Mével, C., Gillis, K.M., Allan, J.F., and Meyer, P.S. (Eds.), 1996
Proceedings of the Ocean Drilling Program, Scientific Results, Vol. 147

17. GABBRO FABRICS FROM SITE 894, HESS DEEP: IMPLICATIONS FOR MAGMA CHAMBER PROCESSES AT THE EAST PACIFIC RISE[1]

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ABSTRACT

Rifting in Hess Deep has exposed complete sections of young oceanic lithosphere generated at the East Pacific Rise. At Ocean Drilling Program Site 894, a 150-m section of gabbroic rocks from the upper part of the plutonic section was drilled. The rocks are not compositionally layered but do have *l* or *l-s* fabrics defined by the shape-preferred orientation of idiomorphic plagioclase and other phases, including magnetite. We show here that the fabrics formed as a result of viscous magmatic flow and that, in contrast to previously drilled sections of ocean-floor gabbro, evidence for solid-state deformation is entirely absent. Restoration of the fabrics to geographical coordinates, and accounting for subsequent tectonic rotations, shows that the magmatic foliation was originally parallel to the East Pacific Rise axis, steeply dipping, and with a strong, near-vertical flow lineation.

From compositional considerations the Site 894 section is thought to have crystallized at fairly high pseudostratigraphic levels within the plutonic portion of the crust, probably slightly below the level of the axial melt lens. This corresponds to a region of moderate seismic attenuation observed at the present-day East Pacific Rise axis, which is believed to represent a crystal mush zone but is otherwise poorly constrained. We discuss the possible implications of the observed fabrics for the mechanisms of melt transport through the mid-crust at fast-spreading ridges.

ODP DRILLING IN HESS DEEP

Hess Deep (2°15′N, 101°30′W) is a 5400-m-deep rift valley lying close to the triple junction of the Pacific-Cocos-Nazca Ridges in the equatorial eastern Pacific Ocean (Fig. 1). Within Hess Deep, lithosphere generated at the north-south-trending East Pacific Rise (EPR) is being dismembered by the westward propagation of the Cocos-Nazca spreading axis at a rate that matches the 65 km/m.y. half-spreading rate of the EPR (Hey et al., 1977; Lonsdale, 1988; Fig. 1). Dredging and submersible investigations of the region have shown that extensive sections of oceanic crust and shallow upper mantle are exposed in the Hess Deep Rift Valley (Francheteau et al., 1990). The principal objective of ODP drilling in Hess Deep was to sample for the first time an in situ section of lower crust and shallow mantle from a fast-spreading mid-ocean ridge. As such, Leg 147 was extremely successful, yielding, at Site 894, gabbros from the upper part of the plutonic section, and (in the adjacent Site 895) harzburgites, dunites, and troctolites from the crust-mantle transition zone (Gillis, Mével, Allan, et al., 1993). It is the gabbros from Site 894 that are the subject of the present paper.

The prime focus of drilling was a fault-bounded horst within the Hess Deep basin, from which gabbroic rocks had been recovered by dredging and from submersibles (Francheteau et al., 1990; Fig. 1). The principal hole at the site, Hole 894G, was located close to the summit of this intra-rift ridge, at a depth of 3023.4 m below sea level, on a southward-facing slope of approximately 23°. The hole penetrated 154.5 mbsf, with moderate recovery (35.8%), into a succession of gabbronorites and gabbros (with or without olivine) cut by two basaltic dikes (Fig. 2; Gillis, Mével, Allan, et al., 1993). Comparison of the petrology and geochemistry of the drilled section with samples recovered during submersible traverses in Hess Deep (Francheteau et al., 1990; Hekinian et al., 1993) suggest that the hole was most probably sited at intermediate to high levels within the plutonic layer (seismic Layer 3) (Gillis, Mével, Allan, et al., 1993). Samples from immediately below the sheeted dike-gabbro transition on the scarps of the northern wall of Hess Deep include oxide-bearing ferrodiorites and tonalites, and hence are significantly more evolved than those recovered at Site 894 (J.H. Natland, pers. comm., 1994). Dick and Natland (1994) suggest that these highly fractionated lithologies mark the site of the axial melt lens, and they place the Site 894 section no more than a few hundred meters below this level. Original suggestions, made by Gillis, Mével, Allan, et al. (1993), that the Site 894 section represented a downward-crystallizing "roof-chill" facies, becoming progressively more evolved downsection (as originally envisaged for ophiolites; e.g., Dewey and Kidd, 1977; Gass, 1980) are not supported by shore-based geochemical studies (T.J. Falloon, pers. comm., 1994; Natland and Dick [this volume]; Pedersen et al. [this volume]).

