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29. INTERPRETATION OF SUBMARINE SEQUENCES OF PILLOWED AND MASSIVE BASALTIC UNITS AS EXEMPLIFIED BY RELATIONS AT SITE 758, NINETYEAST RIDGE, INDIAN OCEAN[1]

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ABSTRACT

Unpillowed sheet flows are now recognized as a significant component of submarine volcanism, but distinguishing such flows from intrusive sills is commonly difficult, especially when interbedded igneous and sedimentary units are sampled—typically incompletely—by drilling. At Site 758 drilling penetrated the top 170 m of a complex basaltic section underlying a sequence of Campanian chalks and intercalated ashes. The excellent recovery led to the recognition of 28 well-defined extrusive units varying in thickness from small cylindrical pillows to massive sheet flows more than 20 m thick, with the thicker units occurring in the upper part of the succession.

A comparison of the characteristics of the Site 758 extrusive section with basaltic sequences reported as containing intrusive basaltic sills, and sampled during drilling on four DSDP Legs, suggests that many of the "sills" can be readily interpreted as massive lava flows and that the importance of the latter was often underestimated. The distinction between flows and sills is particularly difficult if diagenetic changes to sediments adjacent to the basaltic flows mimic the effects of thermal metamorphism.

Ophiolite studies show that lavas are the major component of the upper part of the basaltic crust; sills are relatively insignificant. We therefore suggest that it is reasonable to assume that basaltic units penetrated during drilling in the present ocean basins are flows unless (1) dating shows the basaltic unit to be significantly younger than the overlying rocks, (2) the overlying rocks show the development of high-temperature contact metamorphic minerals, and (3) the basaltic unit contains undoubted inclusions of the overlying rocks which are demonstrably not vesicles in the basalt unit filled by unmetamorphosed sedimentary material from the overlying unit. Where the basaltic units are juxtaposed, multiple sequences of pillowed and unpillowed basaltic units should be assumed to be entirely extrusive unless systematic geochemical or paleomagnetic differences distinguish the two types of units.

INTRODUCTION

The improved core recovery that has come from the replacement of the Deep Sea Drilling Project (DSDP) *Glomar Challenger* with the Ocean Drilling Program (ODP) *JOIDES Resolution* has greatly facilitated ocean crustal studies. In recent years, many more of the delicate contact and structural features that are important in categorizing igneous rocks have been recovered. As a result, distinctions that were usually blurred or impossible to make during the earlier DSDP recovery are now apparent. Of these, perhaps the most critical distinction is between a massive nonpillowed basaltic lava flow and a basaltic sill. Although the physical and chemical properties of these two types of units are similar, and thus the gross properties of the crust are not affected by the distinction, the geological processes involved during emplacement of the units are very different. Contrasting geothermal regimes may be anticipated, and if the date of sill intrusion significantly postdates the formation of the host rocks, then "off-axis" igneous activity is indicated.

A second important distinction is between pillowed and nonpillowed lavas. This distinction has historically been easier to make in recovered cores from the ocean crust. However, during DSDP, recovery of the rather fragile pillowed material was at times poor, and thus it was difficult to quantify the relative importance and interrelationships of pillowed and nonpillowed flows. The two eruptive facies appear to result from different extrusive modes or environments; understanding these differences is clearly important in developing models that generate the extrusive section of the oceanic crust. Improvements in drilling technology during the latter part of DSDP, and more recently during ODP, have also resulted in deeper penetration into the oceanic basement. As a result, the interrelationship of pillowed and nonpillowed flows has become clearer.

During the Ninetyeast Ridge phase of ODP Leg 121, drilling at Site 758 penetrated the top 170 m of a complex basaltic section underlying a sequence of Campanian chalks and intercalated ashes. The section constitutes a well-recovered sample of the upper extrusive portion of the oceanic crust. In the following account we will review the significant features of this basaltic section, paying particular attention to the interrelationship of the pillowed and massive basaltic sections and to the possible occurrence of sills.

Basaltic sills were described from the Pacific, Atlantic, and Indian oceans by scientists participating in more than 10 different DSDP legs. This background information constitutes an important resource in trying to distinguish sills and lavas in the Ninetyeast Ridge section. We therefore review these earlier results in some detail and develop criteria for distinguishing flows and sills. Surprisingly, this review suggests that in many of the earlier accounts the "sills" are more likely to be massive lava flows and that the importance of the latter was commonly underestimated during the earlier phase of the Project.

OBSERVED RELATIONS AT SITE 758 AND THE SPATIAL DISTRIBUTION OF MASSIVE AND PILLOWED BASALTIC UNITS

Site 758 is on the flanks of one of the large en echelon blocks that characterize Ninetyeast Ridge in the area immediately north of the equator. The water depth is about 2922 m. Approximately 178 m of basaltic rocks was cored beneath a sedimentary section totaling 499 m in thickness. The basaltic rocks immediately underlie green and gray Campanian volcanic sediments. The average basement recovery rate was 70%, and the section includes pil-

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lowed and massive units. Some of the fragile contact relations were recovered intact, as well as several examples of delicate internal contacts.

The basaltic section was divided into 29 eruptive units on the basis of the observed contact relations and macroscopic features. Details of each of these units are presented in the *Initial Reports* (Shipboard Scientific Party, 1989, Table 5), and this information is not repeated here. Instead, we describe and discuss features of these units which are important in distinguishing pillowed flows, massive flows, and sills.

Vertical "Thickness" of Units

Even when the actual contacts of the basaltic units were not recovered, it was possible to estimate the apparent vertical thickness in the core of each of the 29 units. These data are included in Table 1 and presented as a histogram in Figure 1. The apparent vertical thickness closely approximates the true thickness where the units are tabular lava flows and coring is orthogonal to the bedding. Because pillows are commonly tubular in shape with circular or oval cross sections, there is a sampling effect that generates an apparent thickness that may be less than the true thickness. However, calculations for pillows with circular cross sections, the most extreme case, suggest that 60% of the apparent vertical thicknesses will exceed 80% of the pillow thickness, and that for more oblate pillows the proportion is even greater (Fig. 2). Thus the bias introduced by sampling with a vertical borehole is not large and the thickness histogram (Fig. 1) is a meaningful indicator of the range of true thicknesses of the units: small pillows greatly predominate.

Table 1. Thickness and inclination data for quenched contacts observed within the basaltic section at Site 758.

Flow unit	Thickness[a] (m)	Dip of contact[b] (degrees) Upper	Lower
758A-			
F1	8.29	n.r.	n.r.
F2	20.34	n.r.	60
F3	16.39	60	20
F4	1.36	15	n.r.
F5	0.76	n.r.	n.r.
F6	0.33	n.r.	n.r.
F7	12.73	n.r.	n.r.
F8	0.91	n.r.	n.r.
F9	1.34	n.r.	n.r.
F10	7.04	0–10	n.r.
F11	5.84	n.r.	45
F12	3.73	n.r.	0–10
F13	1.44	n.r.	n.r.
F14	2.36	n.r.	Irregular
F15	2.44	0–10	40–70
F16	4.26	10–20	n.r.
F17	9.62	n.r.	n.r.
F18	1.77	n.r.	n.r.
F19	1.36 (3)	80–90, 0–10, 10–20, 20–30	20–30
F20	2.22	n.r.	20–30
F21	1.21 (4)	20–30, 0–10, 0–10, 70–90, 30, 90, 45	n.r.
F22	0.85	0–10	n.r.
F23	1.46 (4)	30, 20–30, 20–30, 0–10, 0–10, 0–10	n.r.
F24	2.91	n.r.	0–10
F25	3.40 (4)	0–10, 30–40, irregular, 0–10, 0–10, 45, 0–10, irregular, 45	n.r.
F26	2.19	n.r.	n.r.
F27	2.46	n.r.	n.r.
F28	1.29	n.r.	n.r.
F29	2.00	n.r.	n.r.

