27. PETROGRAPHY OF BASALTS FROM DEEP SEA DRILLING PROJECT LEG 92[1]

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ABSTRACT

Studies of thin sections of basalts from Sites 597, 599, 601, and 602 of Leg 92 reveal textural and mineralogical variations both within and between holes. Hole 597C, the most successful hole drilled to date in crust from a fast-spreading ridge, contains plagioclase-clinopyroxene basalts with abundant titanomagnetite. Minor olivine is present in the upper and lower basalts but is lacking in the interval between. The mineralogical variations cannot be correlated with any specific igneous contacts within the basalt section. A series of fine-grained chill zones occurs in the cores, but no clear-cut igneous contacts are present. A continuum of textures, from fine-grained spherulitic through ophitic, is observed, with both chilled zones and normal basalts coarsening downward in the hole. Rocks from Sites 599 and 601 closely resemble those from Site 597; Site 602 yielded fragments of fine-grained basalts characterized by embayed olivine phenocrysts. Textural relationships and crystal morphologies in Site 597 basalts suggest that two or three massive flows were created by multiple injections of lava into a cooling section. The upper lavas were carrying crystals formed before eruption; the lower flows may have crystallized from partially or completely molten magma. The chilled zones, which lack true quenched margins, appear to have been formed by multiple intrusions during the creation of the major basalt units. The basalts from all the sites are similar to previously drilled rocks from the East Pacific Rise and Mendoza Rise but include coarser sections formed at slower cooling rates or higher temperatures.

INTRODUCTION

Basalts recovered from Sites 597, 599, 601, and 602 on DSDP Leg 92 represent the most successful drilling to date of oceanic basalts formed at a fast-spreading ridge. The four sites were drilled in successively younger crust during a transect of the East Pacific Rise at 19°S (Fig. 1). Hole 597C penetrated 92 m into crust formed at the Mendoza Rise. Holes 599, 601, and 602 were drilled in crust formed at the East Pacific Rise, with recovery of up to 3 m of basalt fragments. The basalts sampled range from olivine-poor tholeiites to ferrobasalts. In order to compare their mineralogical and textural characteristics, polished thin sections of basalts from all four sites were examined in transmitted and reflected light. Figure 2 shows the positions from which closely studied thin sections were taken from Holes 597B and 597C. Careful examination of these sections, which were all relatively fresh basalt, was supplemented by quick checks of additional sections, most of which were cut from more-altered basalt around veins, and by visual inspection of the cores.

SITE 597

Site 597 clearly presents the best opportunity to date to examine a section of crust formed at a rapidly spreading ridge crest. Of the 92 m of basement penetrated, 45 m of basalt were recovered. The samples appear to represent a massive flow or flows rather than pillow lavas, which may account for the unusually successful drilling results. The only evidence for pillows in the basalts from Site 597 is the appearance of the uppermost piece in the first basalt core from Hole 597C, which has the glassy rind and radial fractures characteristic of pillow basalts.

Igneous Units

In hand sample the sections from Site 597 consist of massive gray basalt. Grain size increases from aphanitic in the upper sections to coarse in the lower sections; phenocrysts of plagioclase and clinopyroxene up to 1 cm in length are visible in the latter. The cores contain no unequivocal igneous contacts. However, dark-colored, reflective, fine-grained zones do occur at irregular intervals down the cores. These basalts appear to represent chilled zones, because of the textural contrast with the adjacent coarser basalts, but both the upper and lower margins of the fine-grained zones interfinger with the coarser-grained basalt, and tongues or islands of the coarser-grained basalt are present within the fine-grained zones (Fig. 3). Neither chemical variations nor mineralogical changes occur across these zones (Pearce et al., this volume; Erzinger, this volume; and this study); the distinction between the chilled zones and the surrounding basalts is purely textural.

The mineralogy of the basalts from Hole 597C does suggest the presence of at least two different igneous units, either as one massive unit cut by a sill of a different composition, or as three independent units. Cores 3 through 7, 55.5 to 100.5 m below seafloor, are composed predominantly of plagioclase and clinopyroxene, both as microphenocrysts and groundmass, and titanomagnetite, with minor amounts of altered olivine microphenocrysts. Beginning in Core 8, olivine disappears, and ilmenite exsolution lamellae appear in grains of primary magnetite. In Section 597C-10-2, olivine reappears, and most of the primary magnetite again occurs as a single phase of titanomagnetite, although occasional grains with il-

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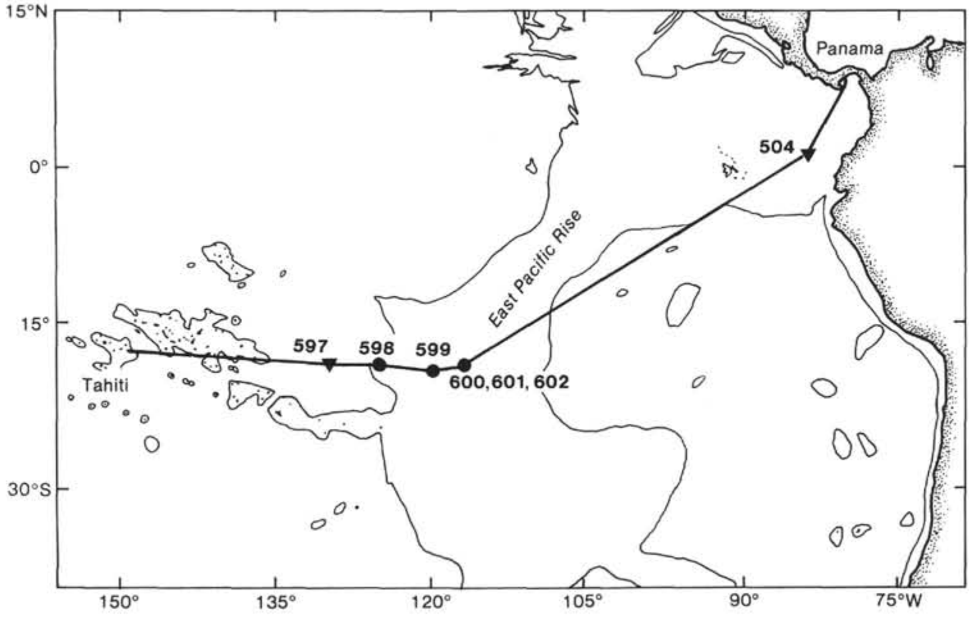

Figure 1. Location of Sites 597 to 602, DSDP Leg 92. Inverted triangle denotes re-entry.

menite lamellae persist through the top of Core 11. As Pearce et al. (this volume) and Erzinger (this volume) indicate, the upper mineralogical boundary coincides with a change in chemical composition at the base of Core 7. The lowermost compositional and mineralogical boundaries do not coincide, but both appear to be transitional over at least a portion of Core 10. Neither of these boundaries can be assigned to any contact visible in the basalts. Core 7 contains an unusually high concentration of fine-grained chilled zones, suggesting the possibility of a complex history of intrusion, but no specific chilled zone can be associated with the change in composition of the basalt. Core 10, in contrast, appears in hand sample to be homogeneous, suggesting that the lower change in basalt type is indeed a gradual transition and not an abrupt contact.

