ophitic and subophitic textures are common, and optically continuous clinopyroxene interstitial to very large plagioclase laths characterizes several rocks. Olivines often have cuspate boundaries with plagioclase suggesting olivine's partial resorption (Malcolm 1979). Diallage structure and exsolution intergrowths characterize many of the large clinopyroxene grains. As classically defined (Wager et al., 1960), cumulate textures do not exist in our suite of samples. Primary mineral layering is not exhibited in either hand specimens or thin sections of any of our rocks.

Deformation effects in our gabbroic samples are similar to those observed in other oceanic gabbroic rocks (Fox and Stroup 1981; Malcolm in press). Apparent recrystallization resulting in grain size reduction characterizes both plagioclases and clinopyroxenes, and apparently recrystallized plagioclase grains (having granoblastic texture about large relict plagioclase or along cracks) have lower An contents than the larger plagioclases that they often surround (Malcolm 1979). Cataclastic deformation has resulted in the production of mylonites, protomylonites and microbreccias, and recrystallization/neomineralization concomitant with brecciation has produced a group of rocks classified here as "gneissic metagabbros" (Table 1). Late-stage microcracks that cross-cut the earlier deformation features, and that are infilled in almost all cases by chlorite and/or actinolite, are present in all samples.

Intensity of alteration is variable through the suite, producing a range from almost pristine rocks, in which only the mafic phases have experienced incipient replacement, to extremely altered samples in which primary phases are completely replaced or psuedomorphed (i.e., the metagabbros and highly metasomatized rocks of Table 1). Hydrothermal retrograde (low-pressure) metamorphism has produced the variety of secondary, generally hydrous phases that are observed as replacements, coronas, psuedomorphs or vein-fillings. Brown hornblende commonly rims clinopyroxene megacrysts; olivine cores, often partially replaced by talc and iddingsite(?), are rimmed outward by the general sequence bronzite, hornblende, mica, mica + chlorite and finally chlorite (Ito 1979). Eight amphibolites were recovered by ALVIN, four of which are foliated (amphibolite II) and four of which are unfoliated (amphibolite I; Table 1). Examination of some of the gabbros suggests that the amphibolites may have been produced by replacement of pyroxenes by green and brown amphibole together with the retention of fairly calcic plagioclase; we appear to have recovered a nearly complete gradational sequence, from fresh gabbro to amphibolite, that exhibits this relationship.

Preliminary bulk chemical analyses of rocks of the gabbroic suite indicate that they follow a fractional crystallization trend and have compositions typical of oceanic tholeiites (Fox and Stroup 1981; Stroup unpublished data). High Mg/Fe ratios and low TiO_2 contents of a number of the least altered gabbroic rocks indicates their relatively undifferentiated nature when compared with other oceanic plutonic rocks. Variability of Al_2O_3 with respect to FeO*/MgO suggests that some of the rocks may have formed by accumulation or removal of plagioclase (CAYTROUGH 1979). Metamorphic reactions involving seawater interaction with the rocks appear to be responsible for the addition of sodium, water and possibly iron and the removal of calcium and possibly magnesium from the samples (Ito 1979). Seawater interaction with the rocks while they were still at elevated temperatures (~500^oC) and probably still within the rift valley floor is indicated by oxygen isotopic compositions of plagioclase and amphibole (Ito 1979).

Tremendous heterogeneity at a fine scale of both primary and secondary mineralogical and textural features is apparent in our suite of gabbroic samples (DeLong et al., 1978). Even within a single hand specimen or thin section the relative abundances of primary phases, and their size and shape, can be dramatically variable. In many rocks the effects of metamorphism at high temperatures (amphibolite facies) are preserved throughout later, lower temperature metamorphism, resulting in the production, by partial or incomplete reactions, of a variety of combinations of coexisting phases. Mylonitized shear zones of <1 to 2 cm width cut through rocks that otherwise exhibit no foliation, and areas of intense replacement and recrystallization grade within a thin section into regions in which the primary phases are nearly pristine (DeLong *et al*., 1978; CAYTROUGH 1979).

Eighteen serpentinized ultramafic rocks were recovered from the two ALVIN dive areas. Serpentinization has almost destroyed the original textures of most of these peridotites, but preservation of some of the phases has allowed us to preliminarily identify lherzolites, dunites and wehrlites. A few of the ultramafic rocks appear to be foliated or otherwise deformed. Ten basaltic rocks were also recovered by ALVIN. Five of these are pillow basalts that were collected from the escarpments and outcrops identified macroscopically. The once glass-rich pillow basalts are, for the most part, exceedingly weathered; most of the crystalline basalts are, however, quite fresh, and chemical analyses indicate that they may represent liquids from which the gabbros were derived by crystallization (CAYTROUGH 1979; Stroup unpublished data). The fresh crystalline basalts are plagioclase phyric, and one of these samples contains remanent olivine. A single diabasic rock was also recovered; this sample is very fresh, and contains large, zoned plagioclase phenocrysts within a matrix of plagioclase, clinopyroxene and olivine.

ALVIN's sampling capabilities are such that we were able to retrieve rocks directly from outcrops, and in situ samples of this type were collected wherever possible. A number of rocks (30 samples from the total population, 25 of which are gabbroic) were collected as fragments from talus piles lying at the base of an escarpment where the fragments appeared to have morphologic characteristics similar to those of the escarpment, and we believe these to be essentially in situ although they have been shed from bedrock by spalling. A small number of samples (19, 11 of which are gabbroic) were collected from talus/ sediment slopes far from any escarpment (Table 1). Thus the majority of our samples are believed to be representative of the outcrops from which or adjacent to which they were collected. Given the large number of well-located samples obtained during our program, we are confident that we have the constraints needed to define, in a first-order way, the range of rock types that characterizes the escarpments, the relative abundances of rock types, and their spatial distribution. One potential sampling bias may, however, affect our observations. We note in reviewing the dive logs a tendency to sample outcrops that have structural integrity and to avoid sampling those outcrops that appear to be badly degraded. Rock types that weather easily (pillow basalt, serpentinized ultramafic) may be to some degree under-represented in our collection. Nevertheless, the recovery of a significant number of gabbroic rocks from the rift valley walls places a first-order constraint on our interpretation of tectonic processes operating in this area.

The distribution of rocks recovered from the two ALVIN dive areas is shown in figures 3 and 4. The spatial distribution of the three major rock types (basaltic, gabbroic, ultramafic) is heterogeneous, and there is no apparent crustal stratigraphy on the walls. Pillow lavas were observed and sampled from outcrops located at the top of the wall in Dive Area 2 (dive 625; fig. 4); pillow and crystalline basalts were also collected in situ from escarpments lower on the slopes (dive 624; fig. 4), but gabbroic rocks were sampled from stations both above and below the latter terrain. In Dive Area 1 basaltic material was recovered as loose talus at two localities but was never sampled in situ.

The upper few hundred meters of the wall in Dive Area 1 are heavily sediment-covered and no rocks were recovered from this terrain, but gabbroic rocks were collected from an escarpment 200 m below the crest of the wall. Serpentinized ultramafic rocks were sampled from outcrops located at a wide range of depths, and these ultramafics seem to be intercalated with the gabbroic rocks in a complex way. In a few places serpentinized ultramafic rocks were sampled in situ, only a few meters from, and apparently within the same outcrop as unaltered and undeformed gabbroic rocks (i.e., dive 616, station 1; fig. 3). Significantly, at three stations serpentinized ultramafic rocks were sampled together with highly metasomatized (partially rodingitized) rocks (dive 624, stations 2, 3 and 6; fig. 4), and at three stations ultramafics were collected with extremely altered gabbroic rocks (amphibolites and gneissic metagabbros: dive 611, station 7 and dive 613, station 3, fig. 3; dive 620, station 3, fig. 4). The single diabase was recovered in situ from an outcrop in sharp contact with a banded rock (dive 611; figs. 3, 7f); the dike appears to be several meters in width and strikes north–south.

There is no regular distribution of the gabbroic rocks on the walls, and hence no regular distribution of major mineral phases within them such as might result from cumulate processes. In several instances two distinctly different gabbroic rock types were collected apparently from the same outcrop or within several meters of each other (i.e., dive 612, station 3; dive 613, station 1; fig. 3). No lateral or vertical correlations or zonations can be made within the gabbroic suite. This random primary rock type distribution is mimicked by an equally heterogeneous distribution of alteration, deformation and chemical features. Our most altered gabbroic rocks - metagabbros and amphibolites -

crop out at all depths, and were often collected from bedrock adjacent to (within 5 to 10 meters of) outcrops of pristine to moderately altered and deformed rocks (for example, samples from dive 616, station 6 and dive 615, station 2, fig. 3). Foliated rocks are interspersed with brecciated but unfoliated rocks at intervals of a few meters to a few tens of meters (i.e., dive 615, stations 4 and 5; fig. 3). Although not depicted on the maps, neither mineral chemistry (CAYTROUGH 1979; Malcolm 1979) nor whole-rock chemistry (Stroup unpublished data) show any regular variability within the dive areas.

Major rock types (basaltic, gabbroic, ultramafic) may be correlated almost ubiquitously with principal outcrop morphologies; thus the random distribution of major rock types (figs. 3 and 4) is reflected in the random distribution of outcrop morphologies. In a first-order way, correlations may also be made between textural/mineralogical features in the gabbroic rocks of the suite and gabbroic outcrop morphologies. A number of outcrops on the rift valley walls exhibit a regular, macroscopic planar banding. This banding may be interpreted as either a primary igneous feature, mineral layering, such as might result from cumulate processes, or a secondary metamorphic feature, a foliation, resulting from deformation of the rocks; examination of the dive photographs alone is insufficient to distinguish the two. However, in examination of hand specimens and thin sections of recovered samples, we observed no cumulate textures nor any mineralogic layering at a scale of up to ~10-15 cm. A number of the gabbroic and ultramafic rocks (32 gabbroic samples out of 116, 5 ultramafic samples out of 18) are foliated. We infer, therefore, that the bandings observed in outcrop are most probably foliations; three-dimensional perspectives of many of these outcrops confirm the planar, penetrative nature of the banding.

We can also infer that the heterogeneous nature of gabbroic outcrop morphologies - the random intercalation of massive, fractured and foliated outcrops - reflects at a large scale the heterogeneous textural/mineralogical characteristics of the gabbroic rocks in thin section. It is not possible, however, to accurately classify gabbroic outcrops by examination of the dive photographs alone. Several of our foliated samples were in fact collected from outcrops exhibiting no apparent banding or foliation; from some outcrops having a very fragmented or fractured appearance we obtained relatively pristine and undeformed rocks. This lack of correlation between sample mineralogy/texture and outcrop may reflect the scale at which the mineralogical and textural variations occur. Within hand specimens and thin sections of the gabbroic rocks variations take place over only a few centimeters, as, for example, in rocks in which the relative abundances of the mafic minerals change dramatically in thin section, or in pristine rocks that are transected by cm-wide shear zones. Thus narrow bands of foliation or fracturing, represented as foliated or cataclastically deformed rocks in hand specimen, may not be obvious in the dive photographs; similarly, small-scale fluctuations in the proportions of primary phases would not be apparent in outcrop.

D. Geologic Model for the Mid-Cayman Rise

The recovery of gabbroic rocks from the inward facing rift valley wall escarpments of accreting plate boundary segments is not common (e.g., Fox and Stroup 1981). It is therefore of interest that on the Mid-Cayman Rise a heterogeneous assemblage of gabbroic rocks is exposed on a large number of apparently small-throw dip-slip faults. The presence of these gabbroic rocks is difficult to explain if normal thicknesses are assumed for the major layers thought to make up the oceanic crust.

The oceanic crust is believed to be composed of two distinct compressional wave velocity intervals: seismic layer 2 (oceanic basement) and seismic layer 3 (oceanic layer). Seismic layer 2 is characterized by a steep velocity gradient with velocities ranging from 3.0 km/sec near the surface to 6.6 km/sec at depths of 1.0 to 2.0 km (e.g. Spudich and Orcutt 1980). Seismic layer 3 underlies the oceanic basement and is defined typically by velocities ranging from 6.7 km/sec to 7.4 km/sec (e.g., Spudich and Orcutt 1980); thicknesses for the latter interval vary from 4 to 7 km. Studies of the crustal stratigraphy developed within ophiolites (e.g., Moores and Jackson 1974; Coleman 1977), analyses of the physical properties of oceanic (e.g., Christensen and Shaw 1970; Fox et al., 1973; Christensen and Salisbury 1975) and ophiolitic (e.g., Peterson et al., 1974; Salisbury and Christensen 1978; Christensen 1978) rocks, and the correlation of physical properties with seismic refraction data lead to a generalized model for the oceanic crust. Seismic layer 2 represents the shallow intrusive and extrusive carapace, 1 to 2 km thick, that is composed of pillow lavas, sheet flows and basaltic rubble zones at shallow depths, and of sheeted dikes at deeper levels. Seismic layer 3 is composed of plutonic (gabbroic) rocks of varying compositions, the upper levels of which are relatively enriched in plagioclase and the deeper levels of which are relatively mafic. At its base the oceanic crust is composed of an interlayered sequence of cumulate gabbros and ultramafic rocks (the transition zone of ophiolites; Casey et al., 1981).

Assuming, for the moment, that normal oceanic crust is accreted along the axis of the Mid-Cayman Rise, and given the constraints imposed by our study, the number of geologic models that can reasonably explain the occurrence of gabbroic rocks on the rift valley walls is limited. One possibility is that the gabbroic rocks that were sampled during our program represent isolated intrusive bodies emplaced at shallow levels within the volcanic carapace along the floor or walls of the Mid-Cayman Rise and exposed by subsequent normal faulting associated with the development of the walls. The two areas that we investigated are 60 km apart on opposite sides of the rift valley (fig. 2). We consider it unlikely that we chose, fortuitously, two field areas that happen to expose rocks associated with isolated intrusions. Moreover, dredging conducted by other investigators (Perfit and Heezen 1978; Eggler et al., 1973) and by us during the Cayman field program (CAYTROUGH 1979 and unpublished data) has routinely led to the recovery of samples of gabbroic rocks as well as basalts and ultramafics from all depths on the Mid-Cayman Rise rift valley walls. We therefore believe that the exposure of plutonic rocks here is a regional phenomenon and cannot be explained as the manifestation of isolated shallow level intrusive events.