[a] Number in parentheses is the minimum number of individual pillows grouped within a multiple-pillow flow unit.
[b] n.r. = not recovered during drilling.

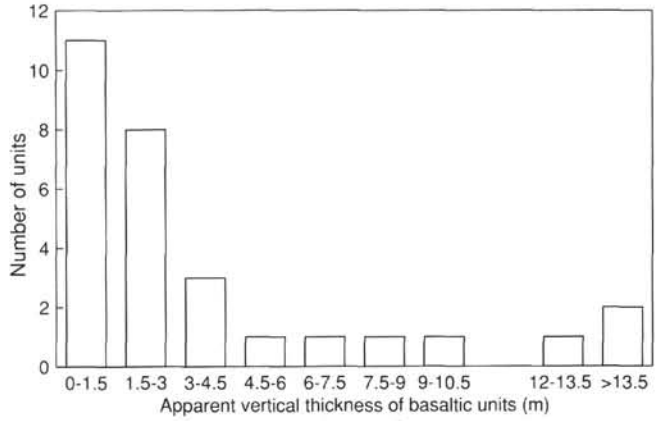

Figure 1. Histogram showing the apparent vertical thickness of the 29 basaltic units at Site 758.

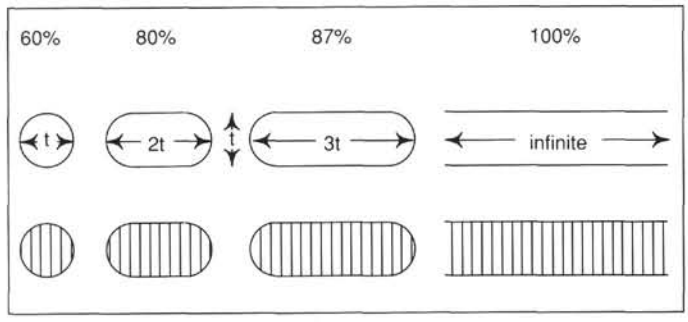

Figure 2. Sampling of cross sections through spherical and oval tubular pillows during vertical drilling compared to that of tabular lavas. The percentage for each geometry is the calculated proportion of the apparent vertical thickness obtained by random drilling that exceeds 80% of the true thickness (t).

Contact Relations of Units

The generally high recovery achieved during the drilling of the basaltic section at Site 758 led to the recovery of fragile cryptocrystalline contact rocks. Where possible, the angle of dip of these contacts was measured (Table 1). In a few cases, the angle was inferred from the attitude of pipe vesicles, which are commonly normal to the pillow margins and radial in pillows with spherical cross sections. A histogram showing these results clearly indicates that flat or very gently dipping contacts (<10°) predominate, making up about 40% of the observations (Fig. 3).

This observed distribution of dip angles can be compared with model histograms derived from the sampling of pillows of varying geometries during vertical drilling (Fig. 4). This comparison suggests that the average aspect ratio of the units drilled is about 1.5:1. A similar distribution of dip angles would be obtained from a mix of spherical pillows and very oblate pillows or sheet flows.

Furthermore, the comparison to this simple theoretical model is valid only if the volcanic succession is horizontal. However, there is no evidence that the flows are steeply inclined; layering in the overlying sediments is essentially horizontal. The presence of a vertically orientated pipe vesicle "train" within flow Unit 758A-F2 in Section 121-758A-59R-7 also suggests that this unit and probably the rest of the 178-m basaltic section are gently dipping or even horizontal. Although changes in dip with depth associated with the development of growth faults during extensional volcanism can occur, such changes are likely to be minimal

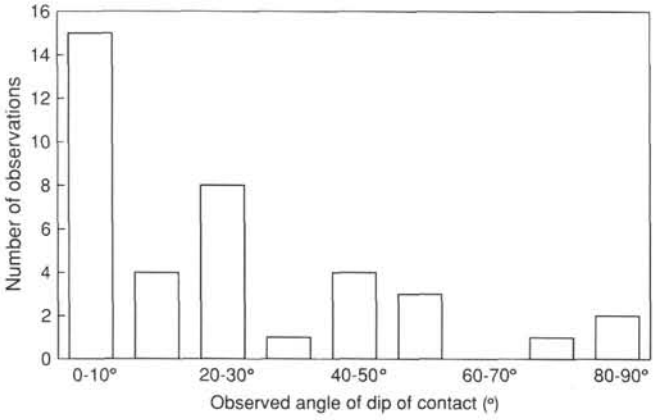

Figure 3. Histogram showing the distribution of the observed angles of dip of the unit contacts at Site 758.

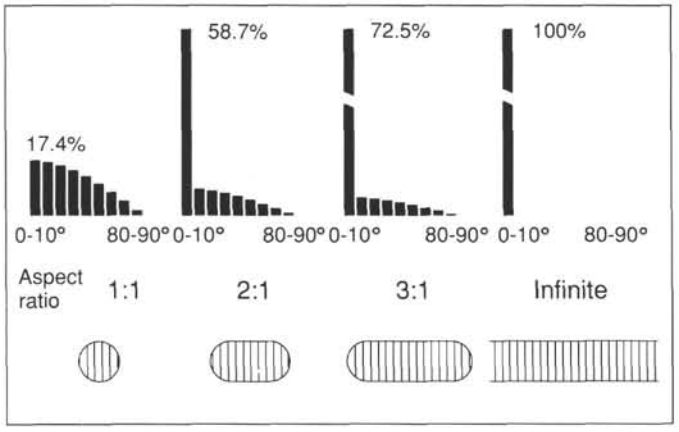

Figure 4. Histograms showing calculated angles of dip for the contacts of tubular pillows with varying cross sections intersected during vertical drilling in comparison to the results for tabular lavas. In all cases the cross sections are assumed to have flat bases and geometries not dictated by preexisting topography.

in this relatively thin section. The distribution of angles in Figure 3 also suggests that small-scale irregularities, visible in a few of the units, are not significant in determining the measured angles of dip in the core and that the latter are a function primarily of the overall pillow/flow geometries.

Development of Glass at Unit Boundaries

The margins of fresh basaltic pillows are normally glassy or microcrystalline. What is less clear from the literature is whether the presence or absence of such quenched textures at unit boundaries can be used to distinguish pillows from more massive flows. Relations observed at Site 758 provide evidence on this point.

The actual contact rocks were recovered for about one-third of the 29 units cored at Site 758. The outermost zone is normally 0.5–1 cm thick, black, glassy or microcrystalline, and altered to chlorite. Vesicles tend to be small and irregular immediately adjacent to the margin. However, inside this marginal quench zone, the grain size increases and vesicles are relatively common, locally exceeding 20% by volume. The vesicles are usually elongate and normal to the margin. In spherical pillows the vesicles commonly appear radial. Surprisingly, perhaps, this description applies equally to pillows and thicker sheet flows that are 10 m or more thick. Work by the shipboard investigators at other sites suggests that such a description might also apply widely to submarine extrusive rocks (see, for example, the later discussion of relations at Site 453). Unfortunately, Site 758 provides no evidence on the appearance of the margins of sills as no unambiguously intrusive rocks were drilled.