Textures

Despite the mineralogical differences between the units, the textures throughout the entire length of cores from Site 597 are similar and consistent. Variations in grain size are superimposed on a general downward coarsening of the basalt fabric. As one moves deeper into the basalt section and away from the fine-grained chilled zones, an entire spectrum of textures can be observed: from microphenocrysts of plagioclase and olivine in a groundmass of coalesced spherulites of plagioclase and clinopyroxene, through sheaf and fan spherulites of radial plagioclase and granular clinopyroxene, to ophitic clinopyroxene hosting tabular laths of plagioclase. Accompanying the changes in grain size are variations in the crystal morphology of the major minerals. Plagioclase evolves from long, acicular crystals (Fig. 4) to tabular laths, and clinopyroxene develops from sheaflike forms to equidimensional grains and poikilitic plates.

The most fine-grained material occurs at the top of Hole 597B (Core 2, Section 1). The groundmass of this basalt consists of coalesced spherulites of plagioclase and clinopyroxene, altered yellow glass, and ubiquitous interstitial magnetite. The spherulites surround microphenocrysts of skeletal olivine and skeletal to acicular plagioclase, and glomerocrysts composed of accumulations of larger, well-developed plagioclase or plagioclase and olivine crystals (Fig. 5). The spherulites that compose the groundmass of the basalt have two distinct morphologies: radial aggregates of plagioclase microlites interspersed with magnetite and red brown altered glass, and feathery dark gray brown microlites of clinopyroxene (Fig. 5). Magnetite also occurs between the fibers of the clinopyroxene spherulites, but the red brown alteration of the groundmass appears to be limited to the vicinity of the plagioclase spherulites.

Although textures as fine grained as this one are unusual in the basalts at Site 597, spherulitic patches do appear rarely in the chilled zones. In addition, material similar to the acicular portions of the spherulitic basalt does occur as groundmass in some of the more coarsely crystalline basalts.

The spherulites forming the groundmass of the most fine-grained samples grade into larger, coarser sheaf and fan spherulites of clinopyroxene and plagioclase (Fig. 6). Plagioclase in these basalts appears as acicular to lathlike crystals usually in a radial arrangement from the center of the spherulite. Clinopyroxene occurs as sheaflike aggregates of grains or as small equidimensional grains that surround plagioclase laths to form a spherulite. Abundant interstitial magnetite is still present, but it too occurs in larger, less skeletal grains. Glomerocrysts of a sort persist in these basalts, in the form of clusters of plagioclase laths which are larger and more tabular in morphology than those forming the spherulitic "groundmass" of the rocks. In olivine-bearing basalts, highly altered and pseudomorphed olivine phenocrysts may accompany the plagioclase (Fig. 7). The actual grain size of the basalts showing this coarser spherulitic texture varies, from sheaves with a maximum length of 0.5 mm

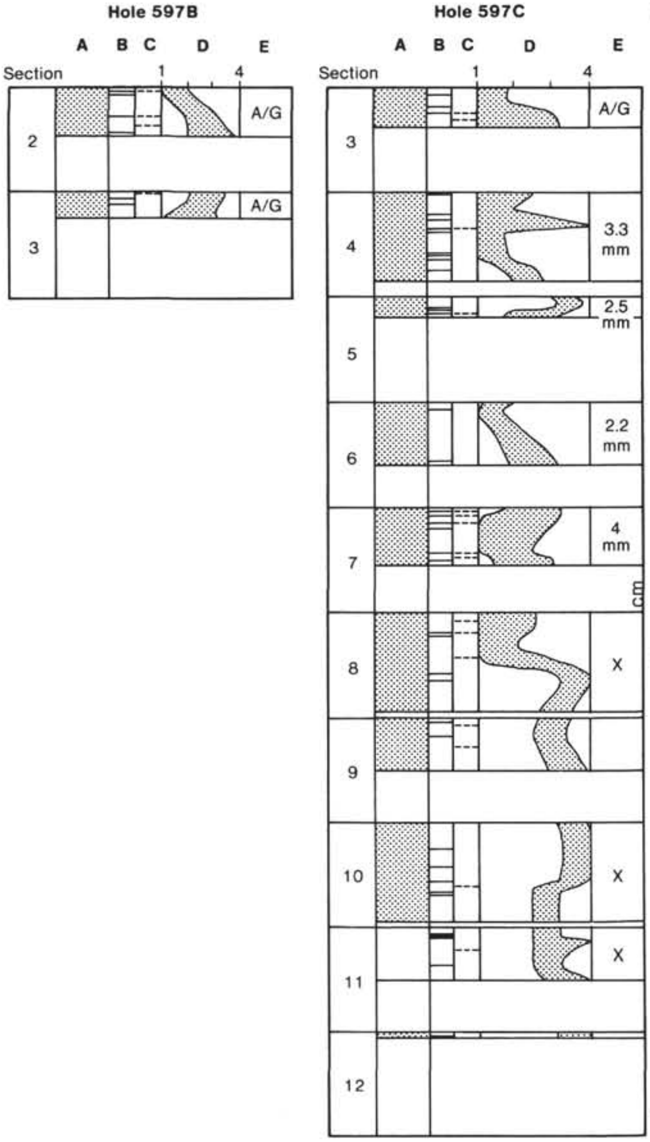

Figure 2. Summary of Holes 597B and 597C. A. Recovery. B. Locations of closely studied thin sections. C. Locations of fine-grained chilled zones. D. Dominant textures determined in thin sections, over a range from (1) spherulitic to (4) ophitic. E. Maximum dimension of largest crystals in thin sections; A/G indicates aphyric basalts carrying glomerocrysts and X indicates that size of individual crystals exceeded the microscopic field of view. In the latter sections, crystals visible in the cores reached 1 cm in length.