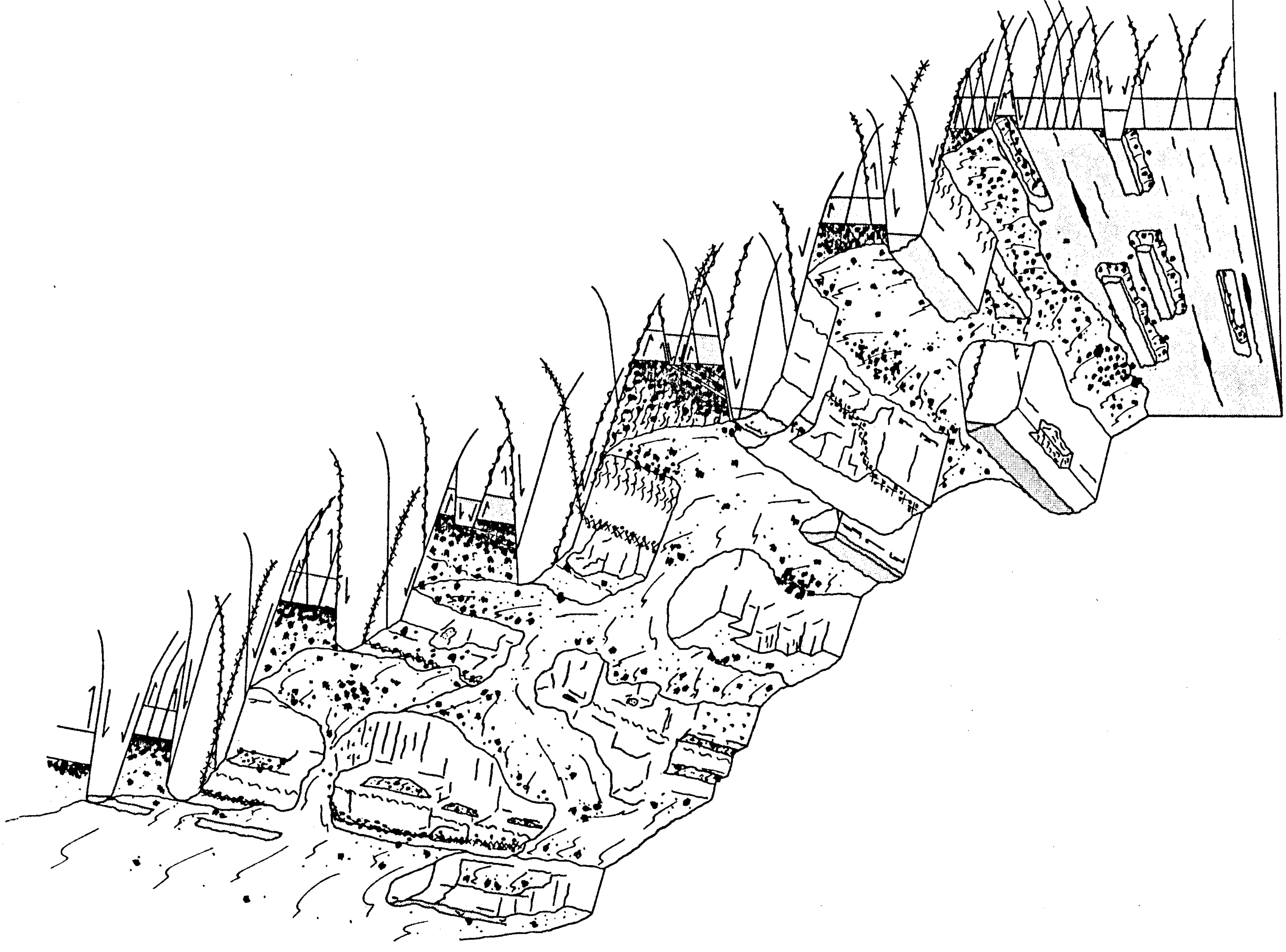
A second possible explanation for the exposure of plutonic rocks is that the shallow intrusive and extrusive carapace of the oceanic crust has been faulted out of the section. Assuming normal crustal thicknesses for the oceanic basement, between 1 and 2 km of basalt and diabase would have had to be removed in order to bring the deeply buried gabbroic rocks close to the surface. Faults with throws of about 1 km are necessary to achieve structural erosion at this scale. If such a phenomenon had occurred not only would gabbroic rocks be exposed but the topographic and structural integrity of the ridge segment would be disrupted in a profound way and this should be apparent in our data. There is no evidence in our bottom observations to suggest structural erosion of this magnitude, and, furthermore, the Mid-Cayman Rise exhibits the first-order topographic and geophysical characteristics (i.e., bilaterally symmetric topographic and magnetic anomaly profiles) associated with slowly accreting ridge segments, leading us to believe that faults of this scale have not developed.

An alternative hypothesis to explain our data is that the layers comprising the oceanic crust in the Cayman Trough are anomalously thin when compared with a typical crustal column. The shallow intrusive and extrusive carapace of the crust in this region would be only a few to several hundred meters in thickness. A thin carapace would permit the exposure of gabbroic rocks on some of the many small-throw dip-slip faults of the rift valley walls. This third model is very appealing in that it is compatible with our field data, and it is the hypothesis that we prefer.

As stated, however, the thin carapace hypothesis is incomplete because it does not explain the almost continuous exposure of gabbroic rocks. We would expect that fine-grained basaltic rocks should be sampled frequently because these rocks should cap the plutonic rocks and be exposed on many of the inward facing scarps. The well-developed talus accumulations that lap up against the bases of the escarpments is evidence of slope degradation by mass wasting, and it is easy to envision that the inherently fractured volcanic carapace will fail readily when it is exposed on steep fault-generated slopes. This is one process that is obviously important in enhancing the relative abundance of gabbroic rocks exposed but we suggest that another fundamental process must be operating in order to create the overwhelming dominance of gabbroic rocks. Following the suggestion of White and Stroup (1979), we infer that the relative absence of basaltic rocks on the rift valley walls may be caused by the downfaulting of the basaltic carapace on a number of small-throw outward facing faults. Movement on inward facing normal faults must be preferred on the walls in order to create their great relief; movement on outward facing normal faults, which may have throws of several up to perhaps 100 m, would downfault the basaltic carapace sufficiently to result in the widespread exposure of deeper crustal components (fig. 8).

In the extensional environment of an accreting plate boundary (Sykes 1967; Sykes and Sbar 1973) the direction of least compressive stress is assumed to be horizontal and perpendicular to the axis of accretion. Conjugate normal faults should develop on steeply dipping planes at or near the axis of accretion and striking parallel with it (e.g., Anderson 1951). Data from a deep-towed camera package (ANGUS) show fissures (gja) and faults within the floor of the Mid-Cayman Rise rift valley that parallel the strike of the Rise axis (CAYTROUGH 1979), and we interpret these data to indicate that conjugate faults have developed within the extensional domain of the valley floor. This interpretation is consistent with the observation made in the Mid-Atlantic Ridge FAMOUS rift valley segment (Ballard and van Andel 1977; Luyendyk and Macdonald 1977) that both inward and outward facing faults with throws of up to 60 m develop within the marginal tectonic province of the valley floor.

Figure 8 Schematic diagram of features developed on the rift valley walls of the Mid-Cayman Rise. The extrusive and shallow intrusive carapace (shaded) is assumed to be 200 m thick and overlies a gabbroic complex (white). S-curves on faults/fractures, that are listric at depth, suggest ductile deformation; X's represent serpentinized ultramafic here suggested to intrude crust along faults.



Although characteristic of the inner rift valley walls at the Mid-Atlantic Ridge (Macdonald and Luyendyk 1977; Macdonald and Atwater 1978; Temple et al., 1979), definite outward facing faults were never observed during any of our dives; but an outward sloping outcrop was seen on one dive (621; fig. 6), and on several dives (615, 612, 621, 622; figs. 3 and 4) shallow depressions are apparent behind north-south striking promontories. We interpret the depressions to represent partially buried graben created by an inward and outward facing fault couplet. Our dives are located on the upper half of the rift valley walls (approximately 1.5 to 2.0 m.y. old from extrapolation of recent spreading rates) and the terraces that link the inward fault scarps there are covered with sediment and talus of an unknown thickness. The graben created by pairs of inward and outward facing faults would form troughs that would act as talus and sediment traps, and in time their presence would be obscured by a thickening wedge of detritus (White and Stroup 1979; fig. 8).

If the rift valley of the Mid-Cayman Rise is a steady-state morphotectonic feature (Deffeyes 1970; Needham and Francheteau 1974; Harrison and Stieltjas 1977) and if the floor of the rift valley straddles an axis of plate accretion (Holcombe et al., 1973), then the fault blocks that we have studied high up on the rift valley walls are being transported up and out of the rift valley (Atwater and Mudie 1968; Fowler and Kulm 1970; Needham and Francheteau 1974). Since there appears to be little or no differential motion between blocks high up on the walls, then the observed vertical offsets between blocks must be created on the lower flanks of the walls. The most likely region for the creation of this first-order step like topography is the interface between the outer edges of the rift valley floor and the base of the walls. Investigation during the FAMOUS project (Needham and Francheteau 1974; Ballard and van Andel 1977; Macdonald and Luyendyk 1977) documented that the boundary between floor and wall is the locus of preferential motion on some inward facing dip-slip faults. These faults exhibit evidence of recent activity, can develop individual relief of up to 650 m, and bound blocks of crust of variable width (a few hundred to 1500 m). The creation of rift floor boundary faults is intermittant, and when the process is time-integrated the observed step-like relief of the walls is created without requiring active faulting high up on the walls. We suggest that as a given block initially rises above the valley floor there is motion within the block on the outward facing dip-slip faults to downfault the volcanic carapace and increase the relative abundance of plutonic rocks exposed on the inward facing escarpments (fig. 8). The cause of uplift of a block at the outermost margin of the valley floor is poorly constrained but probably reflects rapid changes in the buoyancy of the lithosphere as the plate thickens with age (Needham and Francheteau 1974; Ballard and van Andel 1977; Ramberg and van Andel 1977) and/or the effects of viscous forces produced by a rising asthenospheric diapir at the plate boundary (Sleep 1969; Osmaston 1971; Lachenbruch 1973, 1976; Sleep and Rosendahl 1979).

Our sampling program indicates that the distribution of major rock types, the primary igneous mineralogy of the gabbroic rocks and the alteration/deformation history experienced by the gabbroic rocks is extremely heterogeneous. We believe that heterogeneity characterizes the lower oceanic crust and that this is compatible with our suggestion that the shallow intrusive/extrusive carapace is anomalously thin, that the carapace is underlain principally by gabbroic rocks, and that in time this stratigraphic assemblage is disrupted by a large number of conjugate faults (fig. 8). A direct consequence of this model is that a magma reservoir must reside at shallow levels (<500 m) beneath the floor of the Mid-Cayman Rise rift valley. Given the steep thermal gradients that must characterize shallow oceanic crust, the magma body is likely to be small. If our interpretation of rift valley wall structure is correct, then faults will expose plutonic rocks that were emplaced at levels no deeper than a maximum of 500 to 600 m. Therefore, the plutonic rocks recovered from escarpments of the Mid-Cayman Rise should be crystalline material that was plated onto the roof or upper flanks of the magma reservoir. It is this portion of the magma body in which conditions governing the evolution of a melt are most variable, and it is not surprising that a wide range of primary igneous textural relationships and mineralogical associations is exhibited in the rocks collected from the rift valley walls. Furthermore, the tectonic regime that characterizes the rift valley floor will continually be subjecting the newly crystallized gabbroic material and overlying brittle carapace to extension. Faults forming in gabbroic rocks that are still at elevated temperatures may produce the diverse range of deformation and recrystallization features (cataclasites, micro-breccias, protomylonites, mylonites, gneissic metagabbros) that are found in the gabbroic suite. Faults forming in the overlying brittle carapace may become pathways for penetration of seawater which would react with the primary phases in the gabbroic rocks creating the wide range of alteration products (brown hornblende to chlorite) and hydrated deformed rocks (amphibolites) that are observed. In time as the newly accreted crustal assemblage cools and is transported across the rift valley floor a complex and overlapping history of alteration and deformation will be experienced by the gabbroic rocks. The onset of uplift of crustal blocks at the rift valley floor/wall interface will disrupt the primary igneous stratigraphy as well as the pattern of alteration and deformation enhancing, on the rift valley walls, the complex spatial rock distribution that we observe (fig. 8).

Our sampling data also indicate that narrow serpentinized ultramafic lenses cross-cut the gabbroic assemblage at many localities. The source of this serpentinized ultramafic material could be the ultramafic intervals that characterize the base of the oceanic crust and upper mantle (e.g. mafic-ultramafic transition zone, layered ultramafics, tectonized harzburgite). We have no constraints on the thickness of the gabbroic assemblage at the Mid-Cayman Rise but, on the strength of the numerous occurrences of serpentinized ultramafic rocks, we infer that the source for the latter must be shallow and that, like the basaltic carapace, the gabbroic complex is thin. If the thickness of the gabbroic complex is, say, 1000 m or less, then the lithostatic confining pressure at the base of the oceanic crust would be relatively low ($\leq$ 1 kbar) allowing elongate cracks to remain open and making it possible for seawater to pass through the gabbros along pathways and hydrate the underlying ultramafic rocks. The relatively mobile serpentinized products of this hydration could migrate along the faults penetrating the gabbroic layer (fig. 8).

E. Implications of the Geologic Model

We believe that the most satisfying explanation for the structural and geological relationships observed on the rift valley walls of the Mid-Cayman Rise is that the shallow intrusive and extrusive carapace of the oceanic crust in this region is anomalously thin. Although the constraints from our field work are not as strong, we propose that the thickness of the underlying gabbroic complex is significantly reduced as well. The possible existence of anomalously thin crust on the Mid-Cayman Rise suggests that some fundamental aspect of the plate accretion process must be perturbed. There is, in fact, a distinctive plate tectonic characteristic associated with the Mid-Cayman Rise that makes it almost unique in terms of plate geometry.

The Mid-Cayman Rise is a short (110 km long) accreting plate boundary truncated by two long transform faults that juxtapose relatively old (late Mesozoic island arc terrain; Perfit and Heezen 1978) and therefore thick lithosphere against the newly accreted oceanic lithosphere of the Cayman Trough. Sleep (1969) proposed that the distinctive rift valley morphology associated with slowly accreting plate boundaries is a manifestation of viscous head loss experienced by the asthenospheric wedge as it rises beneath the axis of slowly spreading ($\leq$ 4 cm/yr full rate) ridge segments. At these low rates of lithospheric growth significant amounts of heat are lost to the edges of the thickening lithosphere. This heat loss increases the viscosity of the rising wedge and results in a loss of hydraulic head. Consequently, oceanic crust is emplaced at a depth below its level of isostatic equilibrium, creating the floor of the rift valley. Energy is conserved and the head loss is regained as blocks of crust are incrementally uplifted above the rift valley floor creating the rift walls. In an effort to explain the excessively deep closed-contour depressions that are routinely associated with transform fault/rift valley intersections, Sleep and Biehler (1970) took the model one step further and proposed that the depressions are a direct result of the juxtaposition of the cold edge of a transform against the rising asthenospheric wedge proximal to the intersection. Although the Mid-Cayman Rise exhibits all of the first-order morphotectonic and geophysical characteristics thought to be representative of slowly accreting ridge segments, it is distinctive in that the depth to the rift valley floor is approximately 5 km, which is 2 to 3 km greater than depths to the rift valley floor at other slowly accreting ridge segments. The closed-contour depressions of the rift valley/transform intersections at either end of the Mid-Cayman Rise reach depths in excess of 6 km (fig. 2). We believe that the excessive depth of the rift valley floor is a direct consequence of the thermal effect of the juxtaposition of the cold edges of the transforms against this short ridge segment. The thin crust of the Mid-Cayman Rise would be a direct consequence of the anomalous thermal regime of the long transform-short ridge configuration. In this relatively cold environment, a smaller volume of partial melt would be extracted from the rising asthenospheric wedge (Gallo and Fox 1979). Since the thickness of the basaltic oceanic crust is essentially equal to the amount of melt that segregates from the asthenosphere (Sleep 1975), then the oceanic crust accreted at this boundary will be anomalously thin, and the lithosphere here should thicken rapidly with plate age.