Variation in Grain Size within Units

Grain-size variation is marked in thicker units with diabasic textures in the internal sections of the thicker sheet flows (see, for example, the lower part of flow Unit 758A-F2 in Sections 121-758A-59R-7 and 121-758A-60R-1). Where recovery allowed, it is possible to demonstrate that changes in grain size are progressive over 3 m or more. Not surprisingly, there is a clear relationship between the grain size developed and the size of the unit, with diabasic textures restricted to thicker flows. However, work at Site 758 makes it clear that diabasic textures are not restricted in their occurrence to intrusive rocks. The recovery of such coarse-grained diabasic rocks, which may be relatively free of vesicles, is not sufficient reason by itself to designate any drilled section as "intrusive."

Alteration of Sediments Adjacent to Basaltic Units

The sediments immediately adjacent to basaltic units are commonly not recovered during drilling because of the large contrast in the hardness of the rocks and the presence of fractures along the contacts. Where recovered, the rocks close to the contact usually appear indurated and altered. The upper contact of flow Unit 758A-F10 was completely recovered with 15 cm of the overlying tuffaceous sediment (Section 121-758A-65R-1, 30–45 cm). Study of this material and other indurated sediment shows that the alteration appears not to be the result of contact metamorphism—no high-temperature minerals are developed at the contact—but of diagenetic changes to the sediment during subsequent burial. The large chemical gradient at the basalt/sediment interface will result in major diffusion-generated changes at the contact. Such changes may well mimic the effects of contact metamorphism.

Reexamination of Relations at Some DSDP Sites where Massive Basaltic Units Were Described as "Sills"

The notes given in the preceding on the basaltic section at Site 758 indicate that there are no unambiguous examples of sills in the drilled section at this site. We have, therefore, examined relations described by investigators from DSDP legs where sills were recorded. At several early sites (e.g., Sites 16, 32, 80, 105, and 150), the description of the units as "sills" is based largely on their massive nonpillowed nature; the contact rocks were not recovered with only a very small amount of basaltic material. Therefore, we have concentrated on results from four later legs for which the recovery was better and the investigation more detailed. The objective was to obtain an overview of the features of intrusive units in the oceanic section. The sites from these legs are discussed in numerical order, and particular attention is paid to three sites in the Guaymas Basin in the Gulf of California.

Leg 41 Site 368: Cape Verde Rise, Atlantic Ocean

Basaltic rocks were recovered from two sites on Leg 41 (Lancelot, Seibold, et al., 1977): lavas from the bottom of Hole 367 and two thin sills and one thicker intrusion from the lower part of Hole 368, drilled on the Cape Verde Rise, northeast of Dakar. The lower thicker unit is of particular interest as the unit and the immediately adjacent sediments were the subject of detailed shore-based work confirming its intrusive nature. The two thin units and the margins of the thicker unit are very fine-grained, aphyric nonvesicular basalts. The interior of the thicker unit, which was well recovered, is much coarser with the grain size approaching 5 mm and with subophitic textures predominating. Secondary calcite and pyrite fill 1%–2% of vesicles present in the

coarser parts of the sill. Mineralogically and geochemically the rocks are tholeiitic, showing chemical affinities with rocks from the adjacent Cape Verde Islands (Natland, 1977).

The carbonaceous shales that enclose the basaltic rocks are late Aptian–early Albian in age. Obvious contact metamorphic effects associated with the upper thinner units are minimal. The shales overlying the lower unit are bleached within 20 cm of the basalt. However, the effects on the shales beneath the thick basalt unit are much greater and a 90-cm interval shows progressive bleaching and hardening as the contact is approached (Section 368-63-3).

Perhaps the most convincing evidence of the intrusive nature of the units drilled at Site 368 is the radiometric age determined by Duncan and Jackson (1977). The extrusive basalts drilled at Site 367 give a minimum age of 105.1 ± 1.8 m.y., which agrees reasonably well with the Late Jurassic age of the overlying sediments. In contrast, samples from the basaltic unit at Site 368, determined by three methods, are in good agreement and indicate an age of about 19 m.y. Volcanic rocks of comparable age occur near Dakar and in the Cape Verde Islands.

Gas samples collected on board from sediments adjacent to the thick lower basalt unit also provide evidence for its intrusive character. In three such samples the percentage of ethane is significantly larger and the methane $\delta^{13}C$ significantly heavier than gas samples from shallower depths in the same hole that were unaffected by heat from the intrusion (Baker and Huang, 1977). The higher percentage of ethane is presumably the result of the addition of ethane (and other higher hydrocarbons) by thermal generation from the organic-rich shales. Methane produced in this way would also be isotopically heavier in comparison with bacterial methane. Doose et al. (1977) reported a parallel investigation on the same gas samples. They confirmed that the methane $\delta^{13}C$ concentration is indeed significantly heavier for gas samples taken closer to the sill than for other samples at about that depth. However, in contrast, Doose et al. (1977) stressed that the ethane concentration for a sample above the large sill but below the two thinner units is lower than for samples taken above and below this point, and they suggested that "high temperatures in between the diabase sills caused thermal cracking of higher hydrocarbons to methane." They also noted that both the proportion of higher hydrocarbons and the methane $\delta^{13}C$ concentration generally increase with depth at Site 368, complicating the interpretation.

Samples of the carbonaceous shales show considerable thermal alteration adjacent to the larger intrusion (Baker and Huang, 1977). Vitrinite reflectance is increased and textures indicative of "coking" occur. The percentage of organic carbon is also low adjacent to the sill, perhaps as result of expulsion into nearby sediments.

In conclusion, the interpretation of the thicker basaltic unit as a sill is supported by a wide variety of evidence, with the age data particularly persuasive. However, the asymmetric nature of the thermal effects is rather disturbing. The most convincing petrographic, geochemical, and metamorphic effects relate to samples taken from below the sill. Significant thermal effects on carbonaceous sediments have been described for beneath lava flows in Iceland (Walker, 1959).

Leg 58 Site 442: Shikoku Basin, Western Pacific Ocean

A series of massive basaltic cooling units were drilled at this site in Holes 442A and 442B. The units were described in the original accounts as "something of an enigma." Recovery from two adjacent holes indicated that they were laterally continuous and yet "it is evident from the lack of pillow rinds, the relatively coarse textures, and the nearly-continuous recovery of a single unit in cores 442A-7 and 442A-8 that these units are not pillow lavas . . . and . . . these units must be largely shallow intrusives, or surface flows which for some reason did not develop pillow structures" (Shipboard Scientific Party, 1980a). This succession of massive units is underlain by at least 100 m of pillowed flows. It is clear from this account that the upper massive units might indeed be lavas and that the section would then be strikingly similar to Site 758 on Ninetyeast Ridge where a series of massive flows overlies a pillowed basalt section.

Leg 58 Site 443: Shikoku Basin, Western Pacific Ocean

A continuous section of 134.5 m of basaltic rocks at the bottom of this hole was interpreted as entirely extrusive. "The upper six sub-units (29 m) consist of three pillow-basalt sub-units, each with an underlying massive basalt sub-unit of similar lithology. It is assumed that each of the massive basalts represents part of the same flow as the overlying pillow basalt, which flowed out under a carapace of rafted pillows as the flow advanced" (Shipboard Scientific Party, 1980b). This interpretation is fully supported by the paleomagnetic and geochemical data for these six subunits. Pillowed and massive flows are intimately related at Site 758.