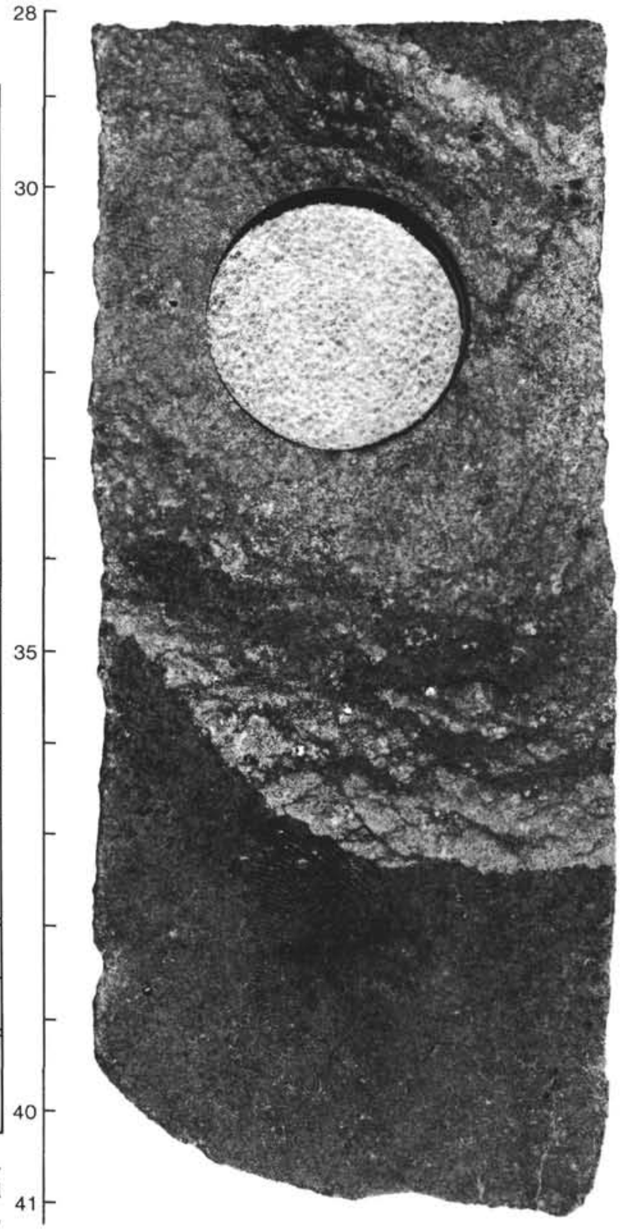

Figure 3. Interfingering of fine-grained (dark) basalt and coarse-grained (light) basalt. Sample 597C-3-3, 28–41 cm.

to those with a maximum length of 3.0 mm, and from acicular plagioclase crystals with a maximum length of 1.1 mm to those with a maximum length of 2.1 mm.

As an intermediate step between these coarsely crystalline clinopyroxene plus plagioclase sheaves and subophitic textures, a curious clinopyroxene–plagioclase intergrowth develops. Best described as a mesh texture or a graphic type of intergrowth, it is characterized by embayed plagioclase laths interwoven with granular clinopyroxene in a squared or rectangular pattern (Fig. 8). The almost acicular or skeletal morphology of the plagioclase contrasts with the more lathlike or tabular plagioclase found elsewhere in the more crystalline basalts. Plagioclase twinning, which occurs almost ubiquitously throughout the entire range of crystallization, is also comparatively rare in these intergrowths.

The least fine-grained basalts from Site 597 are characterized by the presence of subophitic to ophitic textures (Fig. 9). In the coarsest sections, plates of clinopyroxene up to 8 mm across completely enclose plagioclase laths up to 4 mm long. Magnetite grains and clusters of plagioclase laths, not unlike the glomerocrysts found in finer-grained rocks but no longer larger in size than the surrounding matrix, occur with smaller clinopyroxene and with olivine pseudomorphs between the large poikilitic plates (Figs. 10 and 11). The absence of opaque minerals within the ophitic clinopyroxenes results in the visual impression of a texture in which blebs of a light-colored material stand out against a dark background.

Figure 4. Acicular plagioclase with plagioclase-clinopyroxene sheaf spherulites and magnetite. Sample 597B-2-1, 104–105 cm; field of view, 3.6 × 2.4 mm.

The subophitic sections also contain plagioclase laths enclosed in clinopyroxene, but the plagioclase crystals extend over the edges of the clinopyroxene grains, and although masses of clinopyroxene may reach the size of ophitic plates, the grains are not optically continuous. Magnetite and clusters of plagioclase commonly occur between masses of clinopyroxene grains in the subophitic as well as in the ophitic rocks. The plagioclase laths enclosed in both subophitic and ophitic clinopyroxene tend to be more acicular and less well developed than those in the clusters between clinopyroxenes, resulting in a morphological similarity between these minerals and those formed in the graphic intergrowths.

The coarse-grained basalts from Site 597 also appear to have had a more complex crystallization history than the fine-grained basalts. Twinning is nearly universal in plagioclase laths in all textures, but complex twinning and apparent exsolution lamellae are widespread in the plagioclase from the coarsest rocks, and zoning occurs in some plagioclase and clinopyroxene (Fig. 12). The incidence and concentration of inclusions in plagioclase and clinopyroxene, both oriented along twin lines and unoriented, also increase in these sections (Fig. 13).

The transition from spherulitic to ophitic basalts is not simply a reflection of the depth of recovery of the cores, although in a general sense the textures of the rocks do coarsen with depth. The most striking textural changes are those that occur between the chilled zones and the adjacent, more crystalline basalts. Chilled zones occur at irregular intervals throughout the length of basalt drilled at Holes 597B and 597C. Although the upper and lower limits are difficult to define because of the interfingering of fine- and coarse-grained basalts, the chilled zones can extend over intervals greater than 10 cm in length, as does the one in Section 597C-11-1 between 92 and 107 cm. In hand sample, the contact between the finer- and coarser-grained basalts is sharply visible even when both are aphanitic, because the finer-grained material is more reflective and appears to be darker in color. The contact is also sharp in thin section, where it is visible as an abrupt change in grain size, crystal morphology, and (usually) overall texture of plagioclase and clinopyroxene.