The drilling carried out on Leg 147 has given us significant new insights into axial magma chamber processes. Two principal advantages of drilling over and above previous investigations, which have been based solely upon dredging or submersible sampling (Francheteau et al., 1990; Hekinian et al., 1993), are that we not only gain a measure of fine-scale stratigraphic control, but also (as shown here) the opportunity to examine the spatial context of features. The information that core reorientation can yield on the orientations of structures relative to the EPR reference frame is extremely valuable, and it provides what are, thus far, unique constraints on the physical processes of magma transport at fast-spreading ridges.

HOLE 894G GABBROIC ROCKS

Gabbronorites form 80% of the recovered rock types in Hole 894G. The remainder consist (in order of decreasing abundance) of basalt (dike rock), olivine gabbronorite, gabbro, and olivine gabbro. Modal layering was not observed in the drill cores; instead, modal mineralogies are generally very consistent, with plagioclase forming

[1]Mével, C., Gillis, K.M., Allan, J.F., and Meyer, P.S. (Eds.), 1996. *Proc. ODP, Sci. Results*, 147: College Station, TX (Ocean Drilling Program).

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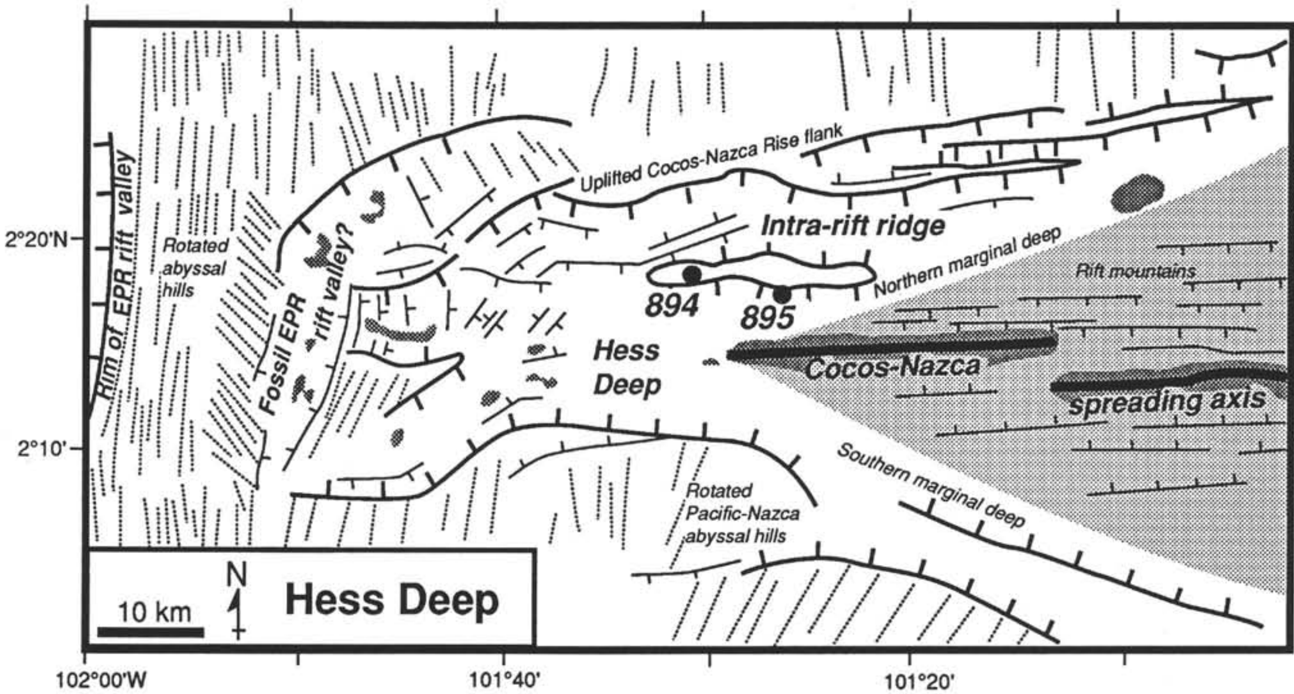