If the oceanic crust is anomalously thin and the lithosphere thick in the Cayman Trough as we predict, then the lithosphere of the Trough should have a deeper level of isostatic equilibrium than oceanic lithosphere that is characterized by oceanic crust of normal thickness that is of equivalent age. The average depth of the Trough at an age of 5 m.y. and 10 m.y. is 4 km and 4.5 km, respectively (Holcombe et al., 1973). The average depth of the crust of the North Pacific or North Atlantic at these ages is 3.1 and 3.5 km (Parsons and Sclater 1977).

Although the Mid-Cayman Rise probably represents an end-member example of the thermal effects exerted by transform faults on processes of ridge accretion, we believe that the thin crust model developed to explain our field data may be applicable to other slowly accreting ridge segment - transform fault environments. The Mid-Atlantic Ridge south of the Azores is spreading at approximately the same rate as the Mid-Cayman Rise and is known to be disrupted frequently by transforms (every 50 to 100 km; Fox, et al., 1969; Vogt et al., 1971; Johnson and Vogt 1973). The thermal effect of these transform faults on accretionary processes will not be as profound as the effect of the Swan and Oriente transforms on the Mid-Cayman Rise because the transforms of the central North Atlantic juxtapose oceanic lithosphere of much younger age (depending upon the length of the transform offset, a few m.y. to 30 m.y.) against the ridge segment. Nevertheless, well mapped ridge axis/ transform fault intersections (i.e., FAMOUS area: Needham and Francheteau 1974; Ramberg and van Andel 1977; Oceanographer Transform: Schroeder 1977; Fox unpublished data) document that the depth to the rift valley floor increases continuously over distances as great as 40 km as the transform intersection is approached, suggesting that the depth of emplacement of oceanic crust may be affected by the presence of a transform over these distances (Fox 1978; Gallo and Fox 1979). Furthermore, the results of a seismic refraction experiment conducted within and proximal to the Kane Fracture Zone at $24^{\circ}N$ indicate that the oceanic crust along the axis of the transform is only 2 km thick (Detrick and Purdy 1978, 1980; Fox et al., 1980).

The bounding walls of transform faults in the central North Atlantic develop between 1 and 5 km of relief, and it is from these escarpments that gabbroic and ultramafic rocks are routinely sampled. These rocks are thought to be representative of deep-seated portions of the oceanic crust and upper mantle, and, in order to explain their presence on transform escarpments, it has been proposed that faults with throws of thousands of meters create the relief of the walls, producing structural windows that cut deep into the oceanic crust (e.g., Miyashiro, et al., 1969; Bonatti et al., 1971; Prinz et al., 1976). Gabbroic and ultramafic rocks, however, are often recovered from outcrops high up on the walls, making it difficult to explain their presence if normal thicknesses of the crustal components are assumed (Francheteau et al., 1976). Moreover, submersible studies (Choukroune et al., 1978), deep tow investigations (Detrick et al., 1973) and SEABEAM surveys (Needham in preparation) of central North Atlantic transforms demonstrate that the great relief of the bounding walls is actually produced by the integrated offset on a series of small-throw faults. These geological relationships, which are characteristic of slowly slipping transform faults, are remarkably similar to observed realtionships at the Mid-Cayman Rise. We suggest that the processes leading to creation of oceanic crust are modified by the juxtaposition of a cold transform edge and an axis of accretion, resulting in the creation of thin crust proximal to this boundary.

Our hypothesis implies that the oceanic crust is much more heterogeneous than previous geologic models have suggested. On a regional scale, over a distance of 10 to 20 km, oceanic crust appears to thin continuously towards its truncation by a transform so that immediately adjacent to the transform the crust is only 1 to 2 km thick. The depth of the magma reservoir within the crust will decrease as a transform boundary is approached, and the mineral assemblage that is plated onto the edges of the reservoir will become texturally and compositionally more heterogeneous because of the variable thermal and structural environment likely to characterize shallow oceanic lithosphere. A consequence of our model is that gabbroic rocks sampled from the walls of transform faults contain a great deal of information about the complex igneous, alteration and deformation processes occurring at relatively shallow crustal levels near transform faults. It is not at all clear, and in fact unlikely, that these gabbroic rocks can be used to infer the constitution of plutonic rocks emplaced at deeper levels ($\geq$ 1.5 km) at accreting plate boundary segments far from a transform fault.

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CHAPTER III

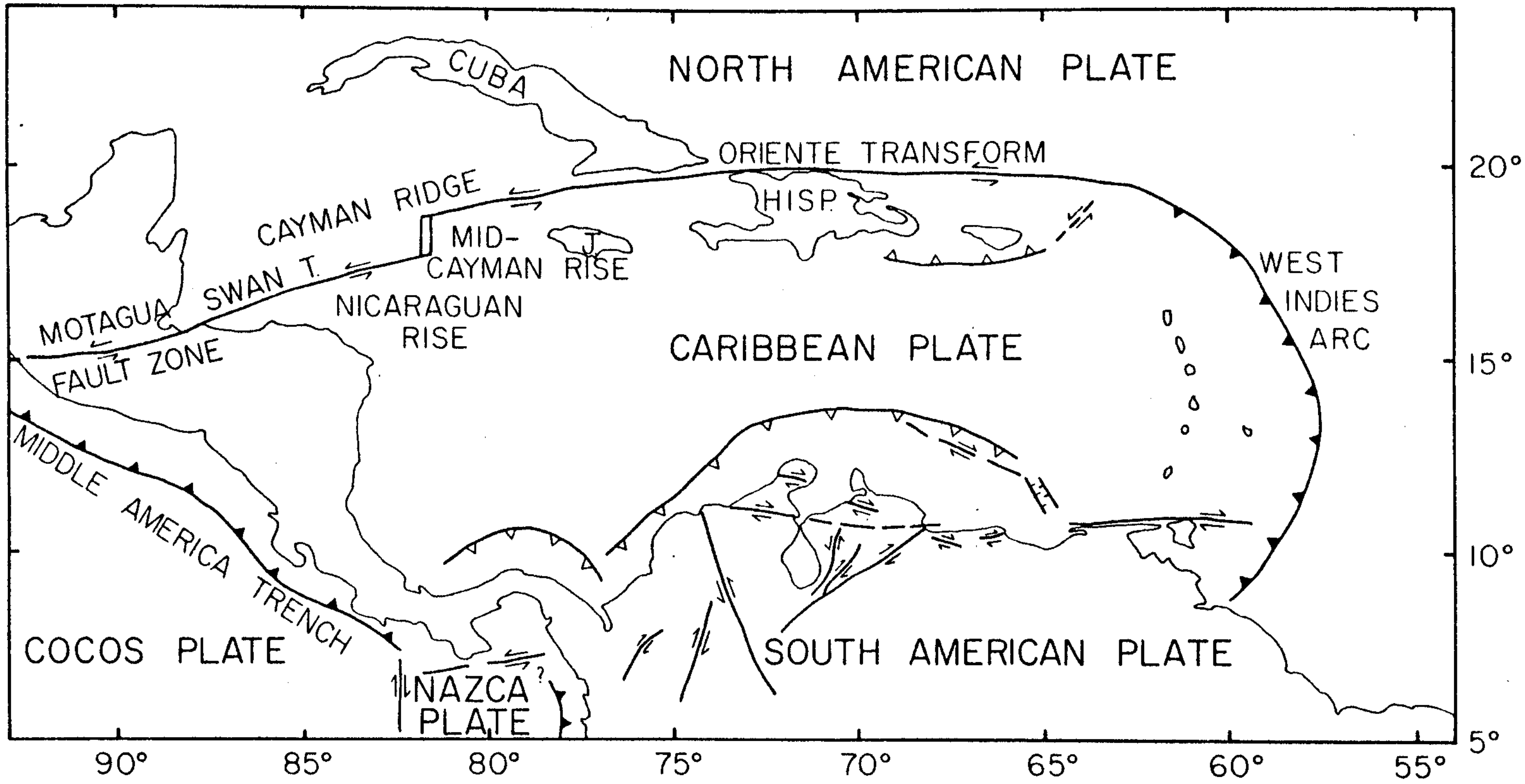
MID-CAYMAN RISE, CARIBBEAN: STRUCTURE AND TECTONICS OF A LONG TRANSFORM - SHORT RIDGE SYSTEM

A. Introduction

The Cayman Trough is a 1600 km long east-west trending morphologic feature that transects the Caribbean Sea. It has been interpreted by Holcombe _et al_. (1973) and Jordan (1975) to be a transform-ridge-transform boundary between the Caribbean and North American plates (Fig. 1). According to this interpretation, two transform faults (Oriente and Swan) with left-lateral relative motion bound a north-south spreading center (Mid-Cayman Rise) that has a total present opening rate of ~20 mm/yr (Macdonald and Holcombe, 1978). The transforms are extremely long (~900-1000 km) and the accreting ridge segment is relatively short (~110 km); in a continuous spectrum from long ridge segments offset by short transform faults to long transform faults offsetting short ridge segments, the Cayman Trough may represent an end-member example of long transform-short ridge systems. The unusual, possibly unique configuration of the Cayman Trough plate boundary system is the focus of this paper. We present an analysis of topographic and structural features of the Cayman Trough and a discussion of the development of these features within this evolving system.

In 1976 several field programs were initiated to investigate the Mid-Cayman Rise, and these programs have provided sufficient bathymetric and photographic data to enable us to make a preliminary interpretation of the structures developed within the spreading center. The programs, comprising the "Cayman Trough Project," were conducted by scientists

Figure 1. Simplified tectonic map of the Caribbean region, modified after Jordan (1975). J = Jamaica; Hisp = Hispaniola.


NORTH AMERICAN PLATE
CUBA
ORIENTE TRANSFORM
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MID-CAYMAN RISE
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SWAN T.
MOTAGUA FAULT ZONE
NICARAGUAN RISE
CARIBBEAN PLATE
WEST INDIES ARC
MIDDLE AMERICA TRENCH
COCOS PLATE
NAZCA PLATE
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SOUTH AMERICAN PLATE
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of the Woods Hole Oceanographic Institution, the State University of New York at Albany, Wesleyan University and the Jamaican Geological Survey, and the initial results of the project were reported by CAYTROUGH (1979). One of the programs involved a bathymetric survey of a one degree square area centered on the Mid-Cayman Rise using the U.S. Navy's multi-narrow beam echo sounding system (referred to in this paper as SASS) on board the USNS BOWDITCH. This sophisticated system provides acoustical information gathered by a hull-mounted sonar array which, when combined with satellite and inertial navigational data, enables investigators to generate a bathymetric map. The map generated by the BOWDITCH survey (shown as Fig. 3) has a contour interval of 50 fathoms (uncorrected) and a scale of 1:136,000, and therefore contains excellent data for structural analysis. Two other Cayman Trough Project field programs provide supplementary data: (1) a submersible observational and sampling survey, conducted in two dive areas on the walls of the Mid-Cayman Rise rift valley, using the submersible ALVIN (Stroup and Fox, in press); and (2) a deep-towed camera package survey, conducted along the axis of the Rise, utilizing the ANGUS photographic system (Ballard and Uchupi, 1978). Additional constraints on the development of topographic features of the Cayman Trough are given by data collected by other investigators.

In an ideal transform-ridge-transform plate boundary system, relative motion between the two plates, and therefore the direction of maximum extension in the system, is parallel with the trends of the transforms. Dewey (1978) has suggested that ridges in long transform-short ridge systems may develop and evolve in response to transform activity. We interpret the available data to indicate that the oceanic crust accreted at the Mid-Cayman Rise is not only modified by structures developed in response to extension perpendicular to the Rise axis, but also by structures developed in response to shear induced by strike-slip motion along the two long and closely spaced transforms.

B. Regional Geology

The Cayman Trough is flanked by two shallow swells, the Nicaraguan Rise to its south and the Cayman Ridge to its north (Fig. 1). The floor of the Trough between 79^o and 84^oW longitude is characterized by a series of north-south trending ridges and valleys that lie to either side of an axial 5-6 km deep V-shaped valley. The Nicaraguan Rise is a broad (~500 km wide), shallow (< 1 km below sea level) and elongate east-west platform whose northern margin is truncated abruptly along the south wall of the Cayman Trough. The Cayman Rise is a narrow submarine ridge (at ~1 km depth) whose southern flank dips steeply toward the Trough and whose northern slope bounds the Yucatan Basin. The Rise and Ridge have crustal thicknesses estimated from seismic refraction studies (Ewing et al., 1960; Edgar et al., 1971) to be roughly 19-22 km; the crustal thickness of the Cayman Trough has been interpreted to be ~5-6 km (Ewing et al., 1960). Studies of dredged rocks suggest that both the Cayman Ridge and the Nicaragua Rise are composed in part of Cretaceous to Paleocene granodiorites overlain by Paleocene volcaniclastics and metasediments, (Perfit and Heezen, 1978). Dredge hauls from the axis of the Cayman Trough indicates that it is composed primarily of basaltic and gabbroic rocks that are chemically and mineralogically similar to oceanic tholeiites (Eggler et al., 19 ; Perfit, 1977; Perfit and Heezen, 1978; CAYTROUGH, 1979).

Arden (1975) interpreted drill-hole data from the Nicaraguan Rise as evidence that most of the Rise is a Cretaceous-Paleocene ensimatic island-arc system. The Rise appears to have subsided during the Middle Eocene following the cessation of magmatic activity associated with arc development (Grippi, 1978). The Rise and Cayman Ridge are interpreted to have been an island arc system that formed the northern boundary of the Caribbean plate until 38 m.y.B.P. and that was then split by left lateral strike-slip motion initiated along this boundary (G.W. White and K. Burke, unpublished data). The Cayman Trough appears to have formed during the late Eocene contemporaneously with strike-slip faulting (Perfit and Heezen, 1978; Grippi, 1978).

Geological and geophysical data (summarized by Holcombe et al., 1973, and Perfit and Heezen, 1978) for the Cayman Trough suggested to Holcombe and coworkers (1973) that the crust of the Trough was generated at an accreting plate boundary and that the current locus of accretion is the Mid-Cayman Rise. In support of this suggestion, magnetic anomaly data for the Trough, interpreted by Macdonald and Holcombe (1978), indicate that the anomaly pattern is bilaterally symmetric about the axis of the Rise. Anomalies 1 to 3' were identified on the east flank and 1 to 4' on the west flank of the Rise. The inferred total opening rates are 20 ± 2 mm/yr for 0-2.4 m.y.B.P. and 40 ± 2 mm/yr for 2.4-6.0 m.y.B.P., and a half-opening rate of 20 mm/yr for 6.0 to 8.3 m.y.B.P. is inferred for the west flank. The suggested age for the initial opening of the Mid-Cayman Rise is 30 m.y. (late Oligocene). Macdonald and Holcombe stress, however, that this may be a minimum age; north-south topographic lineaments within the Trough, presumably composed of crust accreted at the Mid-Cayman Rise after the onset of spreading, can be observed beyond the limit of the magnetic data.