In general, both the chilled zones and the massive basalts become less fine grained deeper in the hole, but the change in crystal sizes and morphologies between finer- and coarser-grained basalts remains similar: plagioclase crystals change from long and acicular to more tabular and lathlike; plagioclase increases slightly in size; and clinopyroxene increases noticeably in size. The texture of the chilled zones increases from spherulitic to subophitic down the hole, whereas the more typical basalts increase from sheaf or fan spherulites to ophitic textures. Figure 2 shows the downhole change in the dominant textures in Holes 597B and 597C and the locations of the fine-grained chilled zones.

SITES 599 AND 601

Although all of the massive basalts obtained on Leg 92 were from Site 597, fragments of basalt were recovered from Sites 599, 601, and 602. The basalts at these sites formed at the East Pacific Rise, unlike those at Site 597, which formed while the Mendoza Rise was still active. Approximately 1.5 m of basalt fragments were re-

A

B

Figure 5. A. Glomerocryst of aggregated plagioclase and olivine grains in a groundmass of spherulites and skeletal plagioclase. Sample 597B-2-1, 43–45 cm. Field of view, 3.6 × 2.4 mm. Crossed nicols. B. Groundmass consisting of acicular plagioclase spherulites, dark feathery clinopyroxene spherulites (lower right corner), and acicular and skeletal plagioclase. Bright area at center of left side is yellow glass. Sample 597B-2-1, 43–45 cm; field of view, 3.6 × 2.4 mm.

A

B

C

Figure 6. Fan and sheaf spherulites of clinopyroxene and plagioclase, with microphenocrysts of acicular plagioclase and granular clinopyroxene. A. Sample 597C-3-2, 108–110 cm; field of view, 3.6 × 2.4 mm. B. Sample 597C-4-5, 81–83 cm; field of view, 2.9 × 1.9 mm. C. Coarse sheaves: Sample 597C-7-1, 57–61 cm; field of view, 3.6 × 2.4 mm.

covered from 9 m of drilling at Hole 599B, about 1 m from 3 m of drilling at Hole 601B, and a few chips within a sediment core at Hole 602B.

The rocks sampled at Sites 599 and 601 consisted of extremely fine-grained aphyric gray basalt, similar to the most fine-grained basalts from Site 597. These fragments, like the section at Site 597, also coarsen with depth. The groundmass of the finest basalt is made up of coalesced

Figure 7. Olivine pseudomorph with plagioclase phenocrysts and plagioclase–clinopyroxene sheaf spherulites. Sample 597C-4-2, 65–67 cm; field of view, 2.3 × 1.5 mm.

feathery sheaf spherulites which take on a very dark color due to the presence of abundant interstitial magnetite (Fig. 14). In reflected light the spherulites can be seen to consist of two minerals, presumably plagioclase and clinopyroxene as observed by Bryan (1972) in other basalts. Interstitial glass is also present; it alters to yellow palagonite and hence is more visible in altered sections. Abundant microphenocrysts of twinned acicular, often skeletal laths of plagioclase reach 0.4 mm in length. Microglomerocrysts of plagioclase and clinopyroxene grains reach 1 mm in their largest dimension. The spherulitic texture coarsens with depth until visible individual spherulites reach the size of small microphenocrysts and the groundmass assumes a mesh texture. At the bottom of the section drilled at Site 599, the coarsest basalts consist of a groundmass of granular clinopyroxene about 0.1 mm across and lathlike plagioclase grains up to 0.15 mm long, with minor olivine about 0.05 mm across and magnetite in possibly skeletal grains up to 0.01 mm across. On a much finer scale, the textures, mineralogy, and crystallization trends of basalts from Sites 599 and 601 resemble those from the upper levels of Site 597.

SITE 602

The basalts from Site 602 differ from those at the three previous sites. The only rocks recovered at this site were fragments embedded in sediment layers from a core that bounced off the basement. These basalts are glassy to extremely fine grained. The groundmass varies from isolated brown spherulites of unidentifiable mineralogy floating in glass to essentially opaque, coalesced spherulites (Fig. 15). Spherulites in similar rocks from other locations on the East Pacific Rise were considered by Natland (1980) to be composed predominantly of plagioclase, but Kempton (1985) determined by the use of backscatter electron imagery that similar spherulites in basalts from Hole 504B and Leg 46 were actually composed predominantly of clinopyroxene surrounding a plagioclase core. A multitude of microphenocrysts of plagioclase and olivine occur within the groundmass, as well as phenocrysts of olivine that are skeletal, embayed, and often exhibit overgrowths of later olivine on rounded cores (Fig. 15). The olivine phenocrysts in particular are not observed in the basalts from the other drill sites on Leg