Leg 58 Site 444: Shikoku Basin, Western Pacific Ocean

The two basaltic units penetrated at this site were interpreted as sills (Shipboard Scientific Party, 1980c). Although no contact rocks were recovered, the evidence cited in the original description in support of the designation of these units as sills includes (1) the lack of pillows or thick glassy margins, (2) anomalies in the organic carbon content of the sediment adjacent to one side of one of the units, (3) a thin layer of reddish sediment overlying one unit—a layer that was interpreted as possibly baked, (4) unusually consistent paleomagnetic inclinations in the sediments overlying the units, (5) a general coarsening of the grain size toward the center of each unit, and (6) maximum concentrations of olivine and magnetite at about two-thirds of the depth of each unit. The two units differ in both their paleomagnetic inclination and in their trace element geochemistry, but both are geochemically similar to other Shikoku Basin material.

The organic geochemical data are the most persuasive evidence, but the other data are unconvincing, and the two igneous units at this site may be unpillowed submarine sheet flows. In particular, the absence of demonstrated symmetrical contact metamorphic effects both above and below the units is critical. The units have potassium argon ages in conformity with their stratigraphic position, supporting the interpretation that they are indeed flows.

Leg 58 Site 446: Daito Basin, Western Pacific Ocean

The approximately 240-m-thick section of interbedded claystones and basaltic units penetrated at Site 466 in the Daito Basin was interpreted as a succession of at least 23 sills (1A–9A, Fig. 5) and 16 sediment interbeds on the basis of "baked contacts, rarity of chill zones, lack of glass at the chilled margins and the massive nature of the basalts" (Shipboard Scientific Party, 1980d). A paleontological age for the overlying sediments of 50–52 m.y. and an observed potassium argon age for a fine-grained basaltic sill of 48.2 ± 1.0 m.y. were used by the shipboard party to support its interpretation.

The paleomagnetic and trace element geochemical data for the basaltic rocks at this site (Shipboard Scientific Party, 1980d) further constrain models for the interpretation of these units, and we have reexamined these data. The basaltic units, viewed as a stratigraphic section, define only six polarity reversals (A–F in Fig. 5). This represents a statistically significant degree of "clumping" of the data, indicating that there is an unusually large chance that any basaltic unit in the section is immediately adjacent

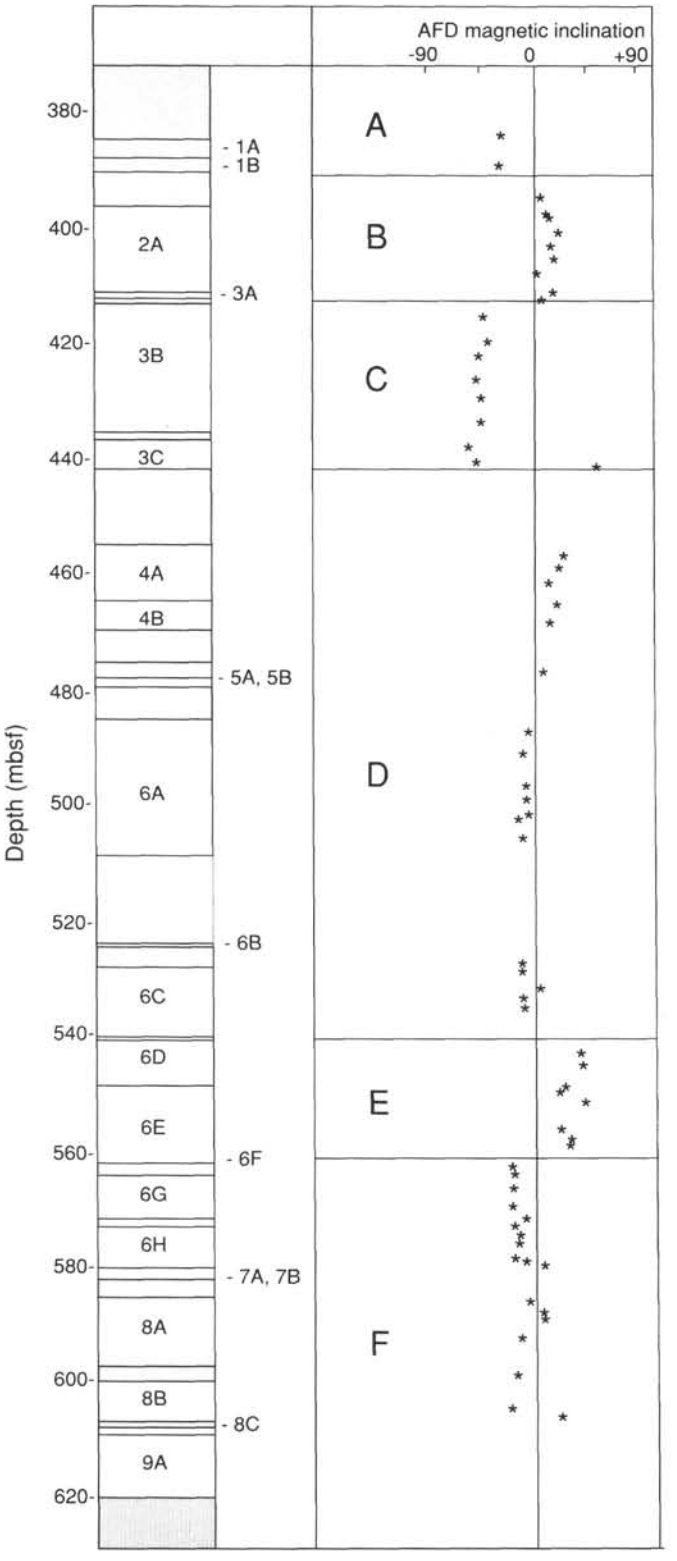

Figure 5. Stratigraphy and paleomagnetic data for the lower part of Hole 446A, Daito Basin, western Pacific. The shaded sections are intercalated sediments. The intervening basaltic units are labeled 1A through 9A.

to a unit of the same polarity. If the units are to be interpreted as sills, the data necessitate a model in which the units are either intruded in their stratigraphic order or in a spatially nonrandom manner. The probability that the observed magnetic stratigraphy was generated by chance by the injection of a series of sills in random order can be calculated from simple probability theory and is only 0.02.

The geochemical and petrographic data are similarly persuasive. For example, only five units contain from 5% to 15% primary kaersutite. These five units are spatially clumped together as groups of two and three units.

In a succession of randomly intruded sills, adjacent units would not normally be petrographically and geochemically similar. Only if the sills were always intruded at the same position in the growing crustal section would a regular intrusive stratigraphy develop. We think that this interpretation is unlikely and that the clumping of the paleomagnetic and trace element geochemical data is, in our view, more readily interpreted as the result of the extrusion of a series of lavas separated by thin claystone horizons. The paleomagnetic reversal sequence can then be interpreted in a conventional sense and might represent Chrons 24 to 26 (Berggren et al., 1985). The geochemical and petrographic clumping would result from the natural tendency of successive lavas to have similar compositions.

The induration of the sediments adjacent to the basaltic units at Site 446, interpreted as the result of baking by sills, is a feature observed at other DSDP sites and was previously briefly mentioned in relation to Site 758.