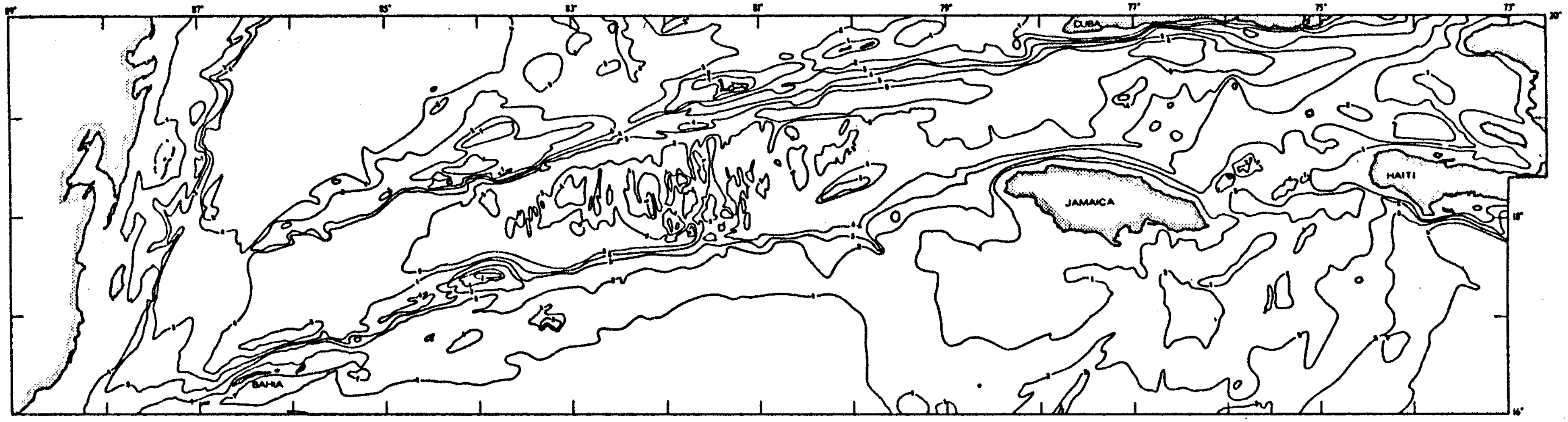
Grippi (1978) has inferred from the topographic data alone that a total offset of 720 km exists between the Caribbean and North American plates. He notes that this value is a minimum for the offset along the Trough, because strike-slip displacement may have occurred prior to spreading, and because of the apparently significant internal deformation experienced by the Caribbean plate between 38 m.y. and 9 m.y.B.P. (Burke et al., 1978).

C. Topography and Morphology

At a large scale the topographic expression of the northern Caribbean plate boundary is well defined. The Oriente Transform is delineated by the Oriente Deep, a narrow, 5-6 km deep 600-700 km long depression that strikes roughly east-west for most of its length (Fig. 2a). The northern escarpment of the transform is a steep wall with about 4 km of relief. The escarpment that defines the tectonically inactive western extension of the Oriente Transform, and that separates the Cayman Trough and the Cayman Ridge, is slightly less steep than the northern transform escarpment. The Swan Transform strikes roughly ENE-WSW from its intersection with the Mid-Cayman Rise to its western extension into the Polochic-Motagua fault zone in Central America. It is bounded on the south by a steep escarpment that rises to the shallow Nicaraguan Rise. The inactive extension of the Swan Transform is denoted by an east-west trending slope that can

Figure 2. a. Bathymetric map of the Cayman Trough, from Holcombe et al., 1973.

b. Trace from Figure 2a of the first-order morphology in the Cayman Trough. The 5 km contour is outlined. The long-dashed line represents the trace of the Cayman Trough plate boundary (i.e., the trace of deepest topography through the Oriente Transform - Mid-Cayman Rise - Swan Transform). The solid and short-dashed lines are drawn parallel with recognized topographic lineaments.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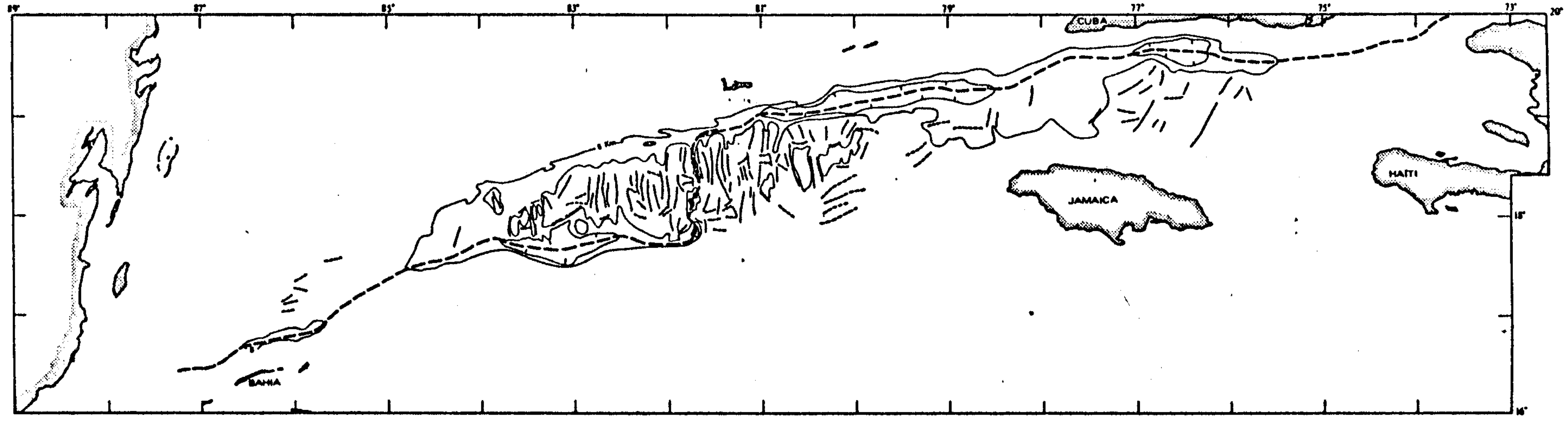
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be traced to the northeast of Jamaica. Along both transform faults the trace of the axial depression is not linear but appears to make a series of northwest and northeast-trending jogs or bends. The most clearly defined depressions along the Oriente Transform are within 500 km of its intersection with the Mid-Cayman Rise, east of which the depressions are masked by sediment; the depressions along the Swan Transform are muted beyond ~250 km of its intersection with the Rise, probably due to the large amount of sediment derived from the Central American continent (Holcombe *et al.*, 1973).

The Mid-Cayman is defined by the narrow, generally north-south valley at 81°40'W longitude (Fig. 3). The Oriente and Swan transforms are roughly orthogonal to the Rise at their intersection with it (Fig. 4). For a distance of about 200 km to both the east and west of the Rise, topographic lineaments that trend approximately north-south dominate the topography within the Cayman Trough (Fig. 2b). These topographic lineaments are formed by north-south trending escarpments that are the flanks of steep-sided ridges that have relief of 200-2000 m (Holcombe *et al.*, 1973). Occasional conical hills are evident in the central portion of the Trough close to the crest of the Mid-Cayman Rise. Beyond 200 km to the west of the Rise topographic features are almost completely buried beneath a thick sediment blanket. To the northeast of Jamaica, however, there is a marked change in the orientation of the dominant topography, from north-south to NE-SW (Macdonald and Holcombe, 1978; Grippi, 1978; Case and Holcombe, unpublished data; Fig. 2b). There is, furthermore, less regularity to the topography within the Trough that lies to the east of the Rise than there is in the western

Figure 3. SASS bathymetric map of the Mid-Cayman Rise. The two ALVIN dive areas are outlined. Depths are given in uncorrected fathoms, with a 50 fathom contour interval; scale is 1:136,000.

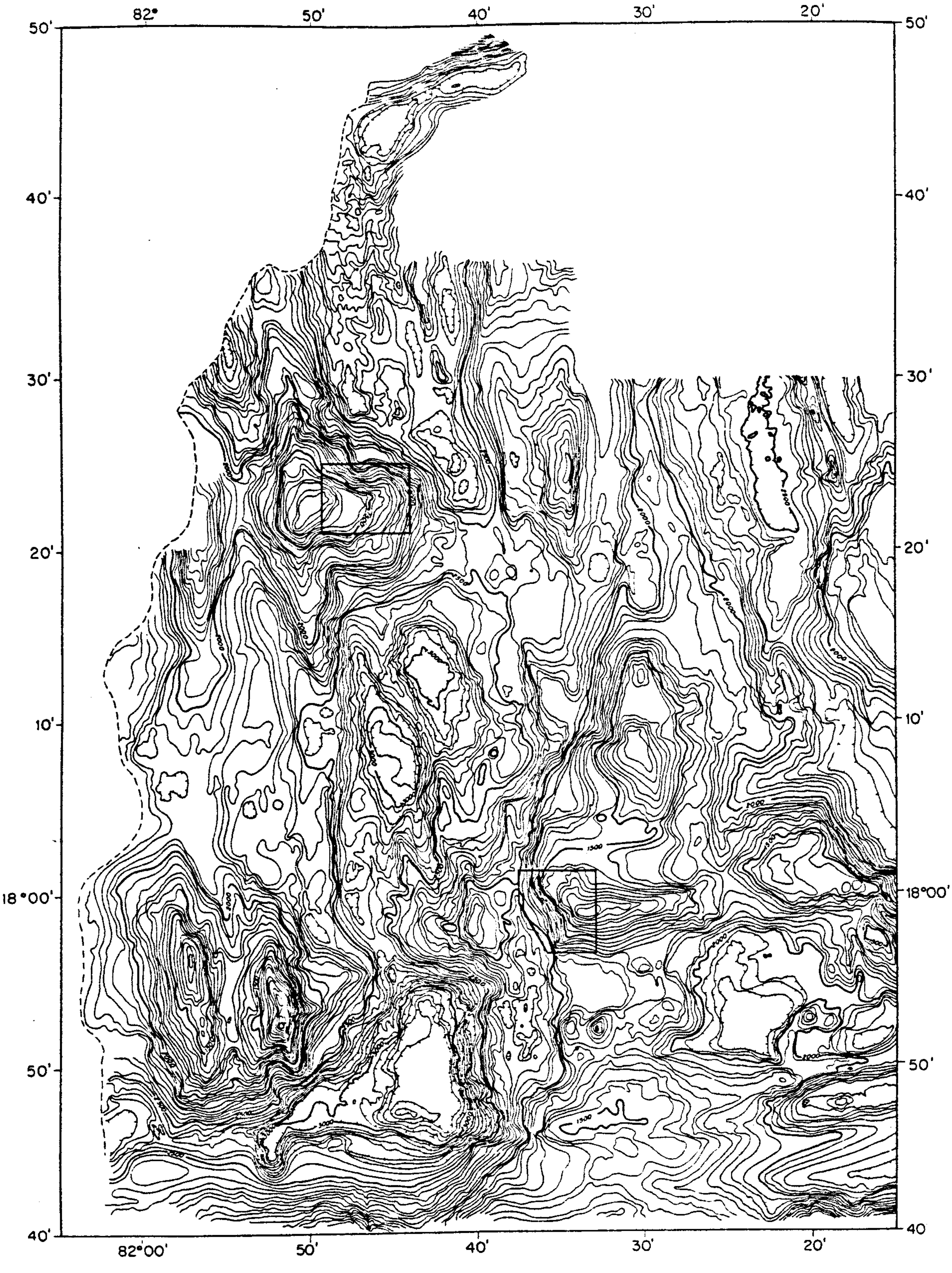
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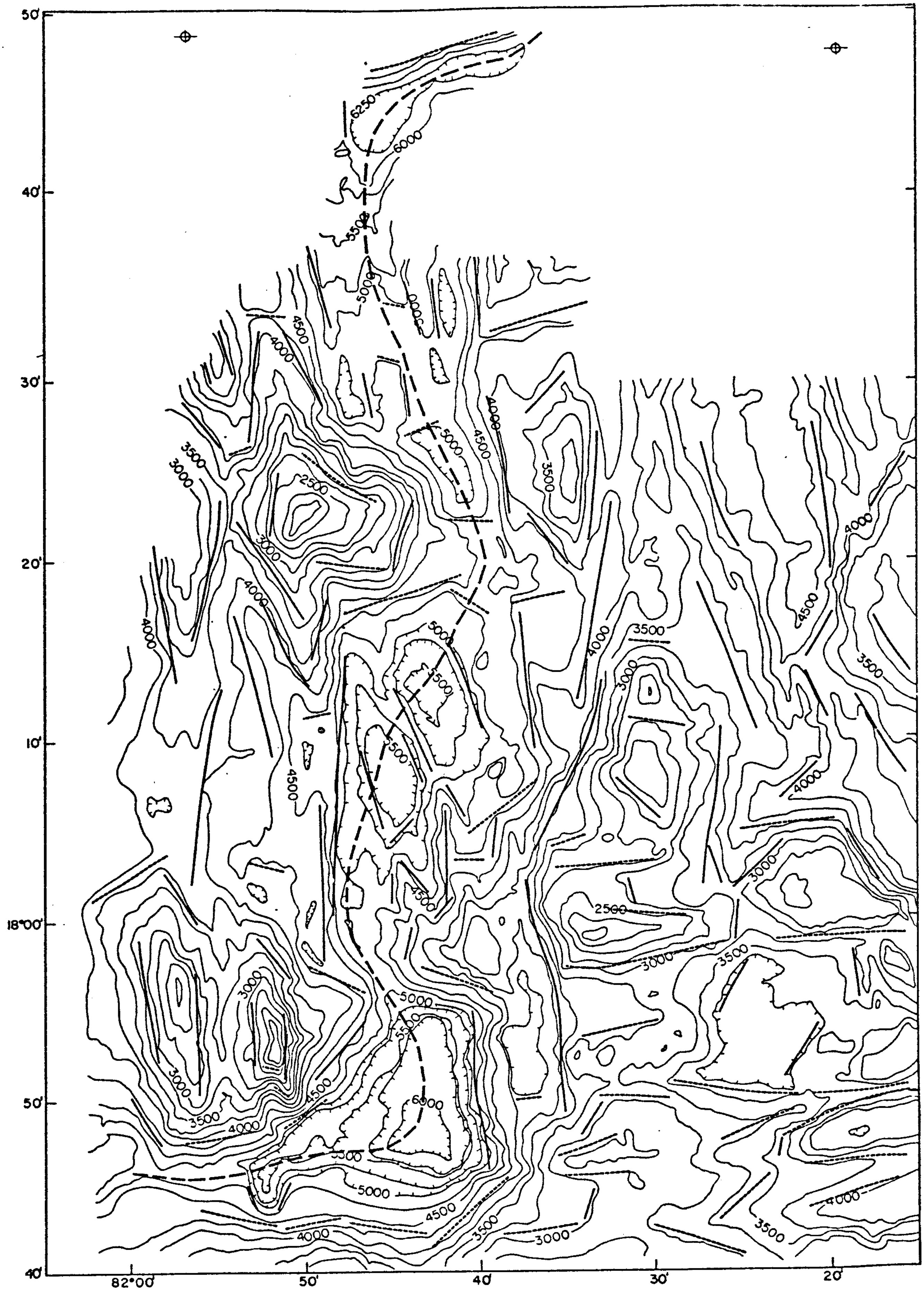
Figure 4. Bathymetric map of the Mid-Cayman Rise with a trace of the topographic lineaments. The bathymetric base map was generated from Figure 3 by translating uncorrected fathoms to meters; the contour interval here is 250 meters. The long-dashed line defines the axial depression through the Rise. Short lines are drawn parallel with all recognized topographic lineaments.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topography: true north-south topographic features are accompanied by topographic features that trend to the east or west of north by an average of roughly 20^o. Secondary large-scale topographic features within the Cayman Trough (Fig. 2b) are the generally short, less well-defined lineaments trending roughly east-west. They appear to cut across the dominant north-south grain, resulting in the production of blocky topography, or of north-south-trending hills with blunt ends.