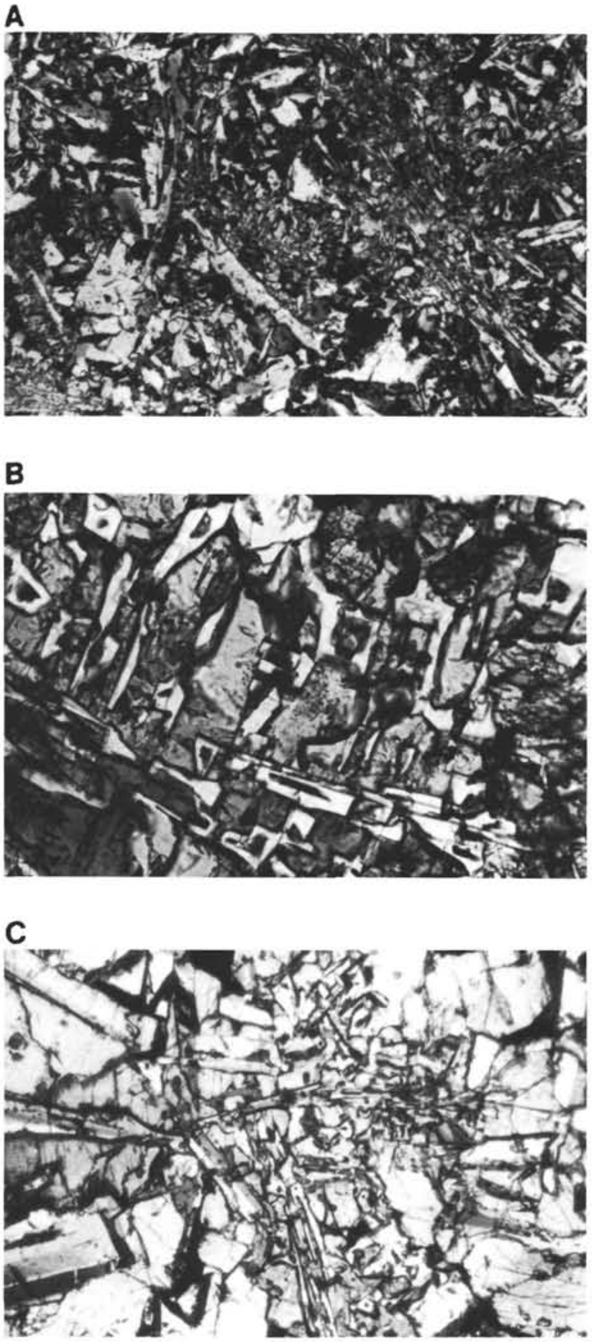

Figure 8. Graphic intergrowths of clinopyroxene and plagioclase, all under crossed nicols. A. Sample 597C-4-3, 72–73 cm; field of view, 3.6 × 2.4 mm. B. Close-up of center of (A); field of view, 0.6 × 0.4 mm. Plagioclase is white and black; clinopyroxene is gray. C. Coarse graphic texture within larger grains of plagioclase (twinned) and clinopyroxene. Sample 597C-5-2, 51–53 cm; field of view, 2.3 × 1.5 mm.

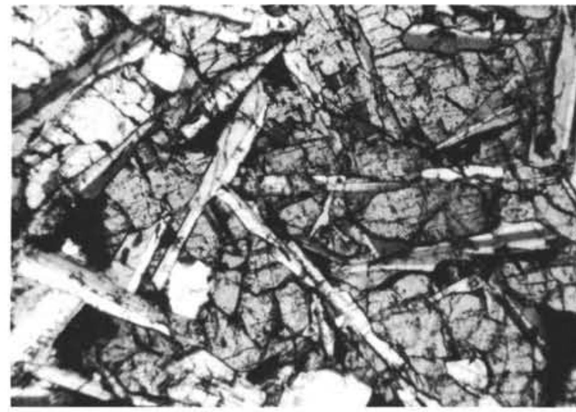

Figure 9. Clinopyroxene ophitically enclosing embayed plagioclase (twinned). Sample 597C-9-1, 30–32 cm; field of view, 3.6 × 2.4 mm.

Figure 10. Olivine pseudomorph in subophitic clinopyroxene, with plagioclase and magnetite (bottom left). Sample 597C-10-3, 121–125 cm; field of view, 3.6 × 2.4 mm.

Figure 11. Plagioclase and magnetite cluster located between ophitic clinopyroxene in bleb-textured basalt, under crossed nicols. Sample 597C-8-5, 36–41 cm; field of view, 3.6 × 2.4 mm.

92. The chemical composition of these rocks also differs from that of the other sites; it is more evolved and not attributable to the same parent magma (Pearce et al., this volume).

BASALT CRYSTALLIZATION HISTORY

Textures of basalts erupted on the ocean floor can be influenced by a wide variety of factors, and hence are not necessarily a straightforward reflection of the cooling history of the erupted lava. The cooling rate of the lava, supercooling caused by the eruption, and any previous superheating of the magma will affect the texture of the solidified rock, as will the composition of the magma and the characteristic nucleation and growth processes of the various minerals. The presence of previous-

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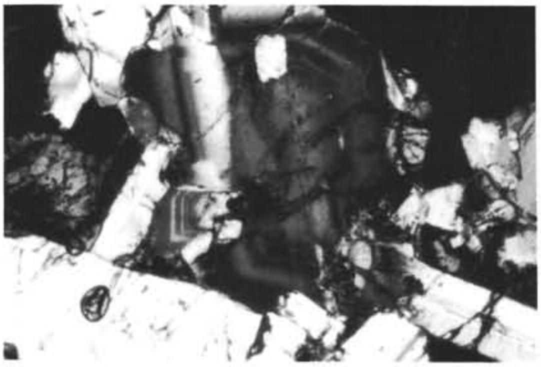

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C

Figure 12. Zoned and complexly twinned plagioclase and clinopyroxene crystals from lower sections at Hole 597C, all under crossed nicols. A. Zoned clinopyroxene, with olivine pseudomorph in upper right corner. Sample 597C-11-1, 105–107 cm; field of view, 2.3 × 1.5 mm. B. Zoned plagioclase. Sample 597C-12-1, 17–19 cm; field of view, 3.6 × 2.4 mm. C. Complexly twinned and zoned plagioclase, Sample 597C-11-1, 105–107 cm; field of view, 2.3 × 1.5 mm.

ly formed crystals in an erupted lava will also influence the subsequent crystallization. A brief summary of the effects of these different factors is given by Basaltic Volcanism Study Project (1981); more extensive discussion and documentation is provided by Lofgren (1980) and the references therein.

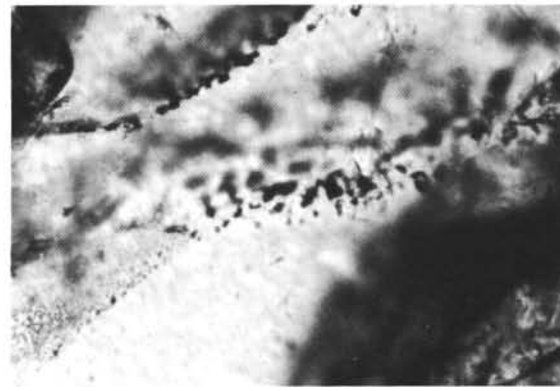

Figure 13. Close-up of unoriented inclusion in clinopyroxene crystal. Sample 597C-11-3, 54–56 cm; field of view, 0.36 × 0.24 mm.