Leg 61 Site 462: Nauru Basin, Central Pacific Ocean

The two adjacent holes drilled at Site 462 in the Nauru Basin both penetrated massive basaltic units that were interpreted as sills. About 33.7 m of igneous rock was recovered from Hole 462, and logging clearly showed that this material was from five major igneous units separated by sedimentary units. These igneous units were further subdivided after examination of the recovered material into a total of 11 subunits, all of which were interpreted as sills. This interpretation was adopted because the recovered chilled margins are subhorizontal, orderly and symmetrically decreasing grain-size variations are observed approaching the margins, and characteristic features of pillow lavas are absent (Shipboard Scientific Party, 1981). However, the authors also noted that the intervening sediments are volcaniclastics and that "the sill-producing magmatic episode was associated with contemporaneous extrusive activity nearby."

The basalts from Hole 462 generally exhibit three distinct groups of stable inclinations. "These three groups of inclinations correspond to separate petrologic units and suggest that petrologic subunits 1 through 6 are contemporaneous and that units 7 through 10 are contemporaneous" (Shipboard Scientific Party, 1981). This again represents a statistically significant degree of "clumping" of the data, indicating that there is an unusually large chance that any basaltic unit in the section is immediately adjacent to a unit with a similar inclination. In our view, these paleomagnetic results are more readily interpreted as the result of the extrusion of a series of nonpillowed, massive lavas separated by thin volcaniclastic horizons.

About 450 m of basaltic rocks was recovered from Hole 462A, and these rocks were divided into about 44 units. Single sills, multiple sills, flows or groups of flows, hyaloclastite and hyaloclastite breccia, and possibly a pillow lava unit were all identified. The features used to classify a basaltic unit as a single sill were the same as those used for Hole 462. Multiple intrusions were inferred from the alternation of fine-grained and coarser grained units that lack glassy margins and where there are abrupt changes in grain size along nearly horizontal contacts. Nevertheless, it was

recognized "that such features also may be developed within single extrusive units" (Shipboard Scientific Party, 1981).

Paleomagnetic data for the long section from Hole 462A (Fig. 6) are somewhat less useful than at other sites, as the complete section displays normal natural remanent magnetization and because of instrumental problems with shipboard alternating field demagnetization. However, the geochemical and petrographic data are very informative (Shipboard Scientific Party, 1981, p. 64, fig. 21). The 450-m section can be subdivided into a number of geochemically homogeneous units, each characterized by different phenocryst assemblages. For example, the section from 780 to 950 m below seafloor (mbsf) is characterized by the phenocryst assemblage augite + olivine + plagioclase and a TiO_2 content of about 1.1%. What is surprising is that the section includes alternations of units described as sills and lavas. Units with this mineralogy and chemistry are very rare in the overlying 200-m section of basaltic units. Thus, the sills and lavas within this section from 780 to 950 mbsf are likely to have been formed during the same magmatic episode and are probably essentially contemporaneous. This in turn implies that the sills were intruded at very shallow depths below the seafloor. Although there are published mechanisms that might allow the intrusion of sills into muds on the seafloor (Einsele, 1982b), no sediments were recovered from the 780 to 950 mbsf section. We conclude that it is much more likely that this particular 170-m section is an alternating series of massive flows and thin extrusive units with internal brecciation and chilling. Although the evidence is less compelling, we think it likely that the other chemically homogeneous sections of core from Hole 462A should be interpreted similarly.

Drilling at Site 462 was continued on Leg 89 with the drilling of a further 140.5 m of basaltic rocks, which was divided into 12 lithologic units that were all interpreted as massive basaltic sheet flows. Saunders (1986), in describing these units, noted the difficulty of establishing unequivocally that some of the younger mafic units drilled at this site during the earlier Leg 61 were indeed sills.

Leg 64 Sites 477, 478, and 481: Guaymas Basin, Gulf of California

The relations described from Leg 64 are commonly quoted as providing the most convincing evidence for the injection of sills at shallow depths into the sediment pile near a spreading axis. The various lines of evidence quoted will therefore be considered in detail on a point by point basis, combining observations from the four holes at the three drill sites.

Regional Relationships

Sites 477, 478, and 481 are all located in the Guaymas Basin, close to the active spreading system in the Gulf of California, in a region characterized by rapid sedimentation and anomalously high heat flow. Massive basaltic units, penetrated in four holes at depths from 50 to 250 mbsf were interpreted as sills intruded into poorly consolidated sediments (Curray, Moore, et al., 1982).

The heat flow is high within the Guaymas Basin and varies from site to site. The regional thermal effects of this high heat flow are superimposed on local effects associated with the basaltic units, and Kastner (1982) recognized two hydrothermal systems in the Guaymas Basin. Unfortunately, the local and regional effects on the physical properties, organic geochemistry, and mineralogy of the sediments are similar.

As all the rocks drilled are very young it is impossible to demonstrate by standard geochronological techniques the age of the basalts relative to the enclosing sediments; thus, the interpretation of the units as sills relies on other lines of evidence. This evidence is reviewed here and followed by a brief discussion.

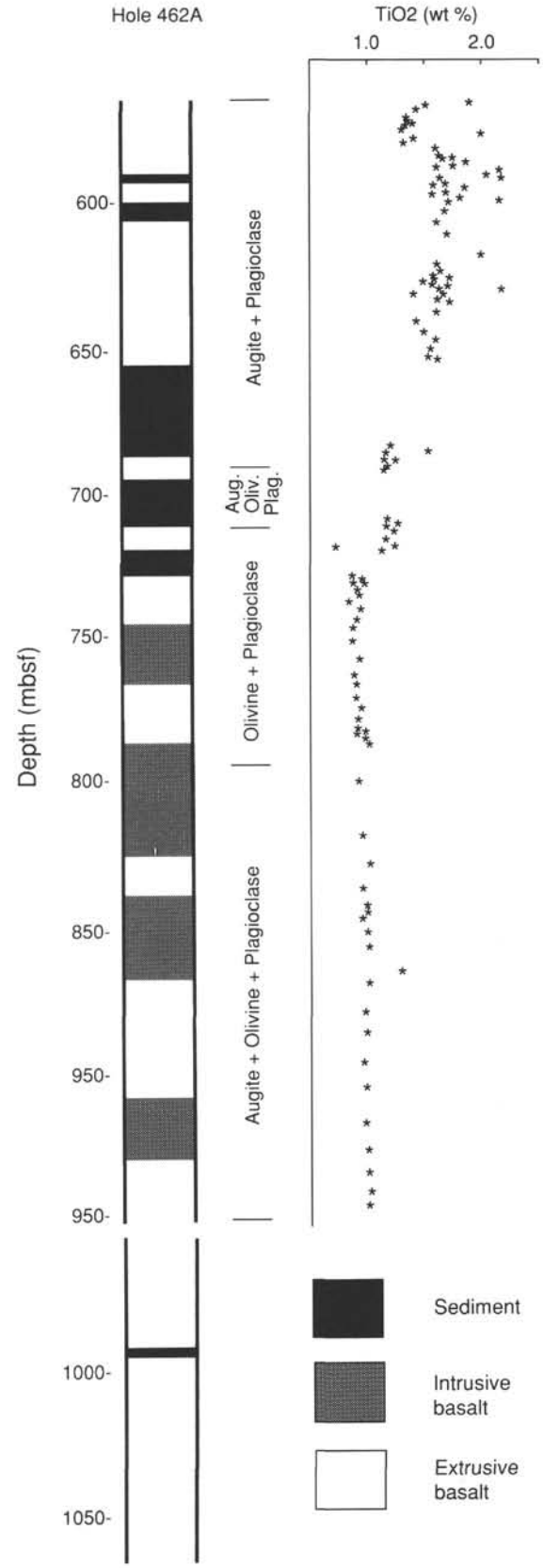

Figure 6. Vertical variation in TiO_2 and phenocryst assemblages in the basaltic section from Hole 462A, Nauru Basin, Central Pacific.