In a first-order sense, the topographic features observed at the Mid-Cayman Rise are similar to those observed at other slowly accreting plate boundaries. The intersections of the Oriente and Swan transforms with the rift valley are well defined by the >6000 m closed-contour depressions at $18^o45'$N and $17^o48'$N, respectively (Fig. 3 and 4). Closed-contour depressions are a characteristic feature of transform fault/rift valley intersections at slowly accreting plate boundaries (e.g., Fox et al., 1969; Sleep and Biehler, 1970), and the triangular shape of the southern depression is particularly characteristic of other well-mapped slowly accreting rift valley/transform fault intersections (e.g. Oceanographer Transform, Fox et al., 1969; Transform A FAMOUS region, Renard et al., 1975).

Along the floor of the rift valley Ballard and Uchupi (1978) and CAYTROUGH (1979) describe volcanic morphologic features that are similar to features observed in other rift valleys at slowly accreting ridge segments (e.g., FAMOUS: Bellaiche et al., 1974; Ballard et al., 1975; ARCYANA, 1975; Ballard and van Andel, 1977; Ballard and Moore, 1977; Macdonald and Luyendyk, 1977). For example, both linear ridges and troughs, that trend roughly north-south (parallel with the general trend of the rift valley), and conical constructional features are evident in the bathymetric maps (Fig. 3 and 4). Photographic data obtained by ANGUS (and observations made in a single dive of the bathyscaph TRIESTE II during the Cayman Trough Project) indicate that the ridges are volcanic constructional features comprised of multiply stacked pillow flows that create steeply dipping flow fronts (CAYTROUGH, 1979). These may have originated above elongate fissures as is suggested for constructional ridges observed in the FAMOUS area (Bellaiche et al., 1974; Ballard et al., 1975; ARCYANA, 1975; Ballard and van Andel, 1977). The troughs between the ridges are floored by interlocking pillow flows that appear to have emanated from the flanking ridges. The conical constructional features, like those seen in the FAMOUS region, are small volcanic edifices apparently built by material emanating from a single vent. A single sheet flow, similar to flows observed at other accreting plate boundaries (Ballard et al., 1979; CYAMEX, 1978), was observed in the southernmost part of the rift valley; it appears to fill a linear depression proximal to a volcanic constructional ridge (CAYTROUGH, 1979). The zone of most recent volcanic activity, where constrained by the ANGUS data, appears to be narrow (2 to 3 km wide; Ballard and Uchupi, 1978), which is consistent with estimates of the width of zones of recent volcanic activity observed in FAMOUS.

The first-order morphologic features of the rift valley walls and flanking rift mountains are also similar to those observed along other slowly accreting plate boundaries. The boundary between the rift valley floor and the flanking walls is defined by an abrupt change in slope from the floor to the steeply dipping inward-facing escarpments that define the walls. As observed by CAYTROUGH (1979) and discussed by Stroup and Fox (in press), the walls are not comprised of a single large-throw escarpment but of a series of steps characterized by short (tens of meters to roughly 100 meters of vertical relief), steeply dipping ($\gtrsim 60^0$) bedrock escarpments linked by more gently dipping (10-60^0) carbonate/talus ramps. These escarpments appear to represent relatively small-throw dip-slip faults that combine to create the relief of the rift valley walls (Stroup and Fox, in press), and the step-like topography created by the escarpments and talus ramps is characteristic of topography observed at other slowly accreting plate boundaries (i.e., Bellaiche et al., 1974; Ballard et al., 1975; ARCYANA, 1975; Macdonald and Luyendyk, 1977). The general strike of the escarpments is north-south, and this dominant north-south grain is present on either side of the rift mountains and is delineated by the ridges and troughs identified in Fig. 2. The first-order topographic elements of the Mid-Cayman Rise are thus the products of combined north-south, dip-slip faulting and volcanism from north-south fissures or from conical edifices. Volcanic activity dominates in the rift valley floor and faulting dominates on the rift valley walls as observed in FAMOUS (Bellaiche et al., 1974; Ballard et al., 1975; ARCYANA, 1975; Macdonald and Luyendyk, 1977).

There are many second-order topographic features at the Mid-Cayman Rise, however, that are not observed at other slowly accreting plate boundaries. For example, on the Mid-Atlantic Ridge segment explored by both ANGUS and ALVIN during the FAMOUS project, the escarpments that define the rift valley walls are parallel with the rift valley and are continuous along strike over distances as great as 14 km and generally 5 to 6 km (Ramberg and van Andel, 1977). The flanking ridges and troughs beyond the rift mountains to either side of the ridge segment in the FAMOUS area, particularly along the ridge segment between transforms A and B, are markedly linear and parallel with the rift valley axis for some distance away from the rift valley (see, for example, Fig. 3 of Needham and Francheteau, 1974; Renard et al., 1975). On the Mid-Cayman Rise, considerable deviations from true north-south, which is the overall trend of the rift valley, are apparent in the trends of the topographic lineaments of Fig. 4. Moreover, although on Fig. 4 the flanking rift valley escarpments appear to be continuous over distances of up to ~15 km, ALVIN data reveal that these escarpments are terminated or offset on the order of every 50 m horizontally by bedrock escarpments striking roughly east-west (Stroup and Fox, in press). The east-west-striking escarpments are usually no more than 25 m in length and 30 to 50 m high, and therefore are subordinate in magnitude to the north-south escarpments; nevertheless, the east-west striking features are sufficiently important that the topographic grain appears to be characterized by a set of small rectangular blocks. The smooth, steeply-dipping bedrock faces of the east-west striking escarpments suggested to CAYTROUGH (1979) that, like the north-south escarpments, they represent small-throw faults. Blocky topography can be observed at a slightly larger scale on Fig. 3 and 4, particularly in the vicinities of the two ALVIN dive areas. This topography contrasts markedly with the long linear ridges and troughs observed trending parallel with the rift valley axis at most other accreting plate boundaries that have been mapped in similar detail.

The morphologic characteristics of the inner rift valley floor of the Mid-Cayman Rise are also notably different in detail from those of the inner valley floor observed at other slowly accreting plate boundaries. The floor of the valley resides at an average depth of 5 to 6 km; this depth is 2 to 3 km greater than the depth to the rift valley floor on the Mid-Atlantic Ridge. The valley floor of the Mid-Cayman Rise is roughly 3.5 km below the tops of the flanking rift mountains, and this relief is more than twice the relief observed at the ridge segments of the FAMOUS area. The most notable contrast between the inner floor of this ridge segment and that of the ridge segments of much of the Mid-Atlantic Ridge, howvever, is the apparent meandering of the line of deepest topography (the trace of the axis of the rift valley; Fig. 4) along the Mid-Cayman Rise. At its intersection with the Swan Transform in the south the rift valley is roughly 15 km wide and 5 to 6 km deep. Roughly 10 km north of this intersection the valley floor shallows to a minimum depth of 4940 m, and narrows to a width of a few kilometers. This narrow passage (at 17°57'N) is offset in a left-lateral sense from the Swan Transform/rift valley intersection depression by roughly 5 km. North of the passage the rift valley floor again widens (to ~18 km), and deepens to two, narrow, northwest-trending closed-contour depressions of ~5500 m depth that are separated by a narrow ridge (at 5 km depth). North of this wide region the valley floor again narrows (to 5 to 10 km width) and shallows (to ~4600 m) to a second passage at 18°21'W. This second passage is offset in a right-lateral sense with respect to the Oriente Transform/rift valley intersection (Fig. 3 and 4). The two narrow passages both trend northwest to give the sense of offset observed and the sinuous shape to the track following the deepest topography of the rift valley. The elongate volcanic topography (ridges and valleys) is observed by ANGUS to trend N-S at both transform/rift valley intersections; between the two narrow passages the volcanic topography trends NNW-SSE (CAYTROUGH, 1979), roughly parallel with the strike of the two depressions observed in the wide zone of the rift valley. The wide zone itself is slightly elongated, and its long axis trends in a northeasterly direction.

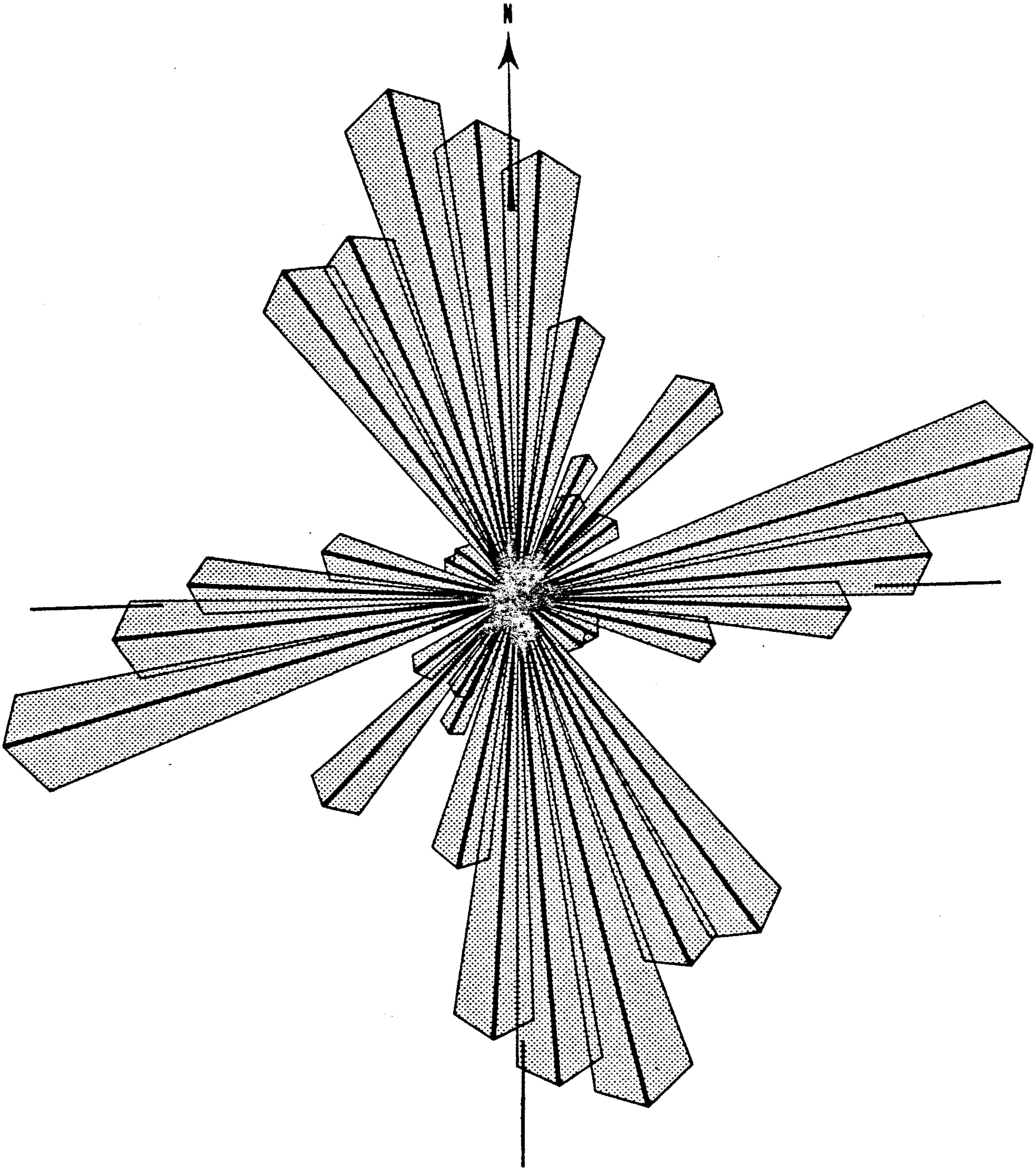
D. Structural Interpretation of Topographic Features

Models of structural behavior at accreting ridge segments have been based upon the analysis of morphologic or topographic features and the structural interpretation of those features. At the most well-studied slowly accreting ridge segments (i.e., FAMOUS) the predominant morphologic features observed on the rift valley walls are the inward-facing escarpments; these escarpments have been interpreted to represent normal faults formed in response to horizontal tensional (least-compressive) stress perpendicular to the axis and associated isostatic readjustment (e.g., Needham and Francheteau, 1974; Macdonald and Luyendyk, 1977). Recently it has been suggested that shear stresses along oceanic transforms may initiate the development of structures within the crust of the transform domain, and at transform/ridge crest intersections, that are analogous to structures observed in continental shear zones (e.g., ARCYANA, 1975; Crane, 1976; Choukroune, et al., 1978; Searle, 1979). The Cayman Trough plate boundary system is an end-member system in which the single, short ridge segment is bounded by two exceedingly long transforms. Furthermore, the transforms juxtapose, to either side of the Cayman Trough, the thick and comparatively old lithosphere of the Nicaraguan Rise and Cayman Ridge against the thin, young and relatively hot lithosphere of the Cayman Trough.

A structural interpretation of the topographic features observed within the Trough must take into account its unique tectonic configuration. The structural interpretation presented here explains the production of some of these topographic features in terms of extension perpendicular to the Rise axis, and of associated isostatic uplift, and of some of these features in terms of a shear couple produced by strike-slip motion on the long and closely spaced transforms. This interpretation is supported by an analysis of recent structures found on the island of Jamaica, which Burke, *et al*. (1978 and in press) suggest reflect deformation produced by a Swan/Oriente shear couple.