Figure 1. Location map of ODP Sites 894 and 895 in Hess Deep. Hess Deep represents the amagmatic tip of the Cocos-Nazca spreading center, which is propagating westward at a rate similar to the half-spreading rate of the East Pacific Rise. The lighter shaded area represents crust thought to have been formed by the Cocos-Nazca spreading axis; the darker, recent volcanics. Thick and thin ticked lines represent major and minor fault scarps respectively, with the tick on the downthrown side. Thin dashed lines represent abyssal hill fabrics as deduced from swath bathymetry and GLORIA sidescan sonar imagery (Searle and Francheteau, 1986). Modified after Lonsdale (1988) with further reference to GLORIA data.

53% of the mode (standard deviation 4.4%), clinopyroxene 31% (±3.5%) and orthopyroxene 14% (±4.4%) (Gillis, Mével, Allan, et al., 1993). Accessory minerals include oxides (average 1%–2%, exceptionally ≥5%) and, in some instances, sulfides, apatite, and/or zircon.

Although the mineralogies are very consistent in Hole 894G rocks, grain sizes, and textures vary rapidly over short distances, even on the scale of a single thin section. Fabrics may either be isotropic or show traces of a foliation. The nature and origin of this foliation is investigated in detail in the following sections of this paper. Textures range from poikilitic to equigranular (hypidiomorphic to intergranular), depending principally upon the grain size of pyroxene grains in the groundmass. No consistent relationship is recognized between the different textural types. Plagioclase crystals in all of these textural types are characteristically idiomorphic and tablet-shaped, ranging from ~2–3 mm long in the equigranular types to 4–5 mm in the poikilitic types. Zoning is common, with normal zoning (i.e., rims progressively more albitic than the cores) predominant (Yaouancq, 1994).

FOLIATIONS IN GABBROIC CORES

Foliations in the Hole 894G cores are penetrative fabrics defined by the orientation of elongate plagioclase laths. In most cases, the foliations are not easy to recognize in hand specimen, depending strongly upon the orientation of the fabric relative to the cut surface of the core. We have, however, been able to identify them in 45 oriented core pieces (oriented relative to the axis of the borehole) from almost the entire section—from Core 147-894G-4R (~46 meters below seafloor [mbsf]) through to Core 147-894G-20R (~150 mbsf)—although they appear to be better developed between Cores 147-894G-9R and 147-894G-13R (70–110 mbsf) (Fig. 2). Fabrics in the uppermost three cores were probably obscured by the cataclasis and increased hydrothermal alteration in Cores 147-894G-1R through 3R (Früh-Green, Plas, and Dell'Angelo, this volume; MacLeod, Célérier, et al., this volume). Foliations were observed in gabbronorites, olivine gabbronorites, and gabbros, and although the majority of measurements were made in gabbronorites, this is only in direct proportion to the relative abundance of this lithology in the recovered cores.

The fabrics are generally better developed in the finer-grained rocks, but also occur in the coarser-grained varieties. In some instances, sharp, near-vertical contacts have been observed between coarse-grained "veins" of gabbronorite and finer-grained, strongly foliated gabbronorites or gabbros (Fig. 3; e.g., Sample 147-894G-12R-2, Piece 9); this contact may be at a slight angle to the foliation. These coarse, cross-cutting gabbronorites are apparently isotropic in texture, but (as shown below) their crystallographic structure shows a weak fabric parallel to their margins. Cross-cutting foliations have also been observed in a few instances; in Sample 147-894G-10R-1, Piece 13, for example, a contact was observed between two different foliations in gabbro (sensu stricto): an older, irregular fabric, cut and deformed (with normal sense of shear) by a well-defined, intense foliation in a finer-grained gabbro.