Changes in Porosity Adjacent to the Basaltic Units

It is clear from the data presented in Einsele (1982a) that there are large variations in the porosity of the sediments at the three sites.

The changes are described as almost entirely the result of the emplacement of sills, and the original interpretation of this critical data is shown in Figure 7A. In three of the four holes (477, 478, and 481A) there are clearly marked local changes in the porosity of the sediments within 50 m of the basalts. In the case of the latter two holes these changes affect sediments above the basalts. The changes are large, well documented, and associated with obvious lithologic changes.

In addition to the local changes immediately adjacent to the basalts, Einsele (1982a) inferred large decreases in the porosity in the lower parts of Holes 477, 477A, and 481A by comparing the observed porosities at these three sites with the much higher values seen at Site 479, a "reference site" devoid of igneous rocks. This comparison led Einsele (1982a) to suggest that the porosity reductions were the result of metamorphism by "unseen deeper intrusions." This explanation is unsatisfactory. It seems much more likely that the vertical variation in porosity with depth in the sediment pile is a function of the diagenetic changes in the sediments which are in turn controlled by the local heat flow. The heat flow is highest at Site 477, where the vertical changes in porosity are most abrupt. The heat flow is lowest at Site 478, where the vertical changes in porosity are less, and are marked only immediately adjacent to the basaltic units.

At all four holes it is possible to draw smooth curves for the variation in porosity with depth (Fig. 7B). If, as we suggest, these curves represent the regional variation, the effects of the basalt are obvious, but only local and restricted to the immediate vicinity of the mafic unit. There is no evidence for the large "sill-induced" reductions in porosity and water loss of Einsele (1982b, table 1).

Lithologic and Mineralogical Changes

In a very careful collation of the mineralogical data, based largely on X-ray-diffraction studies, Kastner (1982) summarized the regional changes that she assumed were associated with shallow magma chambers and contrasted these with the effects of local hydrothermal systems associated with the basaltic units.

From extracts of this summary presented in Table 2, it is clear that the temperatures of formation for the regional mineral assemblage are those of the greenschist facies (i.e., 250°–300°C), whereas the alteration associated with the basaltic units is lower temperature—the minerals formed at about 200°C. Kastner also

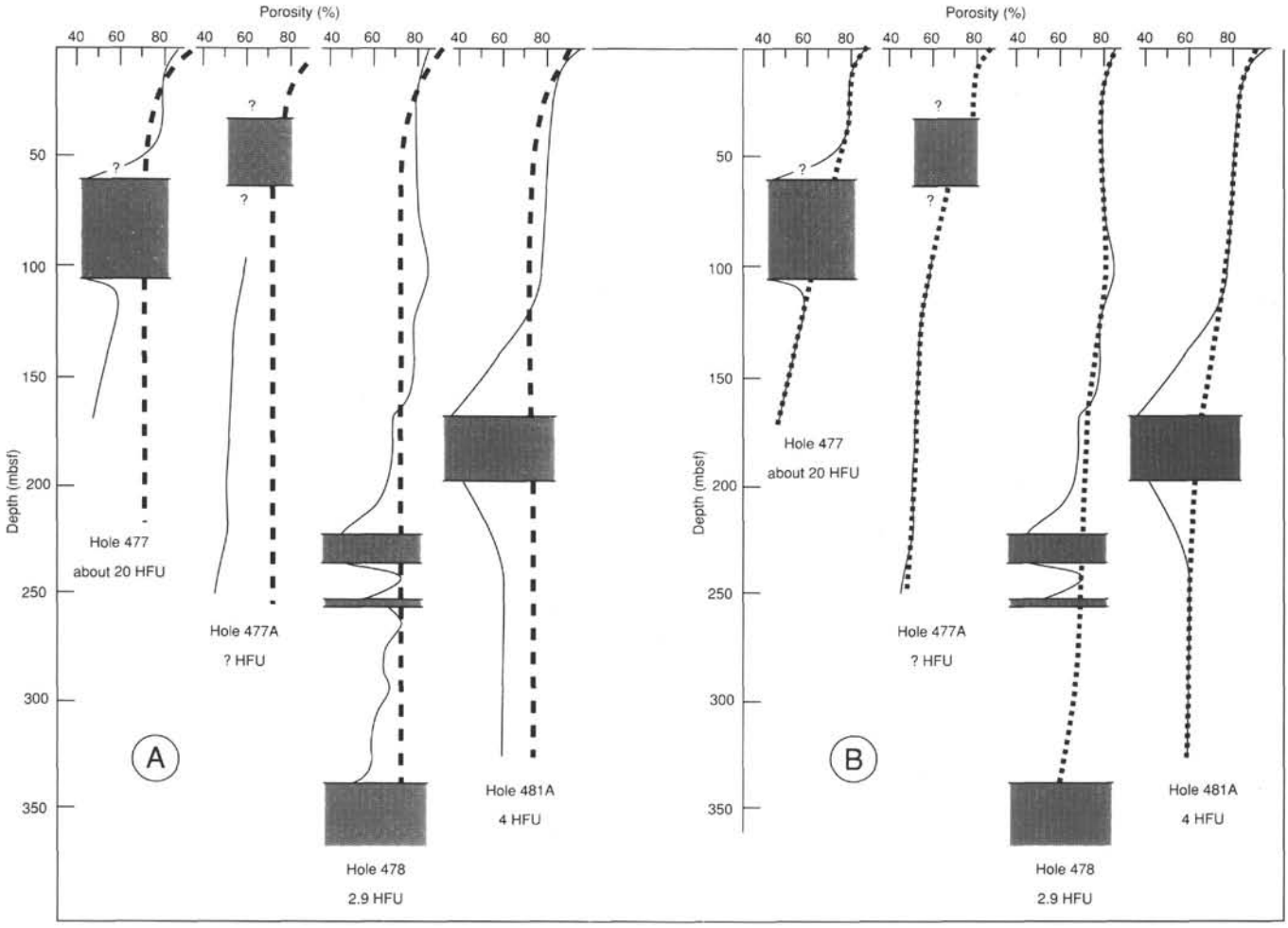

Figure 7. Vertical variations in sediment porosity at the Guaymas Basin sites. Data from shipboard measurements except for Hole 477A which were deduced from the density log. **A.** The interpretation of Einsele (1982a), with a reference porosity line (dashed) from Site 479. Also shown are large areas of "sill-induced" reduced porosity (light shading) below the basalts at Holes 477, 477A, and 481. **B.** An alternative interpretation in which there are assumed to be significant regional variations in porosity, and vertical variation with depth (dotted line) is a function of the local heat flow.

Table 2. Mineralogical changes associated with local and regional hydrothermal systems in the Guaymas Basin, Gulf of California (data from Kastner, 1982).