The lineaments of Fig. 4 have been plotted in a rose diagram shown as Fig. 5. Normal faults that are a product of accretion-related extension should strike roughly perpendicular to the trends of the transforms, i.e., on the Mid-Cayman Rise they should strike north-south. Hence normal faults that are a product of accretion-related extension should strike roughly perpendicular to the trends of the transforms, i.e., on the Mid-Cayman Rise they should strike north-south. Hence normal faults that dip toward the rift valley and strike north-south dominate the overall structural grain observed on ALVIN traverses, and generally north-south-trending lineaments that may represent extensional features associated with spreading (i.e., normal faults) appear to dominate the overall topographic grain as represented in Fig. 4 and 5. The development of a second-order, but pervasively present, set of east-west-trending topographic lineaments on the Mid-Cayman Rise cannot be explained in terms of models of plate accretion proposed for other slowly accreting ridge segments, and these features appear to be unique to the Rise when it is compared with other well-

Figure 5. Rose diagram showing directions of topographic lineaments on the Mid-Cayman Rise (Fig. 4). The total number of observations (Σ N) is 126 and the lengths of the arms on the diagram are proportional to N; the longest arms (trending ENE and NNW) are each equivalent to N = 13. The arithmetic means of the directions, calculated for 10^0 intervals, are shown as lines; the shaded areas represent twice the standard deviation about the mean.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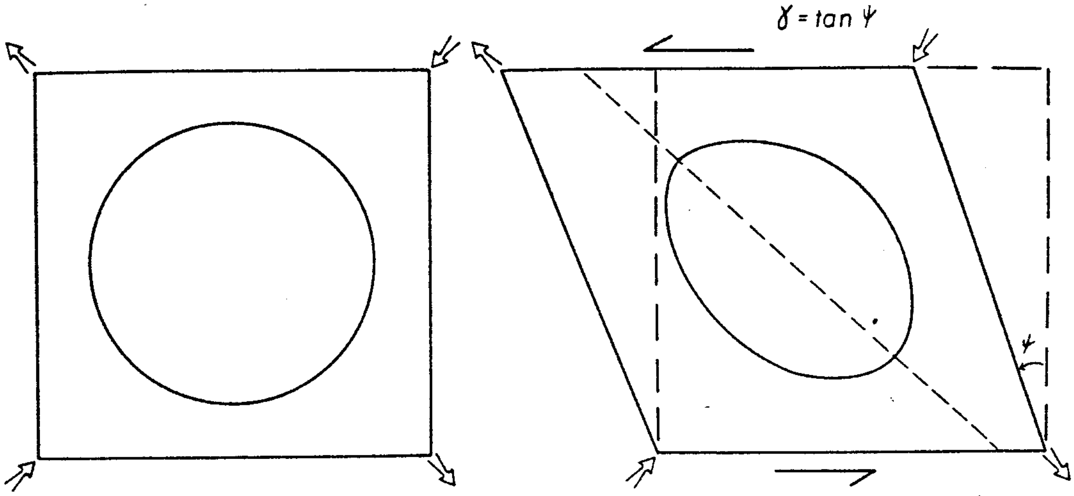
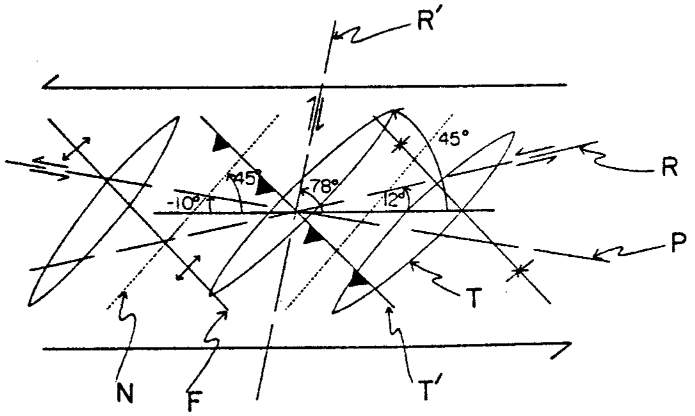
studied ridge segments such as those of the FAMOUS area. The observation of escarpments with these trends in the bottom photographs indicates that their observation as lineaments on the SASS map of the Rise (Fig. 3 and 4) is not an artifact of the map construction. The development of the east-west features may be explicable in terms of models of deformation induced by shear.

In experimental work and in nature, and at scales varying from the microscopic (deformation of rocks) to the megascopic (deformation of the earth's crust), the displacements occurring within shear zones are accompanied by deformation producing certain well-documented first-order structures (Riedel, 1929; Moody and Hill, 1956; Wilson, 1960; Tchalenko, 1970; Tchalenko and Ambraseys, 1970; Fig. 6). Strain geometry in naturally and experimentally deformed rocks is summarized in Fig. 6a. Failure of a material under finite simple shear may occur in theory by (1) extension, producing structures oriented normal to the direction of maximum extension, (2) by compression, producing structures oriented normal or approximately normal to the direction of maximum compression, and/or by (3) shear fracturing oriented symmetrically, an angles of $<45^0$, with respect to the direction of maximum compression (Wilson, 1960). Tchalenko (1970) has presented a summary of some of the first-order structures that develop during the evolution of an ideally plastic material subjected to homogeneous simple shear; he describes the special case of simple parallel wrenching (Wilcox *et al.*, 1973). Two of the more significant of the structures described by Tchalenko are (Fig. 6b): (1) Riedel shears, which have, at the time of their first appearance, an inclination to the shear zone of $12^0 \pm 1^0$ and which may be bodily rotated during shearing to a maximum

Figure 6. a. Representation of a unit circle subjected to left-lateral finite simple shear and progressively deformed to a strain ellipse (after Ramsay and Graham, 1970). The angular shear strain, Ψ, may be found from the shear strain, $\lambda = \tan \Psi$. The direction of maximum shortening is parallel with the minor strain ellipse axis, and the direction of maximum extension is parallel with the major strain ellipse axis (double arrows).

b. Theoretical and observed structures developed in left-lateral shear. R = Riedel shear; R' = anti-Riedel shear; P = P-shear; T = tension gash; T' = thrust or reverse fault; N = normal fault; F = fold.


γ = tan ψ
ψ


R'
45°
45°
78°
-10°
12°
R
P
T
N
F
T'

inclination of 16°; and (2) P-shears, which, with an average inclination of -10°, are roughly symmetric with respect to the Riedel shears. Both sets of shears have the same sense of displacement as that of the shear zone (i.e., in a left-lateral shear zone the Riedels and P-shears experience left-lateral offset). As shearing continues, new Riedels develop at inclinations that are progressively more parallel with the inclination of the shear zone.

If deformation due to left-lateral shear is accommodated by structures developed on the Mid-Cayman Rise, then Riedels and P-shears should be observed because they are the dominant structures formed initially in shear zones. A large number of topographic lineaments that trend at angles between 0° and 20°, and between 0° and -20°, can be observed on Fig. 4 and are represented on Fig. 5 . The lineaments that trend at angles of 0° to 20° may represent Riedels formed in response to left-lateral shear, and those that trend at angles of 0° to -20° may represent P-shears formed by left-lateral shear. The variation of the orientations of the east-west features as represented on Fig. 5 from their orientations as predicted by experimental work (Fig. 6b) is not great given the ambiguities inherent in averaging these trends over tens of kilometers. Both sets of shears may be experiencing a dip-slip component of motion in addition to strike-slip, since the bedrock escarpments observed on ALVIN traverses appear to offset topography not only laterally (east-west) but also vertically, but this supposition cannot be documented. Dip-slip motion is clearly indicated on north-south trending fault scarps by downslope-trending slickensides (Stroup and Fox, in press) although none were observed on the east-west scarps. Strike-slip or dip-slip offset on these east-west faults, however, must be very minor relative to the displacements occurring on north-south faults given the regularity of magnetic anomaly lineations.

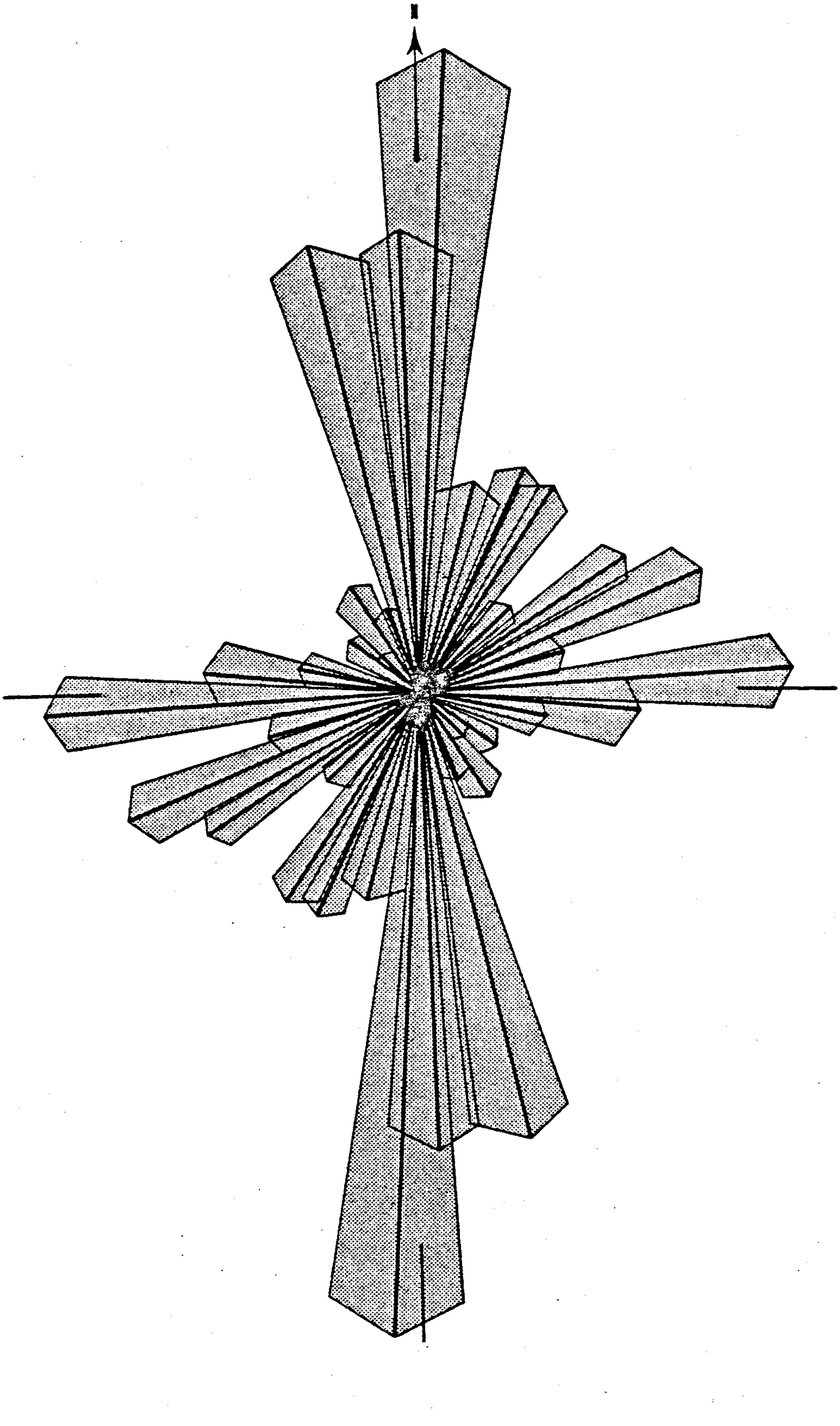
Topographic lineaments that trend at angles intermediate between those that define the primary north-south grain and secondary east-west grain are far less numerous on Fig. 4 and 5. No ALVIN data can enable us to determine what these topographic lineaments represent: we observed no morphologic features with these orientations on the rift valley walls in our two dive areas (Stroup and Fox, in press). If they are interpreted as structures accommodating shear zone deformation, then those with orientations appropriate for these structures, as observed in experimental and field work, may be tensional or compressional features, or anti-Riedel shears (Wilson, 1960; Tchalenko, 1970; Wilcox et al., 1973; Fig. 5b).

Features developed in the inner rift valley floor of the Mid-Cayman Rise have not been investigated by ALVIN, and only indirect inferences as to their nature may be made from the existing analysis of the ANGUS data. Extensional features associated with accretion (fissures and constructional volcanic ridges) have been documented (Ballard and Uchupi, 1978; CAYTROUGH, 1979). The strike of most of the linear volcanic edifices is north-south, which is consistent with their formation as constructional piles built over fissures opened in response to east-west spreading. The observed offset of the trace of deepest topography in the rift valley and the existence of a northeast-trending central wide zone, as evident in Fig. 4, are not readily interpretable. The wide zone has been suggested previously to be the site of combined accretionary and strike-slip activity (i.e., the site of an incipient leaky transform; Macdonald and Holcombe, 1978; CAYTROUGH, 1979). These authors propose that left-lateral slip is taking place along faults parallel with the north-northeasterly-trending boundaries of the zone, and normal faulting is taking place on structures represented by the north-south-trending boundaries of the zone. While these suggestions may be correct (the orientations of the inferred structural features are appropriate for deformation due to the combined effects of accretion and left-lateral shear), the authors explained neither the geometry observed in the offset of this zone through the two narrow northwest-trending passages to the north and south of the zone (Fig. 4), nor the orientation of the two northwest-striking depressions and the ridge between them that occupy the central portion of the zone. Until more high resolution data has been obtained we cannot propose a structural model that will account for these features.

The first and second-order north-south and east-west trending lineaments that are exhibited on the SASS map of the Mid-Cayman Rise are also observable on the large-scale map of the Cayman Trough (Fig. 2b). This suggests that the structures defined by these topographic lineaments have been developed within the Cayman Trough for at least as long as this topography can be recognized (i.e., a minimum of 30 m.y., Macdonald and Holcombe, 1978). Figure 7 is a rose diagram of the trends of the lineaments outlined in Fig. 2b. The dominant topographic grain shown on Fig. 7 is north-south, suggesting that it was produced, like the topographic grain exhibited at a finer scale (Fig. 5), by accretion-related processes. Second-order topography trends roughly east-west, which may be a function of structural control by shear-zone-related deformation.

Topographic features having trends intermediate between north-south and east-west, in particular, those with northeasterly trends, are more

Figure 7. Rose diagram of topographic lineaments in the Cayman Trough (Fig. 2b). Diagram was constructed in the same manner as Fig. 5. The longest arm here (trending roughly north-south) is proportional to $N = 21$; $\Sigma N = 136$.


N

numerous at this scale than they are at a smaller scale, as can be seen by a comparison of Fig. 5 and 7. This may reflect the contribution of the many north-easterly-trending lineaments located at the eastern end of the Oriente Deep to the northeast of Jamaica. The change in orientation of topography from predominantly north-south to northeast in this area was observed by Macdonald and Holcombe (1978), who suggested that it reflects some aspect of the early opening history of the Mid-Cayman Rise (for example, a different orientation of the spreading center). Grippi (1978) also discussed this marked change in orientation and observed that in left-lateral shear north-easterly-trending structures should theoretically be extensional features (Fig. 6b); he suggested that opening of the Mid-Cayman Rise spreading center may have been initiated along extensional fractures formed as a result of left-lateral displacement along the proto-Cayman Trough plate boundary. Dewey (1978) has suggested that new accreting plate boundary segments may initiate in response to shear zone deformation along transform faults, and may nucleate on structures (Riedels, tension gashes) formed within the shear zone. There are no data available at present to verify or refute the suggestion that the Mid-Cayman Rise ridge segment may have nucleated on a structure formed in response to left-lateral shear. It is clearly evident, however, that many topographic features preserved within the older portions of the Cayman Trough have orientations that must reflect their formation by some process other than pure accretion.

In the Cayman Trough many deviations in the strike of the transform segments from their assumed overall strike (east-west) are apparent (the trend of the long-dashed line in Fig. 2b). These jogs or bends in topography may also reflect the orientations of structures developed in response to left-lateral shear. More refined data are needed before an analysis of the possible structures developed on a large or small scale along these transforms can be undertaken.