PETROFABRICS

To corroborate and investigate further the shipboard observation of a fabric in many of the Hole 894G gabbros (sensu lato) the fabrics of 24 gabbronorite and olivine gabbronorite specimens were examined in thin section. These samples cover the complete section of Hole 894G. In all samples a foliation was detected, even if none were visible in hand specimen (Yaouancq, 1994). This foliation is defined by the preferred orientation of anisometric euhedral-subhedral plagioclase crystals, in a matrix formed by anhedral or poikilitic crystals of pyroxene. It could be determined irrespective of the size of the plagioclase tablets, which range from 2–3 mm long in the fine- or medium-grained gabbronorites to 4–5 mm in the coarse-grained gab-

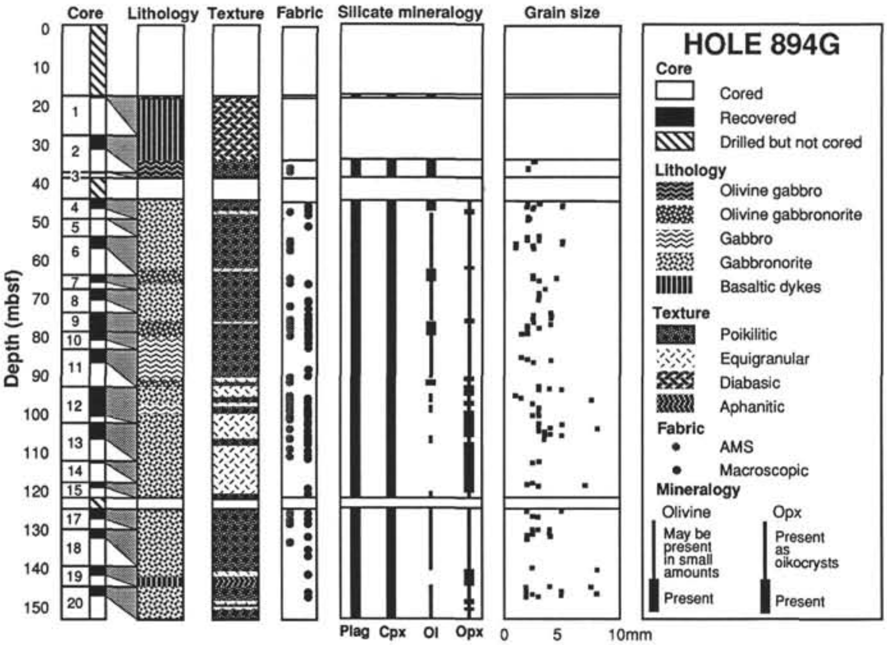

Figure 2. Lithostratigraphy of Hole 894G, from Gillis, Mével, Allan, et al. (1993). For presentational purposes, information in the columns lithology, texture, silicate mineralogy, and grain size is adjusted to an "expanded" depth scale (i.e., expanding the proportionate thicknesses of the recovered core as if it were representative of the recovered interval). The predominant texture is shown in the texture column. Poikilitic and equigranular types are interspersed on a much finer scale than that displayed here. The fabric column indicates where a magmatic foliation was detected, either by macroscopic observation or from the anisotropy of magnetic susceptibility. Foliated rocks occur throughout the stratigraphic section and are not restricted to particular lithologies, textures, or grain sizes.

bronorites). On surfaces cut parallel to the foliation trace, it was also possible to detect and measure a lineation.

The elongation of anisometric plagioclase crystals is parallel to the albite twinning direction (Fig. 4). The shape anisotropy of the grains is large (c:a aspect ratio = 2–3:1), and greatest in the finer grained rocks. Both albite and pericline twinning have the regular and parallel shape characteristic of growth twins. Plagioclase aggregates are devoid of high-temperature recrystallized triple-junction boundaries, as well as edge mechanical twinning. This is strong evidence that the fabrics result from magmatic, rather than solid-state, flow. No evidence has been found for any plastic strain being superimposed on these magmatic textures. The ortho- and clinopyroxene grains that form the matrix to these rocks are devoid of any trace of deformation or recrystallization. Note that this absence of deformation extends to the cross-cutting foliation described above (Sample 147-894G-10R-1, Piece 13), suggesting that it was a true "magmatic shear zone."