Local effects associated with basaltic units	Regional effects associated with possible high-level magma chambers and high heat flow
Thickness of altered zone extends from 3 to 50 m outward from the basalt contact and averages 20–30 m	Thickness of altered rocks exceeds 140 m
Smectite is the most important and generally the only sheet silicate, illite is uncommon, and chlorite is rare and coexists with illite only in the upper part of Hole 481	Chlorite dominates as the only hydrothermal sheet silicate
Analcime is the main Na-silicate, clinoptilolite is rare, and detrital plagioclase is not albitized	Albite is abundant and the dominant Na-silicate, analcime and clinoptilolite are absent, and detrital plagioclase is albitized
Epidote, sphene, and pyrrhotite are absent	Epidote, sphene, and pyrrhotite are present
Calcite and sporadic dolomite are present except immediately adjacent to the basalt	Calcite and dolomite are absent
Pyrite is present	Pyrite may be abundant

noted that the alteration effects associated with the basalts are markedly asymmetric, much thicker above the mafic units than below. This suggests in turn that the alteration is not a result of conductive thermal heating but the upward movement of hydrothermal solutions. In fact, the absence of high-temperature minerals in the sediments adjacent to the basalts is a striking feature of the local alteration zones.

Organic Geochemistry

The organic geochemistry of sediments recovered from the Guaymas Basin is controlled by two major factors: the sources of the organic matter and the subsequent thermal stress. Unfortunately, the importance of the different sources can vary significantly from hole to hole and vertically in the section, whereas the thermal stress generally increases with depth of burial. Possible changes resulting from the emplacement of the basaltic units are superimposed on these complex lateral and vertical changes. It is perhaps not surprising that the metamorphic effects of the "sills" are difficult to interpret and vary widely from site to site.

Simoneit and Philp (1982), in a careful study of the lipids and kerogen, noted that "the lipids from Hole 481A, occurring in depth across two basalt layers, are essentially unaltered and reflect primarily their biogenic origin." These authors were so puzzled by this apparent lack of contact metamorphic effects that they suggested that "the section above the sill (a megaturbidite) . . . may have been emplaced on a flow of basalt after cooling." Most of the samples from Site 478 were also described as "immature and unaltered, reflecting the primary biogenic residues." Only at Site 477 was a significant thermogenic component identified, ranging from C_{20} to C_{33} with a maximum at C_{25} and with no even-to-odd carbon number predominance. However, these effects are not restricted to samples adjacent to the basaltic unit drilled at this site, but are typical of all samples with a sub-bottom depth of more than 50 m and thus can be interpreted as resulting from the high heat flow encountered at this site. Simoneit and Philp (1979) reached highly similar conclusions from their study of the kerogens: thermal effects at Sites 478 and 481 are minimal, but marked in the lower part of Site 477 where they are not restricted to units immediately adjacent to the basalt.

Whelan and Hunt (1982) analyzed the C_1–C_8 hydrocarbon distribution in sediment samples from Sites 477, 478, and 479. At Site 477 they showed an "exponential increase in total C_2–C_8 hydrocarbons with depth . . . typical of an increase in thermally generated hydrocarbons." These authors also noted that "sediments above the sill show approximately the same hydrocarbon levels and distributions as detected for the Site 474 and 476 sediments, with a modest increase in several compounds just above the sill. The results suggest that the sediments above the sill have not been heated to temperatures above 50°C and that the sediments were deposited after the sill had been formed." Whelan and Hunt (1982), in their discussion of the results for samples from Site 478, noted that "the sills appear to have had minimal influence on production of C_2–C_8 hydrocarbons." However, at Site 481 these authors noted that C_2–C_8 hydrocarbon levels "increased significantly in samples taken closest to sills," and they interpreted this increase as resulting from localized heating.

We conclude from this brief reevaluation of some of the organic geochemistry conducted during and after Leg 64 that the results provide unequivocal evidence only of the high regional thermal anomaly, as evidenced by the high heat flow, but do not provide convincing evidence of thermal metamorphism associated with the basaltic units.

Interstitial-Water Chemistry

Work on the hydrothermal alteration occurring during high-temperature interaction between basalts and seawater (Bischoff and Dickson, 1975; Bischoff and Seyfried, 1978; Seyfried and Bischoff, 1979) showed that elements such as Li^+ and K^+ are released from the basalt and precipitated in hydrothermal phases in the surrounding areas. At lower temperatures these trends reverse with the uptake of Li^+ by the basalt.

The interstitial-water data for Li^+ at Site 481 show clearly the effects of this low-temperature uptake of Li^+ by the basalts; the results at Site 478 are more equivocal. Gieskes et al. (1982), in discussing these results for Site 477, noted that "the sill intrusions . . . would have caused increases in Li^+, Rb^+, and K^+ in the interstitial waters surrounding the sills. After the sills cooled, however, reversals in these concentrations would occur as a result of 'retrograde' reactions. Thus the anomalies caused by the high-temperature interactions between basalts-sediment-pore water are in a state of decay at this site." A simpler explanation is that the basalts are lavas, and thus only low-temperature diagenetic effects are to be expected at the contact between the basalts and the enclosing sediments. These interactions are marked at Site 481 but are minimal at Site 477, where the basalt is much younger (Fig. 8).

Oxygen Isotopic Composition of the Sediments

Kastner (1982) provided a detailed study of the oxygen isotopes of the sediments and pore fluids from Sites 477 and 491. The results for the sediments are shown in Figure 9. The isotopic data provide unequivocal evidence of the effect of the basalts on the surrounding sediments, and these effects are particularly marked at Site 481 and extensive *above* the basalt layer. In contrast, the isotopic changes at Site 477 are restricted to the rocks immediately adjacent to the basalt and perhaps are barely perceptible below the basalt. If the basalts are indeed sills, these relationships are surprising; the "sill" at Site 481 is about 60% of the thickness of the comparable unit at Site 477, and yet the "metamorphic effects" are greater at Site 481.

An alternative explanation is that there has been isotopic exchange between ^{18}O from the sill (about 5.5–6.0 $\delta^{18}O$) and the surrounding sediments during diagenesis, with pore fluids acting as the facilitating medium over time. This would explain why the isotopic changes in the sediments are much more extensive in the older, deeper intrusion at Site 481. At Site 477, there has not been sufficient time for the development of extensive diagenetic changes. The upward flow of fluids at these sites would also