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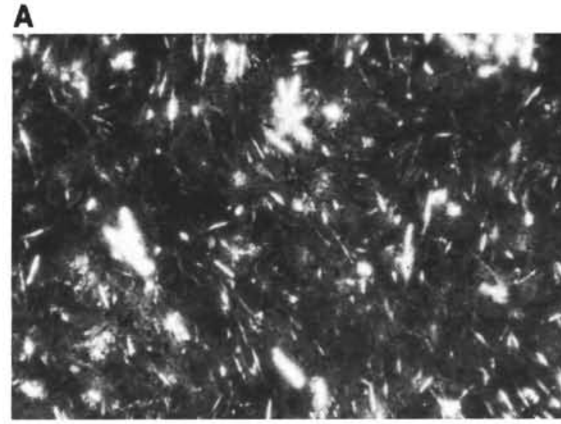

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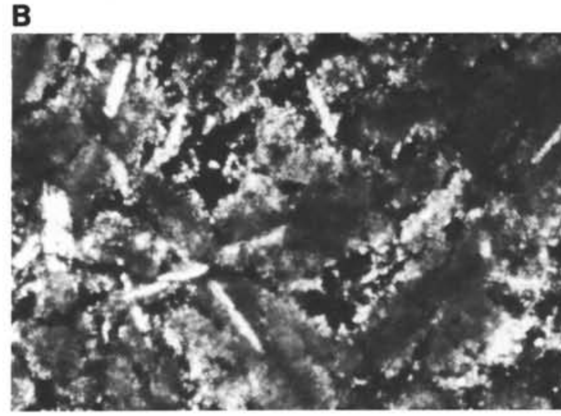

Figure 14. A. Feathery spherulites enclosing microphenocrysts of plagioclase. Sample 599B-3-2, 18–19 cm; field of view, 3.6 × 2.4 mm. B. Close-up of (A) showing spherulites growing around plagioclase microphenocrysts, with abundant interstitial magnetite (black). Field of view, 0.57 × 0.38 mm.

In natural systems the influences of these different factors are of course intimately intertwined, and the environment that produces one effect may of necessity produce another simultaneously. In a lava flow extruded onto the ocean floor, different degrees of supercooling go hand in hand with different cooling rates in different parts of the flow. Logically, the border of the flow ad-

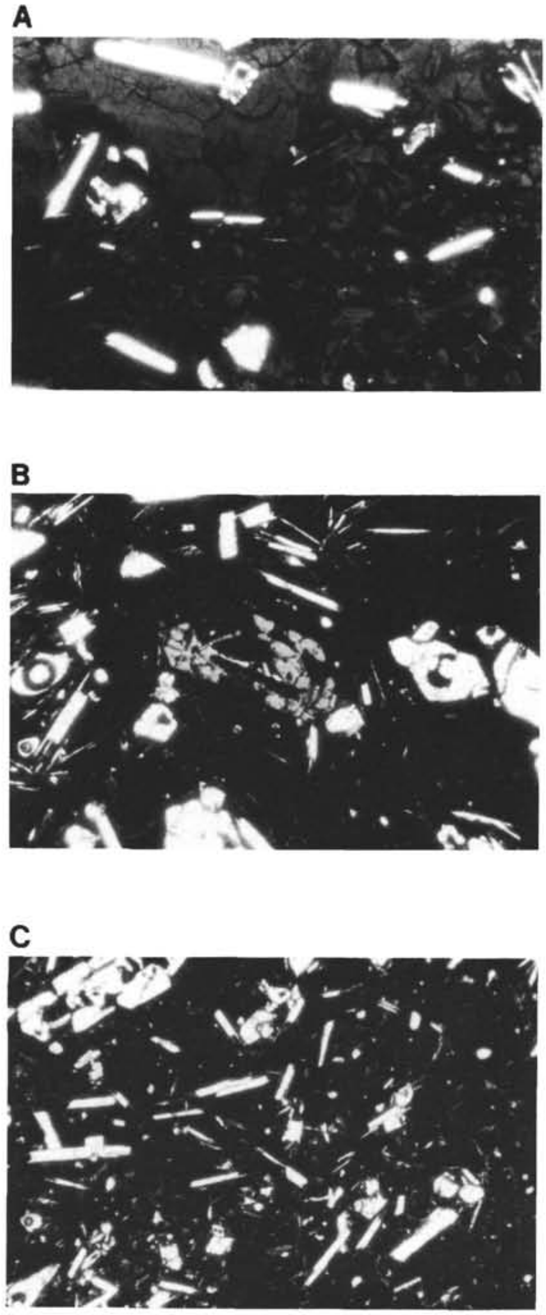

Figure 15. Sample 602B-1-2, 101–102 cm. A. Glassy edge showing isolated spherulites and microphenocrysts of plagioclase, taken on thin edge of slide to show detail. Field of view, 2.25 × 1.5 mm. B. Skeletal, embayed, and overgrown phenocrysts of olivine with skeletal plagioclase microphenocrysts in opaque groundmass of coalesced spherulites. Field of view, 2.3 × 1.5 mm. C. Typical view with abundant plagioclase and olivine microphenocrysts, embayed olivine phenocryst, and opaque groundmass. Field of view, 3.6 × 2.4 mm.

joining cold seawater or previously solidified basalt should exhibit features associated with the greatest degrees of supercooling, highest cooling rates, or both, while the interior exhibits characteristics of smaller degrees of supercooling, slower cooling rates, or both.

Variations in crystal morphologies of plagioclase and pyroxene in pure mineral systems have been studied as functions of cooling rates and/or degrees of undercooling. As cooling rates are increased or the degree of supercooling is increased, plagioclase changes from tabular to thin acicular to skeletal crystals to dendritic to coarse to fine spherulitic forms (Lofgren, 1973, 1976). Dendritic plagioclase is less common in experiments conducted with varying cooling rates; acicular crystals formed at intermediate cooling rates tend to transform directly to spherulitic forms at faster cooling rates. In addition, acicular crystals formed in cooling rate experiments tended to be arcuate compared to those from supercooling experiments (Lofgren, 1980). Studies of plagioclase nucleation indicate that the incubation time for nucleation is usually on the order of 1 week or more (Lofgren, 1980). The nucleation rate and probably the incubation time are greatest at very low and very high degrees of undercooling, and the nucleation temperature is lower at higher rates of cooling (Gibb, 1974). Plagioclase nucleation is complicated by the presence of a temperature interval in which random nucleation occurs above the nucleation temperature proper (Gibb, 1974).

Systematic variations in morphology as a function of cooling rate have also been observed in pyroxene. Although the transitions between crystal shapes occur at different rates in rocks of differing compositions, the overall trend is from euhedral or blocky crystals at slow cooling rates through elongate and skeletal crystals to dendritic and then to coarse, and fine spherulitic forms at faster cooling rates (Lofgren et al., 1975; Fleet, 1975; Lofgren, 1980).

The crystallization behavior of minerals in a pure system may vary considerably from that observed in more complex natural rock systems. Gibb's (1974) study of feldspar suggested that the nucleation of plagioclase and possibly of clinopyroxene in a natural system may be sufficiently suppressed by undercooling as to alter the actual or apparent order of mineral precipitation. Since the composition of the solidifying rock will influence the crystallization process, the most useful studies to apply to interpretation of the Leg 92 basalts are those carried out on other ocean floor basalts. Bryan (1972) has provided a detailed description of crystal morphology in oceanic basalts, from quench zones at the outer edges of pillows, to their crystalline interiors. In general appearance, the crystal morphologies correspond well to those obtained in mineral experiments with faster and slower cooling rates, but basaltic systems do not display the variety of shapes that plagioclase in the pure system does. In specific, Lofgren (1974) found that complex dendritic forms were absent in plagioclase crystallized from an ocean ridge basalt.