The crystallographic fabrics of plagioclase crystals have been constructed from universal-stage measurements of the optical directions of the albite (010) or pericline twinning planes on representative specimen 147-894G-12R-3, Piece 8B (142–150 cm). Data were treated using the Benn and Mainprice (1989) computer program; three-dimensional statistical representation was obtained by measurements on two complementary thin sections, XY (parallel to the lineation, in the plane of the foliation; Fig. 4A) and XZ (parallel to the lineation, perpendicular to the plane of the foliation; Fig. 4B. The crystallographic fabric of plagioclase (Fig. 5) is consistent with the strong shape anisotropy of crystals, marked by a strong maximum of [001] (crystal elongation) in the foliation plane, and sub-parallel to the lineation; [010] forms a girdle perpendicular to the lineation, indicating that the fabric is predominantly linear rather than planar. Crystallographic fabrics of ortho- and clinopyroxene are inconsistent; grain sizes are too large on the scale of the specimens (and therefore the crystals too few in number) for their crystallographic orientations to have any statistical significance.

GEOMETRY OF FABRICS

Methodology

Measurements of the orientations of the fabrics described above were made on the cores both during and after Leg 147. Traces of a foliation were identified visually or with a binocular microscope on the surfaces of the core. The fabric was most obvious on cut or (better) polished surfaces, and was systematically stronger on planes cut parallel rather than perpendicular to the axis of the borehole, suggesting a steeply plunging lineation; however, this was difficult to quantify accurately from hand specimen alone. For this reason, further laboratory investigations of samples were carried out in order to identify and make accurate lineation measurements post-cruise. All lineation data discussed in the following sections are derived from these laboratory measurements.

Foliation planes were reconstructed from two apparent dip measurements, in some cases also with a strike measurement from horizontal surfaces. Measurements were verified where possible by laboratory examination of oriented thin sections. Preliminary cuts made parallel to the foliation provided favorably oriented sections for identification of a lineation; thin sections were then made parallel to this lineation, both parallel and perpendicular to the foliation. Following the procedure described by MacLeod et al. (1992, 1994; summarized in Gillis, Mével, Allan, et al., 1993), the axis of the borehole was considered to be vertical, and azimuths measured relative to artificial "core-liner coordinates." "North" was defined as perpendicular to the cut surface and lying in the working half of the core. Preliminary restoration of the core fabric measurements to a common reference frame was made by rotating the stable magnetic remanence direction measured in the same contiguous core pieces (Gillis, Mével, Allan, et al., 1993; MacLeod, Manning, et al., this volume) to the same horizontal direction. A second rotation was then made to bring the measurements to a common magnetic inclination as well as declination. Inclinations of the stable remanence directions at Site 894 are consistently skewed by approximately 35°–40° down toward the declination direction when compared to the expected field direction for the latitude of the drill site of +4.6° (Pariso et al., this volume). This disparity in inclinations is most readily interpreted in terms of a tectonic rotation (probably of the entire intra-rift ridge) with a horizontal component of this magnitude (Gillis, Mével, Allan, et al., 1993; MacLeod, Célérier, et al., this volume).

Restoration of the samples relative to the stable magnetic remanence direction assumes that all of the samples acquired their magnetizations in the same field direction. Secular variation is unlikely to be significant because the rocks cooled slowly. Gillis, Mével, Allan, et al. (1993) and Pariso et al. (this volume) have shown that the stable remanence is carried by pure magnetite, which has a Curie tempera-