Discussion

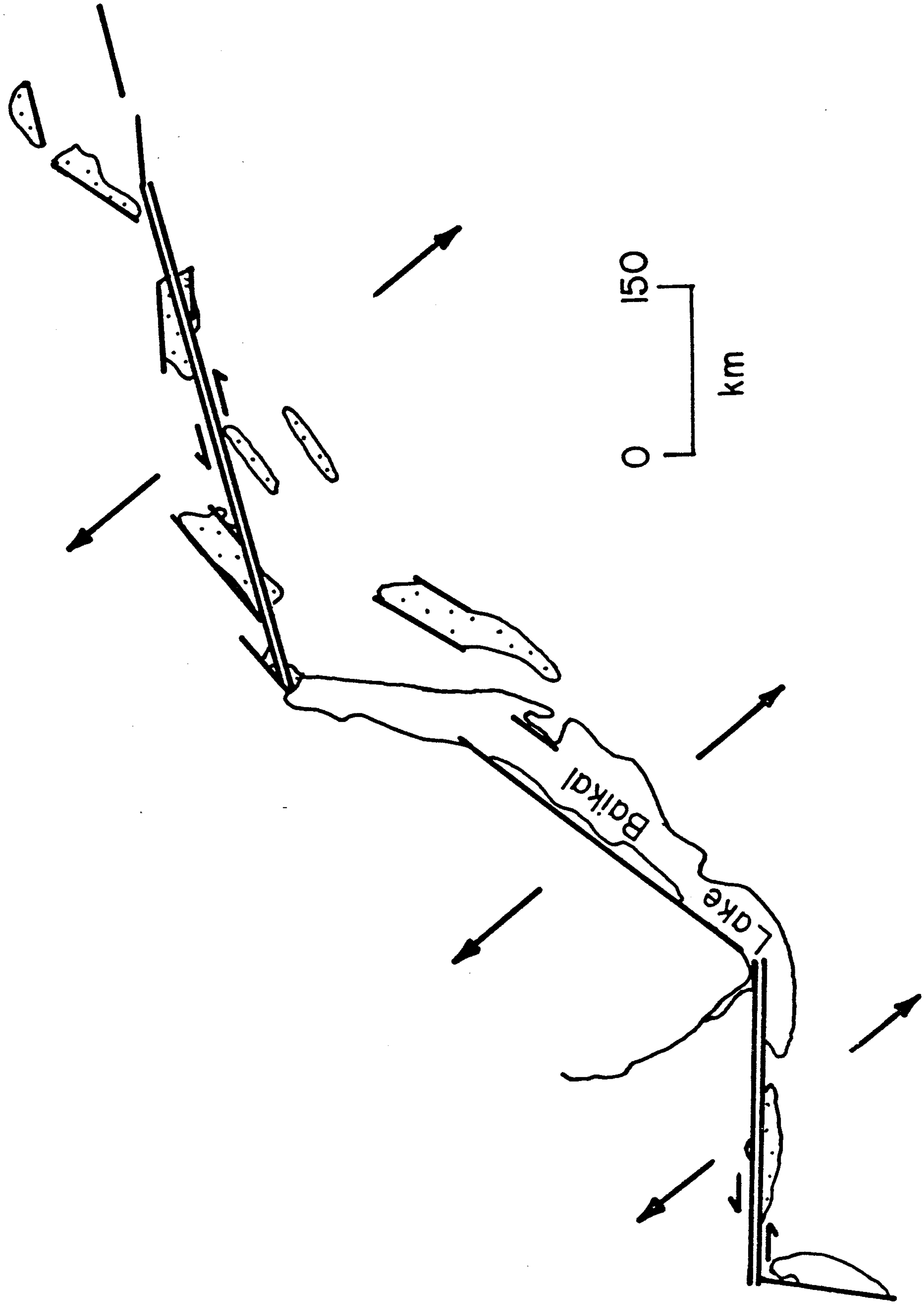
Our structural interpretation of the morphotectonic features developed on the Mid-Cayman Rise and in the Cayman Trough suggests that the Trough is notably different from other similarly well-studied oceanic transform-ridge-transform systems, in that the two extremely long transforms form a shear couple and that structures developed in response to deformation induced by shear are present throughout the entire 110 km width of the Trough. Other differences between the Cayman Trough and most transform-ridge-transform systems have been observed: the Mid-Cayman Rise rift valley is characterized by a depth 2 to 3 km greater than the rift valley depth observed at other slowly accreting ridge segments; the anomalous thinness of the oceanic crust accreted at the Rise is indicated in part by the exposure of plutonic rocks to within 400 m of the top of the rift valley walls in the two ALVIN dive areas (CAYTROUGH, 1979; White and Stroup, 1979; Stroup and Fox, in press). If our interpretation of the morphotectonic features here is correct, then two factors may contribute to the development of all of these differences: these are (1) the relative lengths of the Oriente and Swan transforms and the Mid-Cayman Rise ridge axis, and (2) the contrasting thicknesses of the lithospheres of the Cayman Trough and the bounding Nicaraguan Rise and Cayman Ridge. Intuitively, these factors could enhance the development of features in the Trough that are observed to develop to a less pronounced degree in other plate boundary systems. For example, the extreme thermal contrast between the Cayman Trough and the bounding Ridge and Rise may perturb the processes of plate accretion to create the observed exaggerated depth of the Mid-Cayman Rise rift valley floor, much as the thermal contrast at many rift valley/transform fault intersections has been suggested to account for the increase in depth of the rift valley floor towards its intersection with the transform (Sleep and Biehler, 1970). Similarly, this high thermal contrast, and the spatial proximity of the two long transforms, may result in the production of the apparently anomalously thin oceanic crust of the Trough, much as crustal thinning has been inferred to take place proximal to other ridge/transform boundaries (Fox, 1978; Fox et al., 1980; Stroup and Fox, in press).

Within the oceanic transform environment, deformation inferred to have resulted from shear on a transform is observed to be confined to a very narrow region of the crust only a few kilometers wide (the principal transform deformation zone or PTDZ; ARCYANA, 1975; Crane, 1976; Choukroune et al., 1978; Macdonald et al., 1979; CYAMEX, 1978, 1980). Complex deformation due to shear in oceanic transforms tends to migrate into regions of younger, hotter crust. This tendency is manifested by the apparent predominance of second-order faulting associated with shear in the PTDZ proximal to the ridge/transform intersection as opposed to the median portion of the transform (in Transform A; Choukroune, et al., 1978), and by the observation that the PTDZ appears to shift in time through wider regions of the crust at fast slip-rate transforms than at slow slip-rate transforms

(CYAMEX, 1978, 1980). At ridge/transform intersections structures apparently produced by deformation due to shear and deformation related to accretion coexist over only very short distances (a few kilometers) into the rift valley (Detrick *et al.*, 1973; Macdonald *et al.*, 1979). We have inferred that the unique tectonic environment of the Cayman Trough enhances the development of shear-related deformation over the entire length of the Mid-Cayman Rise axis; at other slowly accreting plate boundaries the less extreme lithosphere thickness contrast across a transform results in the confinement of shear-related deformation to the transform domain or to the ridge axis close to the ridge/transform intersection. The morphotectonic elements observed in the Cayman Trough may be the expression of structural evolution of an end-member (long transform - short ridge) of transform-ridge-transform systems.

A model for the early history of the Cayman Trough may be found from a comparison of the Trough with the Lake Baikal rift zone (USSR), which has been suggested to be comprised of a central northeasterly-trending tensional feature or graben (Lake Baikal) that extends into two left-lateral continental transform faults (to the southwest and northeast of Lake Baikal; Sherman, 1978; Fig. 8). The rift zone appears to be experiencing currently active rift development, based upon the observation of recent large-scale vertical displacements, a thickness of 8 km of sediments and a high level of seismic activity within the rift valley system (Logatchev and Florensov, 1978; Golenetsky and Misharina, 1978). The direction of maximum extension within the rift valley as determined from seismic focal mechanisms appears

Figure 8. Map of the Lake Baikal rift zone, USSR, from Sherman, 1978. Two left-lateral continental transforms are connected by the Lake Baikal rift valley. Smaller rifts oriented parallel with the Lake Baikal valley are also outlined. Large arrows are parallel with the direction of maximum extension in the rift zone as determined from seismic focal mechanisms.


Lake Baikal
0
150
km

to be roughly perpendicular to the northeasterly strike of observed normal faults forming the rift and slightly oblique to the two left-lateral strike-slip faults (Golenetsky and Misharina, 1978; Sherman, 1978; Fig. 8). If, as Sherman (1978) suggests, the Lake Baikal rift system is a continental transform-rift-transform system experiencing left-lateral oblique slip along the two transforms, then it may serve as an analogue for the proto-Cayman Trough. Sherman's analysis suggests that the Lake Baikal rift zone may be responding in part to a left-lateral shear couple, and therefore the Lake Baikal depression and the large number of smaller northeast-trending graben within the rift zone may be extensional features produced by shearing.

Although our explanation for the morphology observed on the Mid-Cayman Rise rift valley walls suggests that lateral displacement has occurred on east-west-trending features, the rough regularity of the magnetic anomaly pattern in fact indicates that east-west lateral displacement must be very small. Elsewhere (Stroup and Fox, in press) we note that in the dive areas there is evidence (i.e., welded, undisrupted talus; sediment dusting and manganese encrustation on all exposed bedrock) that little or no recent tectonic activity has occurred on at least the upper portion of the rift valley walls. We have inferred that most vertical displacement at the Mid-Cayman Rise is produced at the transition from rift valley floor to rift valley walls, and that this displacement takes place on fault planes that form as fracture planes in the floor (White and Stroup, 1979; Stroup and Fox, in press). We suggest that following the initial formation, in the rift valley floor, of structures responding to extension (fractures and fissures parallel with the rift valley axis) and to a Swan/Oriente shear couple (predominantly Riedels and P-shears) the blocks of crust produced by this pattern of deformation are isostatically uplifted. Displacements taking place in the rift valley floor on either of these sets of fault/fracture planes are small. Once dip-slip motion resulting from isostatic adjustment of the crust has formed the observed vertical offsets, it appears that essentially no further tectonic activity occurs on the Mid-Cayman Rise rift valley walls. The blocky topography observed in the older parts of the Cayman Trough thus would reflect the preservation of structures formed in response to isostatic adjustments of the crust on structural planes formed initially in response to extension and to shear. For example, given time and the continued opening of the Lake Baikal rift, the spreading center initiated within the rift might rotate into an orthogonal (least-work) position with respect to the bounding transforms. Thus the Cayman Trough may be a future Lake Baikal system. Conversely, the northeasterly-trending topographic lineaments at the eastern end of the Cayman Trough may represent structures, like the present bounding escarpments of the Lake Baikal rift valley, formed at angles oblique with respect to the transforms early in the history of the Cayman Trough.

The Cayman Trough is to some degree an end-member of transform-ridge-transform plate boundary systems, in that the transforms are exceedingly long relative to the ridge segment. The shear effects of the transform probably result in deformation instantaneously at the axis of accretion (the Mid-Cayman Rise), where the crust is thinnest and hottest, and this deformation is preserved in structures in the older crust, on the flanks of the Rise, which exhibits a box-like topography. Our interpretation of the morphotectonic elements present in the Cayman Trough suggests that along the axis of accretion of the Mid-Cayman Rise structures are produced as a consequence of the instantaneous effect of transform activity.

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APPENDIX I

"Distribution of rock types in the Mid-Cayman Rise, Caribbean Sea, as evidence for conjugate normal faulting in slowly spreading ridges"

Gary W. White and Janet B. Stroup

ABSTRACT

The seemingly enigmatic exposure of predominantly plutonic rocks on the outer walls of the Mid-Cayman Rise can be explained by a structural model involving both inward-facing and outward-facing normal faults in the region of the median valley. Movement along inward-facing faults must dominate within the median valley to produce the topography observed; the less prominent scarps, which result from movement along outward-facing faults, are readily concealed by talus and pelagic sediment. Movement along these outward-facing faults increases as the crust passes through the transition between median-valley and rift-mountain topography.

INTRODUCTION

The Cayman Trough is a 1,600-km long, 110-km-wide feature in the Caribbean Sea. It extends eastward from the Gulf of Honduras to the Windward Passage to the southeast of Cuba and projects westward into the Polochic-Motagua fault zone in Central America. The central part of the Cayman Trough is defined by a rugged east-trending ridge that is transected by a series of linear north-trending ridges and basins (Holcombe and others, 1973). A 5- to 6-km-deep, V-shaped north-south valley at about lat 18° to 19°N, long 81°40'W symmetrically divides the ridge-and-basin topography. Seismic reflection profiling reveals that the sediment blanket in the Cayman area thins symmetrically toward the axis of the central valley (Holcombe and others, 1973). Seismic activity in the Cayman Trough is confined to a zone that includes the north-trending central valley, a linear deep to the northeast termed the Oriente Fracture Zone, and a second linear deep to the southwest called the Swan Fracture Zone (Sykes and Ewing, 1965). First-motion studies by Molnar and Sykes (1969) indicate predominantly left-lateral strike-slip movement along the Oriente and Swan Fracture Zones. These seismic data, coupled with the topographic and sedimentologic data, indicated to Holcombe and others (1973) that the Cayman Trough is a transform-ridge-transform boundary between the Caribbean and North American plates (Fig. 1), and they called the accreting plate boundary the Mid-Cayman Rise. Heat-flow measurements (Erickson and others, 1972) as well as deep-towed camera package and direct sampling data (Ballard and Uchupi, 1978) support this hypothesis. Magnetics work by Matthews (1974) indicates that magnetic anomaly lineations are bilaterally symmetric about the axis of accretion. More recent work by Macdonald (1978) has confirmed Matthew's conclusion and, further, indicates that the Mid-Cayman Rise is spreading with a half-rate of about 1 cm/yr, a figure deduced by Holcombe and others (1973) using indirect methods. Petrologic work by Perfit (1977) on dredged samples and by CAYTROUGH (1978) on samples collected by submersible from the Mid-Cayman Rise has demonstrated that these rocks have the tholeiitic affinities typical of basalts and gabbros found at other accreting plate boundaries.

OBSERVATIONS

The Mid-Cayman Rise was the locus of two series of dives made by the DSRV ALVIN in an attempt to sample from the bounding rift-valley walls and to examine the structure and detailed morphology of the rift-valley terrain. The ALVIN dives were part of a larger program principally involving investigators from the Woods Hole Oceanographic Institution, the State University of New York at Albany and Wesleyan University. The first twelve dives were made in the spring of 1976, with six dives positioned along the east wall (dive area 1) and six dives along the west wall (dive area 2) within the rift valley. The ALVIN returned in April 1977 to dive area 1 and completed six additional dives (Fig. 2).