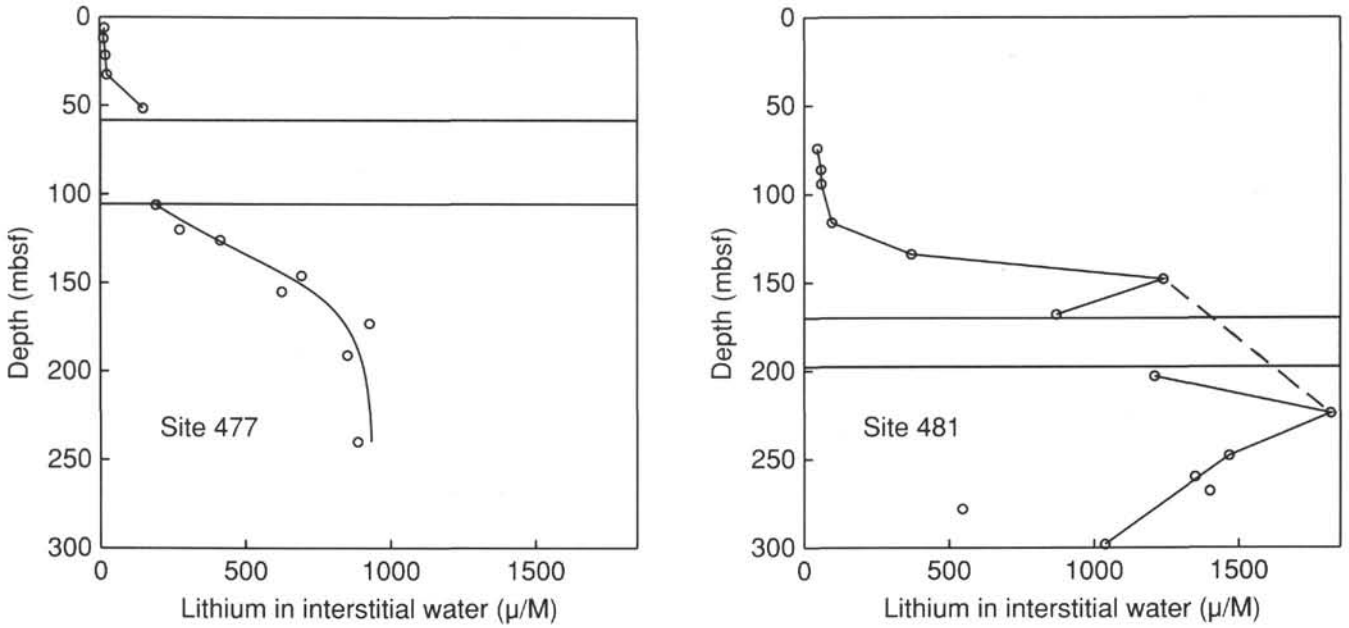

Figure 8. Lithium concentration of interstitial-water samples taken from sediments at Sites 477 and 481, Guaymas Basin, Gulf of California. Data from Gieskes et al. (1982).

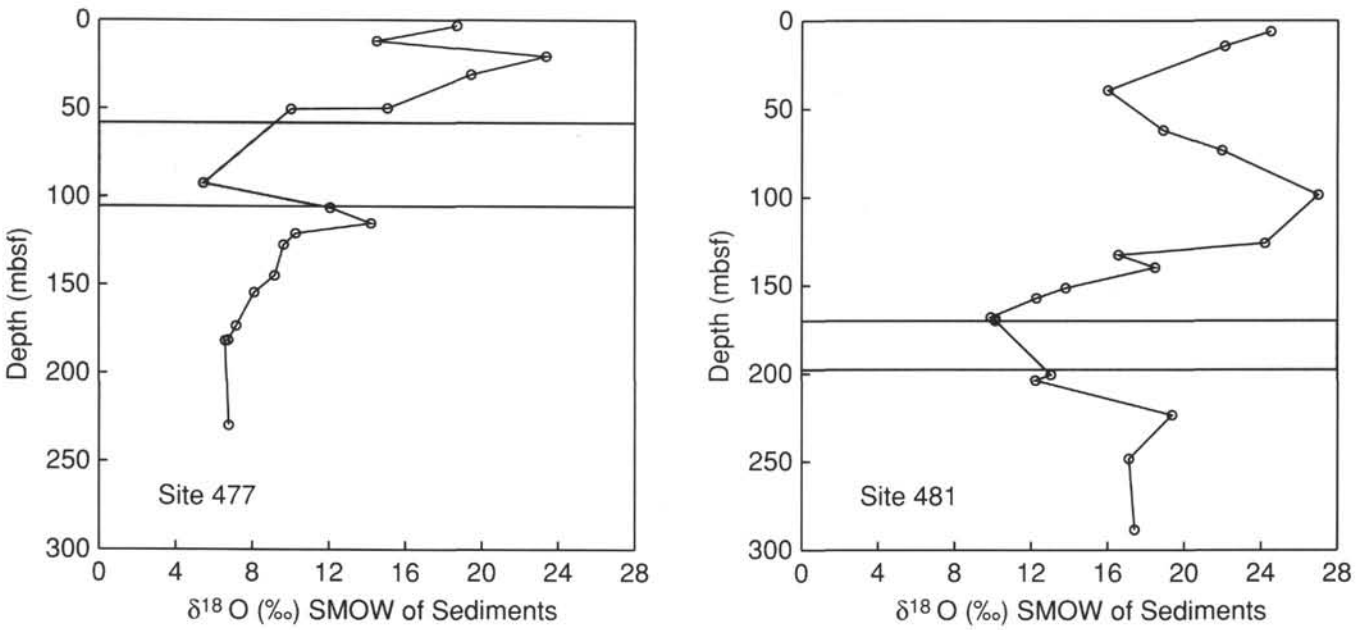

Figure 9. Oxygen isotope composition of whole-rock silicate samples taken from sediments at Sites 477 and 481, Guaymas Basin, Gulf of California. Data from Gieskes et al. (1986).

explain why the alteration effects are so much more pronounced above the basalts.

Summary of Results from Leg 64

We conclude from this reexamination of the results obtained on Leg 64 that although the massive units in the Guaymas Basin may indeed be sills, as originally suggested, the evidence to support this contention is weak. The lack of high-temperature thermal effects in the overlying sediments is very noticeable and was the subject of comment by several of the original shipboard scientists. Unfortunately, an analytical approach to the problem of thermal metamorphism at sill contacts is unlikely to be useful. Although one can readily model the contact metamorphic effects at the margins of sills and dikes intruded into lithified sediments and calculate the likely temperatures that will be reached in the adjacent rocks, such calculations are difficult for water-saturated sediments. In the latter environment convective cooling may transfer heat very effectively from the sill contact and thus generate minimal metamorphic effects.

In the absence of any positive indication that the massive basaltic units in the Guaymas Basin are indeed intrusive, we prefer to accept the interpretation that the units are massive lavas produced by periodic volcanism in an area of rapid sedimentation. Unfortunately, the matter remains one of interpretation; there is no positive evidence of extrusive activity in the Guaymas Basin.

DISCUSSION

There are two general lines of evidence that we consider to be significant in the interpretation of basaltic massive units drilled on the seafloor. First, ophiolite studies (see, for example, Moores and Vine, 1971; Hopson et al., 1981; Harper, 1984;) show that lavas are the major component of the upper part of the ophiolitic basaltic crust and that sills are relatively insignificant. Second, sheet flows dominate in the some areas of active submarine volcanism. For example, sheet flows are the dominant extrusive type at the Galapagos Rift at 86°W (Lonsdale, 1977a; Ballard et al., 1979; van Andel and Ballard, 1979), and were first described from the East Pacific Rise at 21°N by Normark (1976) and later at 3°25′S by Lonsdale (1977b).

These two lines of evidence and our review of some earlier DSDP sites suggest to us that it is only reasonable to assume that the majority of basaltic units penetrated during drilling in the present ocean basins are flows unless (1) dating shows the basaltic unit to be significantly younger than the overlying rocks, (2) the overlying rocks show the development of high-temperature contact metamorphic minerals, and (3) the basaltic unit contains undoubted inclusions of the overlying rocks which are demonstrably not vesicles in the basalt unit filled by unmetamorphosed sedimentary material from the overlying unit.

Unfortunately, although sills may be an important element in the oceanic crust, definitive criteria of the type noted here that distinguish flows and sills in submarine sequences may be absent in many cases. Lewis, Robinson, et al. (1983) noted this problem in the interpretation of massive basaltic units recovered during Leg 65 and the investigation of sections at the mouth of the Gulf of California. They also noted that units may have started as surface flows that then burrowed into soft sediments. Such cases may be particularly difficult to interpret, but where the basaltic units are juxtaposed, multiple sequences of pillowed and unpillowed basaltic units should be assumed to be entirely extrusive unless systematic geochemical or paleomagnetic differences distinguish the two types of units.

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