Lofgren and Donaldson (1975) have examined the crystallization of a tholeiite from the Nazca Plate. Although its behavior also resembled that of the pure mineral systems, some significant aberrations occurred. Specifically, if the melted basalt was cooled rapidly and continuously, plagioclase nucleation did not occur and the solidified rock was characterized by augite spherulites and olivine dendrites. However, if the melt was first held below the liquidus for a few hours to allow plagioclase to nucleate, the resulting rock consisted of acicular plagioclase and spherulitic augite.

Experimentally, dramatic differences exist between rocks crystallized from a complete melt and those crystallized from a partial melt (Lofgren and Donaldson, 1975; Lofgren, 1980). Solidification from a partial melt yields even-grained, poikilitic to subophitic rock textures, whereas the same composition cooled from a complete melt yields spherulitic or acicular textures. Variations in the texture of the partial melt product are related to the nucleation density in the melt; variations in the complete melt product are related to the length of time that the melt was held above the liquidus, with a longer time producing a finer texture as a result of a decreased nucleation rate. The difference in textures between the partial melt and complete melt products implies that plagioclase and pyroxene nucleated and grew at higher temperatures in the partial melt than in the complete melt, presumably as a consequence of the presence of pre-existing nuclei in the partial melt.

The results of these experiments clearly have a direct bearing on the interpretation of intersertal to ophitic textures. The development of intersertal, subophitic, or ophitic texture depends on the density of plagioclase nucleation and the timing of pyroxene nucleation (Lofgren, 1980). Experimentally, all such coarser textures are formed most easily by crystallization from a subliquidus starting point in melts of near cotectic compositions containing 5 to 15% by volume of crystals evenly distributed throughout the liquid (Lofgren, 1980). However, the effects observed in experimental work are innately limited by the cooling rates achievable in the lab. Very slow cooling of multiply saturated melts, at rates slower than those viable experimentally, could produce intersertal to ophitic textures from completely melted materials (Lofgren, 1980).

The texture of the basalts from Leg 92 can be interpreted as the product of crystallization at systematically varying rates of cooling and/or degrees of supercooling. The fine-grained chilled zones, although they lack the glassy edges of a true quenched margin, do display the spherulitic plagioclase and clinopyroxene characteristic of rapid cooling or extreme undercooling. The abrupt change in grain size and texture between the chilled zones and the adjoining basalt suggests that the bulk of the basalt cooled more slowly and/or from a higher temperature. Similarly, the overall coarsening of texture down the section from Site 597 suggests that the basalts at the base of the section crystallized at a slower rate than those at the top of the section. This implies that the crustal section was not built up by successive extrusions of lava at the surface, but by the intrusion of layers within an accumulating volcanic pile.

The fine-grained zones are clearly intervals of unusually rapid cooling or extreme undercooling. As such, they were presumably formed by cooling against either seawater or previously erupted basalt. The results of Kempton's (1985) study of quenched margins of pillows and flows from Hole 504B suggest that these chilled zones do lack normal quenched margins. The finer-grained basalts from Site 597 appear to fall in her Zone 5 of dike margins; that is, they are characteristic of the coarser sections of the chilled margins of dikes. The truly quenched edges she describes do not appear at the edges of the chilled zones in Site 597 basalts. Given the lack of quenched margins and the interfingering between the chilled zones and basalts on either side, the zones most likely formed by intrusion of a fresh basalt flow into a previously erupted but still plastic basalt. However, the textures do not allow an unequivocal choice to be made between the interpretation of the chilled zones as individual injections of thin layers of lava or as the upper or lower margins of larger intrusions.

The presence of acicular plagioclase and spherulitic clinopyroxene in the Leg 92 basalts, combined with Lofgren and Donaldson's (1975) experiments, suggests that the rocks crystallized under conditions that permitted the nucleation of plagioclase before rapid cooling occurred. Several possibilities for creating such conditions exist. If the basalts were very plagioclase-rich, delayed nucleation of plagioclase could lead to the simultaneous crystallization of plagioclase and clinopyroxene. Analyses of the basalts, however, do not reveal any unusual composition (Pearce et al.; and Erzinger, both this volume). Alternatively, physical conditions during the crystallization and eruptive process could be responsible for plagioclase nucleation.

In Lofgren and Donaldson's (1975) experiments, nucleation of plagioclase was achieved by holding the charge at a temperature below the liquidus for several hours before cooling it rapidly. In a natural system, such an effect might be attained if the lava erupted after crystallization had already commenced in the magma chamber, resulting in the sudden cooling of a melt from a point below the liquidus.

There is evidence within the rocks from Leg 92 that crystallization had occurred before the eruption of the basalts. In the upper portion of the section, the rocks consist of a fine-grained matrix of spherulites and skeletal plagioclase hosting glomerocrysts composed of well-developed plagioclase and olivine crystals. The mere presence of a porphyritic texture does not require a two-stage history of crystallization; Lofgren et al. (1975) demonstrated that porphyritic textures can develop from a one-stage cooling history if a sufficient temperature interval exists between the formation of the phenocryst phase and the formation of the matrix. However, the morphology of the phenocrysts and matrix should reflect similar cooling rates for a one-stage history. The well-developed crystals of plagioclase and olivine composing the glomerocrysts in the Leg 92 basalts imply formation at a relatively slow cooling rate, in contrast to the rapid cooling of the matrix. This combined with the mineral chemistry of the glomerocrysts (Pearce et al., this volume) suggests that the glomerocrysts did indeed form prior to eruption of the basalts.

Textures deeper within the section are more difficult to interpret in terms of pre-eruptive crystallization. The subophitic and ophitic textures of the coarser basalts could be the result of cooling from a subliquidus melt containing an earlier crystal population, or could be the result of slow cooling from a completely melted magma. In either case, slower cooling or a lesser degree of undercooling must be invoked to explain the development of coarser textures in the deeper section, since even the most fine-grained basalts apparently cooled from a subliquidus state.