The 5- to 6-km deep rift valley of the Mid-Cayman Rise is flanked by escarpments (the rift-valley walls) that rise above the valley floor in a series of steps and have a total vertical relief of 3.5 km; the integrated slope of the rift-valley walls ranges from <20° to 30°. ALVIN dives were conducted to a depth of 3.6 km and therefore traversed roughly the upper half of the rift-valley walls. Individual scarps have from a few tens of meters to approximately 100 m of relief, and they dip toward the rift valley at angles of 60° or more. Intervening sediment-covered surfaces dip toward the rift valley at angles of 20° to 60°; they are commonly characterized by intermittent talus ramps or by prominent crags that may be either large talus blocks or in situ material. Bedrock exposure is nearly continuous in parts of some traverses, in which near-vertical scarps are broken only by very steeply dipping, narrow (~20 m) sediment-covered slopes.

As indicated by Figure 2, the sampling interval along the ALVIN's traverse was approximately every 50 m. The samples were recovered from the faces of individual scarps and only very rarely from talus. Analysis of the dives conducted on the east wall of the rift valley (dive area 1) reveals that ALVIN sampled a large number of plutonic rocks (72 samples), including fresh and altered isotropic gabbros, troctolites, amphibolites and serpentinized ultramafics (CAYTROUGH, 1978). Two samples of greenschist facies metabasalt were recovered from talus slopes, and no basalt was observed or sampled in situ in this area. On six traverses conducted on the west wall 60 km to the north in dive area 2, ALVIN recovered the same range and relative abundance of rock types. In addition, in this area pillow basalts were observed and sampled near the top of the rift-valley wall. In both dive areas plutonic rocks were sampled to within 200 m of the summit of the rift-valley walls.

OUTER WALL STRUCTURE

The recovery of greenschist facies metabasalt from talus slopes on the east wall and the observation of in situ pillow basalt on several scarp faces high on the west wall indicate that extrusive and shallow intrusive rocks cap the plutonic complex at the top of the rift-valley escarpment. On the basis of these observations, it is suggested (P.J. Fox, in prep.) that the carapace of extrusive and shallow intrusive rocks in the Cayman area is anomalously thin, perhaps as thin as 100 m. Thinning of the basaltic carapace does not explain the gross distribution of volcanic and plutonic rocks on the rift-valley walls, nor does it account for exposure of deeper levels of the crust on individual scarps that have observed vertical displacements less than the minimum thickness of the extrusive lid (100 m). The suggestion that the plutonic complex was intruded at shallow levels of the oceanic crust is negated by the observation that plutonic rocks predominate on both sides of the rift valley over a distance of 60 km. We are, therefore, forced to explain the distribution of rocks sampled from the rift-valley walls of the Mid-Cayman Rise within the geometrical and mechanical constraints placed on this divergent plate boundary by observations and modeling of extensional systems.

Sykes and Sbar (1973) have shown that the least compressive stress in rifted ocean ridges is nearly horizontal and parallel with the spreading (extension) direction. Therefore, the plane containing the maximum and intermediate compressive stresses is nearly vertical and parallel to the spreading axis. Anderson (1951) has shown that in an extensional regime, like that described above, normal faults are relatively high angles to the least compressive stress direction; in this case, normal faults should develop along steeply dipping planes at or near the axis of spreading. Therefore, it is unlikely that exposure of only plutonic rocks along the entire outer wall in dive area 1 is the result of very large dip-slip displacement along a fault dipping at only 20° to 30° through the oceanic crust in which the volcanic layer is very thin. It is equally unlikely that an originally steeply dipping fault scarp, with at least 2 km of dip-slip movement was rotated to the relatively gentle slopes observed. The improbability of rotation on the scale required, when combined with the nature of experimentally observed extensional fracturing, indicates that the gentle slope is the result of smaller displacements on many faults that are steeply dipping. The steplike topography observed on the rift-valley walls (CAYTROUGH, 1978) indicates that this is true. If, however, most or all of these faults are inward-facing normal faults, as suggested by gross features observed in the topographic profiles from this area (CAYTROUGH, 1978) and by studies in other median valleys by Macdonald and others (1975) and Macdonald and Atwater (1978), then the probability of observing and sampling only plutonic rocks on fault scarps is extremely small even if the volcanic layer is very thin. In fact, extrusive rocks should be present on every fault scarp (Fig. 3a). We therefore suggest an alternative structure for the outer wall, in which the basaltic cover is faulted down along outward-facing normal faults that are conjugate to the inward-facing faults. This mechanism of conjugate normal faulting was suggested by Cann (1968) as a possible explanation for the exposure of metabasalts dredged from mid-ocean ridge crests. Detailed sampling and observations made from ALVIN at the Mid-Cayman Rise indicate that this mechanism will also explain the continuous exposure of the plutonic complex and the paucity of the capping extrusive and shallow intrusive rocks.

DISCUSSION AND IMPLICATIONS

The existence of outward-facing normal faults in slowly spreading mid-ocean ridges has been reported in studies of the Mid-Atlantic Ridge (Macdonald and others, 1975; Needham and Francheteau, 1974; Macdonald and Luyendyk, 1977; Ballard and van Andel, 1977; Macdonald and Atwater, 1978). The role of these faults in the evolution of the median valley into the rift mountains is of particular interest. It was suggested by Macdonald and Luyendyk (1977) and Needham and Francheteau (1974) that the transition from the median valley to the horst-and-graben terrain of the rift mountain is accomplished by introducing a system of outward-facing normal faults in the region of the rift mountains. Although there are other methods of producing rift-mountain topography, normal faulting on inward- and outward-facing planes seems most convincing and this agrees with seismic studies by Sykes (1967), Weidner and Aki (1973) and others. Macdonald and Atwater (1978) gave a concise analysis of these models and of the constraints imposed by normal faulting throughout the ocean ridges. They concluded from analysis of deep-tow observations that outward-facing normal faults are created or activated in a zone just beyond the rift-valley outer walls in the rift mountains. This conclusion is supported by the large increase in the number of outward-facing fault scarps in the region of the rift mountains (Needham and Francheteau, 1974; Macdonald and Luyendyk, 1977).

However, outward-facing fault scarps have also been recognized in the inner rift valley and the terraces of the Mid-Atlantic Ridge (Ballard and others, 1975; ARCYANA, 1975; Macdonald and others, 1975; Ballard and van Andel, 1977; Ramberg and van Andel, 1977). The argument against movement on outward-facing faults in the median-valley walls is based largely on the paucity of outward-facing scarps in the rift-valley walls (Macdonald and Atwater, 1978). If, however, the outward-facing faults have small throws relative to the inward-facing faults, as suggested here, outward-facing scarps would be small and would tend to act as traps or dams for talus and pelagic sediment (Fig. 3b). In addition, small horsts bounded by inward- and outward-facing faults might be difficult to distinguish from volcanic constructions.

Sleep (1969) and Lachenbruch (1973) have suggested that the distinctive rift-valley morphology associated with slowly accreting plate boundaries (< 4 cm/yr) is a function of increased magma viscosity resulting from heat loss to the bounding conduit walls ("viscous head loss"). If the median valley present at slowly spreading ridges is formed by viscous head loss, then movement along inward-facing faults will be preferred in the effort to establish isostatic recovery. Extension in the region of the median-valley walls may, however, be accommodated along inward-facing faults, outward-facing faults or both. Because outward-facing scarps have been observed to some degree in other median valleys and because the existence of outward-facing faults convincingly explains the distribution of plutonic rocks in the Mid-Cayman Rise, it seems likely that these faults occur throughout this rifted ocean ridge, although movement along them is necessarily less than movement along inward-facing faults in the median-valley walls.

If our assumptions are correct, then the faults that we predict are the result of movement along conjugate fractures formed in the rift-valley floor. An evolutionary sequence of conjugate fracturing in the inner rift floor and dip-slip movement on both sets of fractures as crust moves up the rift-valley walls explains both the rock distribution and the median-valley topography as a steady-state feature. It can be seen from Figure 4 that the crust at shallow levels along the inner rift floor must be pervasively fractured and must have undergone a complex faulting history by the time that it reaches the rift-valley mountains. Because of the equal probability of forming inward- or outward-facing fractures if there are no lateral anisotropies (Anderson, 1951), the fault density of outward-facing faults should be equal to that of inward-facing faults, although movement on both sets is not necessarily equal (Fig. 4). Movement along outward-facing faults tends to decrease the slope of the rift-valley walls, whereas movement along inward-facing faults tends to steepen the slope. Therefore, the slopes observed are the result of competition between these two sets. This would suggest that decay of the median-valley topography to that of the rift-mountain topography is accomplished by increased dip-slip movement on pre-existing outward-facing faults and not by a new system of faults in the region of the rift mountains.

Because the conjugate faults are formed very near the spreading axis where the lithosphere is thin and the temperature increases rapidly with increasing depth, these faults, as schematically shown in Figure 4, are only the near-surface expression of tectonism in the spreading center. We expect the faults to be listric if they continue to depths where increasing temperature and pressure dictate a change in fault orientation; however, because more extension can be accommodated by plastic deformation and shallower-dipping normal faults at depth, the fault density probably decreases with increasing depth in the transition zone from brittle to more ductile deformation.

CONCLUSIONS

Movement along outward-facing normal faults seems to be the best explanation for exposure of only plutonic rocks on the eastern wall of the Mid-Cayman Rise. We suggest that the displacement on these outward-facing faults is less than that on inward-facing faults in the median-valley walls, but increased movement is predicted on the outward-facing faults in the region of the rift-valley mountains to effect the decay of the median-valley topography. Both sets of faults are created in the region of the inner rift-valley floor and are active to varying degrees as the crust passes through the different topographic regimes observed at the Mid-Cayman Rise. This study demonstrates the value of direct observation and controlled sampling in an effort to understand the tectonics associated with accreting plate boundaries, and we believe that the structure determined from detailed study of rock distribution for the outer wall of the Mid-Cayman Rise places some constraints on evolutionary models of this and possibly other accreting plate boundaries.

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APPENDIX 2

Rocks Collected by ALVIN from the Rift Valley Walls of the Mid-Cayman Rise

DIVE #	STA #	DEPTH IN METERS	ROCK TYPES COLLECTED (# of samples)
		I. Dive Area 1, 1976	
611	1	3623	olivine gabbro (1)
	2	3584	olivine gabbro (1)
	3	3561	diabase (1)
	4	3434	orthopyroxene gabbro (1)
	5	3327	olivine gabbro (2)
	6	3223	olivine gabbro (1)
	7	2997	spinel lherzolite (1); amphibolite II (1)
612	1	3062	amphibolite I (2)
	2	2950	spinel harzburgite (2), T
	3	2904	gabbro (1); orthopyroxene gabbro (1)
	4	2919	gneissic metagabbro (2)
613	1	3524	orthopyroxene gabbro (2); gabbro (1)
	2	3379	olivine gabbro (1), t
	3	3230-3220	gneissic metagabbro (1); spinel harzburgite (1)
	4	3139	spinel harzburgite (3); spinel lherzolite (1)
	5	2989	crystalline basalt (1), T
614	1	3130	amphibolite II (1)
	2	3050	gabbro (1)
615	1	3036	olivine gabbro (1)
	2	3030	olivine gabbro (1); amphibolite I (1); gneissic metagabbro (1)
	3	2913	gabbro (1), t; gneissic metagabbro (1), t
	4	2855	olivine gabbro (1)
	5	2800	amphibolite II (1), t

Note: "T" after the rock type collected indicates that the sample was collected from talus that is not adjacent to bedrock; "t" after rock type indicates that the sample was collected from loose rubble that appears to be talus from an immediately adjacent bedrock outcrop.

DIVE #	STA #	DEPTH IN METERS	ROCK TYPES COLLECTED (# of samples)
616	1	3660	spinel lherzolite (1); troctolite (1)
	2	3607	olivine gabbro (3)
	3	3517	spinel harzburgite (1), t
	4	3385	olivine gabbro (1)
	5	3186	olivine gabbro (2)
	6	3055	gneissic metagabbro (1), t olivine gabbro (1), t.
	7	3017	gabbro (2)

II. Dive Area 2, 1976

620	1	3632	spinel-plagioclase dunite (1), t
	2	3599	crystalline basalt (1)
	3	3594	gneissic metagabbro (2); spinel-plagioclase dunite (1).
	5	3425	olivine gabbro (1); plagioclase wherlite (1)
	6	3313	gneissic metagabbro (1)
	7	3229	gabbro (1), t
621	1	3110	olivine gabbro (1)
	2	3080	olivine gabbro (1)
	3	3125	troctolite (2)
	4	3090	olivine gabbro (2); troctolite (1)
	5	2975	troctolite (1)
	6	2925	troctolite (1)
	7	2825	olivine gabbro (1)
622	1	2865	olivine gabbro (2); breccia (1)
	2	2755	gneissic metagabbro (2)
	3	2531	highly metasomatized rocks (1)
623	1	3647	olivine gabbro (1), t; troctolite (3), t.
	2	3642	olivine gabbro (1), t.
	3	3529	olivine gabbro (1); troctolite (1).
	4	3420	olivine gabbro (2), t; troctolite (1), t.
	5	3254	olivine gabbro (1)
	6	3160	olivine gabbro (1), t.
624	1	3652	spinel harzburgite (1), T(?)

	2	3621	spinel harzburgite (1), T(?);
			highly metasomatized rock (1), T(?);
			plagioclase wherlite (1), T(?)

	3a	3543	highly metasomatized rock (1), t; spinel harzburgite (1), t

DIVE #	STA #	DEPTH IN METERS	ROCK TYPES COLLECTED (# of samples)
624, cont.	3b	3540	crystalline basalt (1), t.
	4	3450	crystalline basalt (1)
	5	3400	gabbro (1), t.
	6	3374	highly metasomatized rock (1); spinel lherzolite (1)
	7	3353	highly metasomatized rock (1)
	8	3252	pillow basalt (2)
625	1	2086	pillow basalt (1)
	2	2096	pillow basalt (1)
	3	2220	pillow basalt (1)
		III. Dive Area 1, 1977	
737	1a	3511	amphibolite II (1), T
	1b	3494	orthopyroxene gabbro (1), T
	2	3421	amphibolite I (1), T
738	1	3436	olivine gabbro (1), t; gabbro (1), t
739	1	3599	olivine gabbro (1), T
	2	3623	amphibolite I (1), t; troctolite (1), t
	3	3650	olivine gabbro (1), T
	4	3568	gabbro (1); orthopyroxene gabbro (1); troctolite (2)
	5	3477	orthopyroxene gabbro (1)
	6	3394	olivine gabbro (1)
	7	3327	olivine gabbro (1)
740	1	3103	gabbro (1), T
	2	3068	gabbro (1), T
	3	3015	orthopyroxene gabbro (1), T
	4	2947	olivine gabbro (1), T
	5	2898	breccia (1), T
	6	2780	gabbro (1)
	7	2770	gabbro (1)
741	1	3356	olivine gabbro (2)
	2	3244	gabbro (1), t; olivine gabbro (1), t
	3	3180	olivine gabbro (1), t.
	4	3074	olivine gabbro (1)
	5	2906	gabbro (1)
	6	2616	gneissic metagabbro (1)
742	1	2774	olivine gabbro (1), t
	2	2677	gabbro (1), t.
	3	2525	olivine gabbro (1), T;

DIVE #	STA #	DEPTH IN METERS	ROCK TYPES COLLECTED (# of samples)
742, cont.	3	2525	crystalline basalt (1), T; gabbro (1), T
	4	2437	gabbro (2)
	5	2300	olivine gabbro (2)