The possibility does indeed exist that only the uppermost flows were carrying crystals. The "graphic" texture described above as intermediate between the coarsely spherulitic and subophitic basalts is a texture found experimentally in samples cooled from a complete liquid, but not in samples cooled from subliquidus conditions (Lofgren, 1980). This does not constitute proof that the deeper basalts were erupted as complete liquids, but the current experimental results allow for varying interpretations of the coarser-textured basalts.

In terms of texture, the crustal section drilled at Site 597 is consistent with a composite basalt flow formed by multiple injections of magma into a crystallizing massive flow. In terms of mineralogy, as mentioned earlier, a distinct unit, olivine-free and Ti-rich, appears to exist between Section 597C-8-1 and Core 597C-10 or 11. The boundaries of this unit as defined chemically (Pearce et al.; and Erzinger, both this volume) appear to be fairly sharp at the upper limit and transitional at the lower limit. If the chilled zones in the basalts do represent sites of intrusion, then Core 7, which contains six of these zones, had a history of repeated intrusion and may have provided a hospitable site for the injection of a body of different material. The absence of a clearly defined lower boundary for the unit suggests that the basalt below was still partially molten and that some mixing did occur between the two magmas.

Basalts from Sites 599 and 601 resemble those from Site 597 and presumably formed in a similar fashion. The samples recovered from the sediment from Site 602, however, are dissimilar and open to a somewhat different interpretation. The glassy and extremely fine spherulitic matrix suggests formation at even more rapid cooling rates and/or extreme degrees of undercooling than the basalts from Site 597. The presence of skeletal olivine is also indicative of rapid cooling or extensive supercooling (Bryan, 1972; Donaldson, 1976), although the extreme quench morphologies were not observed. The Site 602 basalts also differ from those at the other sites in that the samples from Site 602 appear to be pieces of pillow lavas, based on Kempton's (1985) analysis of the differences between chilled margins of pillows and dikes in Hole 504B.

COMPARISON WITH OTHER MID-OCEAN-RIDGE BASALTS

The basalts drilled at the first three sites (597, 599, and 601) consist predominantly of pyroxene and clinopyroxene in approximately equal quantities, accompanied by smaller but still significant amounts of titanomagnetite, minor sulfides, and minor if any olivine. Point counts of minerals in thin section reveal both plagioclase and clinopyroxene in the 40–60% range, with no systematic variation. In those samples containing olivine, the rocks could at most be described as olivine-poor tholeiites; the olivine-free samples are clearly plagioclase-and-clinopyroxene basalts. Basalts characterized by such abundant clinopyroxene are relatively rare compared with plagioclase–olivine basalts (Bougault and Hekinian, 1974; Shido et al., 1974; Shibata, 1976; Bryan and Dick, 1982; Bryan, 1983).

On the other hand, most of the seafloor basalts included in generalized studies originated at a slow-spreading ridge, usually the Mid-Atlantic Ridge. The basalts from Leg 92 do bear a strong resemblance to other rocks recovered from the East Pacific Rise crest and flanks on DSDP Legs 34 and 54, and during dredging in those areas (Ade-Hall et al., 1976; Bunch and La Borde, 1976; Donaldson et al., 1976; Kempe, 1976; Mazzullo et al., 1976; Thompson et al., 1976; Yeats, Hart, et al., 1976; Srivastava et al., 1980). Natland (1980) has constructed a detailed petrographic classification based on the basalts drilled during Leg 54 and additional dredge hauls in the same area. The Leg 92 basalts fit well into his scheme, and allow the textural sequence he describes within a pillow or relatively thin flow to be extended to the larger scale of the massive basalts from Site 597. Natland's classification is based on the progressive textural and mineralogical changes inward from the glassy rim of a basalt pillow to a coarse-grained flow interior. Based on the nearly aphyric nature of the finest-grained basalts, the lack of olivine, and the presence of lathlike plagioclase and granular clinopyroxene, the basalts from Sites 597, 599, and 601 of Leg 92 appear to be transitional between olivine-poor tholeiites and ferrobasalts, whereas those from Site 602 are closer to olivine tholeiites. The presence of thick, massive basalts allows an additional level to be explicitly added to Natland's descriptive scheme—the occurrence of an ophitic zone after the stage of spherulitic and granular clinopyroxene and plagioclase.

SUMMARY

The basalts recovered from Sites 597, 599, 601, and 602 of Leg 92 are typical East Pacific Rise–Mendoza Rise basalts, mineralogically and texturally. They range from possible olivine tholeiite at Site 602 to olivine-poor tholeiites to ferrobasalts at Sites 597, 599, and 601. The section drilled at Site 597 is the most successful yet achieved in crust formed at a fast-spreading ridge, but appears to have penetrated massive basalts forming composite flows rather than the more usual thin flows and pillow lavas.

The predominant mineralogy at Site 597 consists of plagioclase, clinopyroxene, and titanomagnetite, plus minor olivine in the upper (Cores 3 to 7) and lower (part of Core 10, Cores 11 to 12) sections. The presence or absence of olivine is not associated with any textural variations, but does correlate with compositional changes which divide the basalts into two or three major units (Pearce et al., this volume).

Although the major compositional units cannot be associated with visible igneous contacts, fine-grained chilled zones do occur at irregular intervals in the cores. These zones are mineralogically and compositionally similar to the adjoining coarser-grained basalts, but texturally they appear to have cooled much more rapidly. These zones presumably mark divisions between flows within the major units. However, the absence of true quenched

margins suggests that they formed by injection of new lava into incompletely cooled older basalt.

The textures of both the chilled zones and the intervening basalts coarsen downward through the cores. The uppermost, finest-grained rocks consist of plagioclase and olivine microphenocrysts and glomerocrysts in a spherulitic groundmass of plagioclase, clinopyroxene, and titanomagnetite. As the cooling rate increases and the degree of supercooling decreases, the textures change through coarse fan and sheaf spherulites of plagioclase and clinopyroxene, to graphic intergrowths of clinopyroxene and plagioclase, to subophitic and ophitic clinopyroxene hosting plagioclase, all accompanied by abundant interstitial titanomagnetite. While both the chilled zones and the adjacent basalts are more coarse grained deeper in the cores, there is a consistent abrupt change in grain size at the contact between the two.

The textural sequence observed in the Leg 92 basalts is similar to that reported from other East Pacific Rise and Mendoza Rise basalts from Legs 34 and 54. However, the more extensive section obtained from Site 597 and the presence of more massive basalts allows the textural and mineralogical variations previously described as functions of the cooling rate within pillows and thin flows to be extended to the wider range found within a massive flow.

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