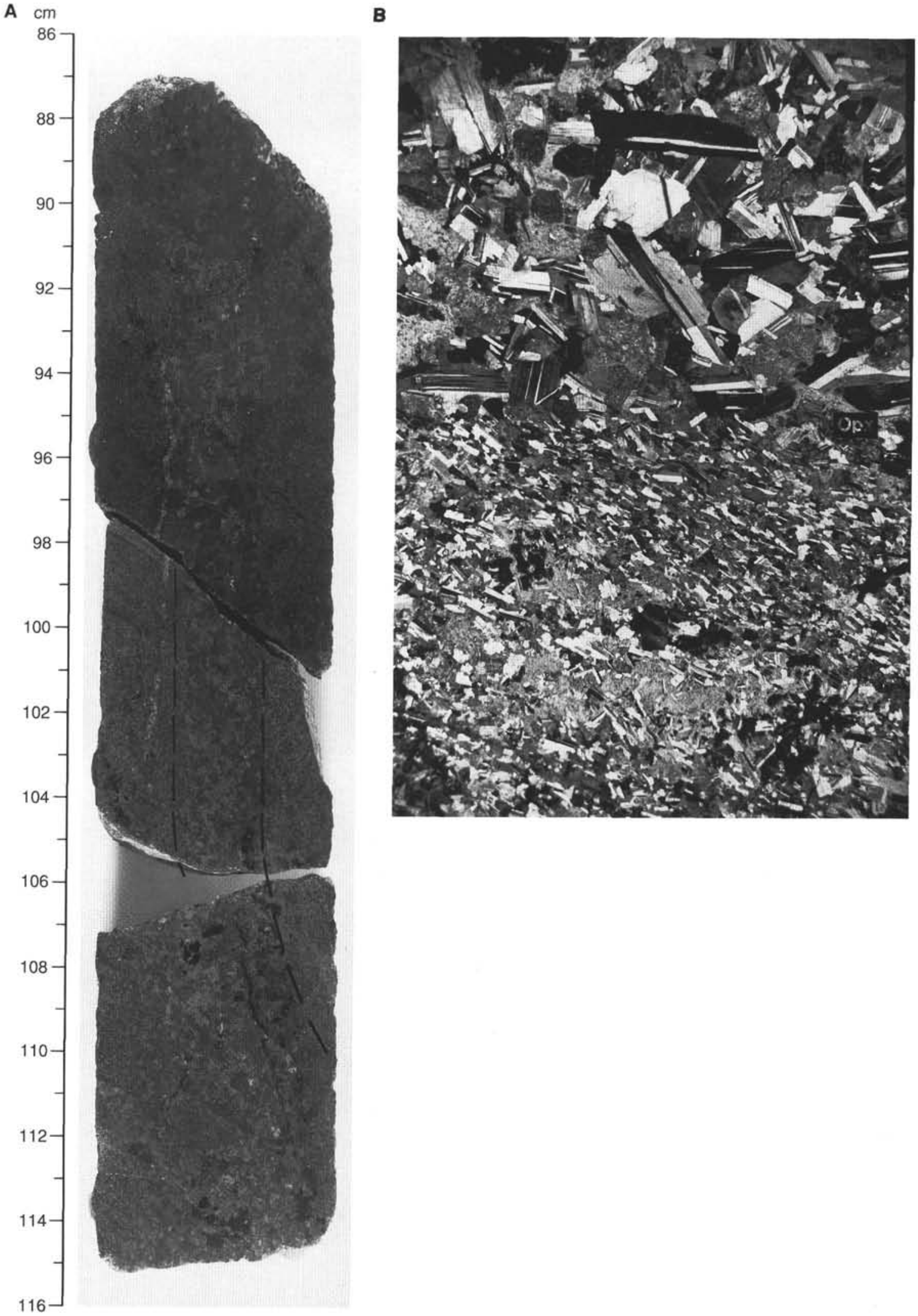

Figure 3. **A.** Core photograph of Sample 147-894G-12R-2 (Pieces 9A, 9B, and 10B, 86–116 cm). **B.** Photomicrograph of 2- to 3-cm-thick vein of coarse-grained equigranular gabbronorite cutting a medium-grained, strongly foliated gabbro. The boundaries between the two are marked on Figure 3A by white dashed lines. The coarse-grained, apparently isotropic gabbro vein in the center of the core is slightly oblique to the foliation. Note the difference in lithology, with orthopyroxene (marked "opx" on Fig. 3B) present in the cross-cutting vein and absent in the foliated host; note also the complete lack of chilling of the coarse-grained cross-cutting gabbronorite. Fabric studies of similar samples show that, although apparently unfoliated, the coarse-grained veins possess a weak magmatic foliation parallel to their margins. This is confirmed by AMS data (see text). Field of view of Figure 3B = 4 cm (long axis).

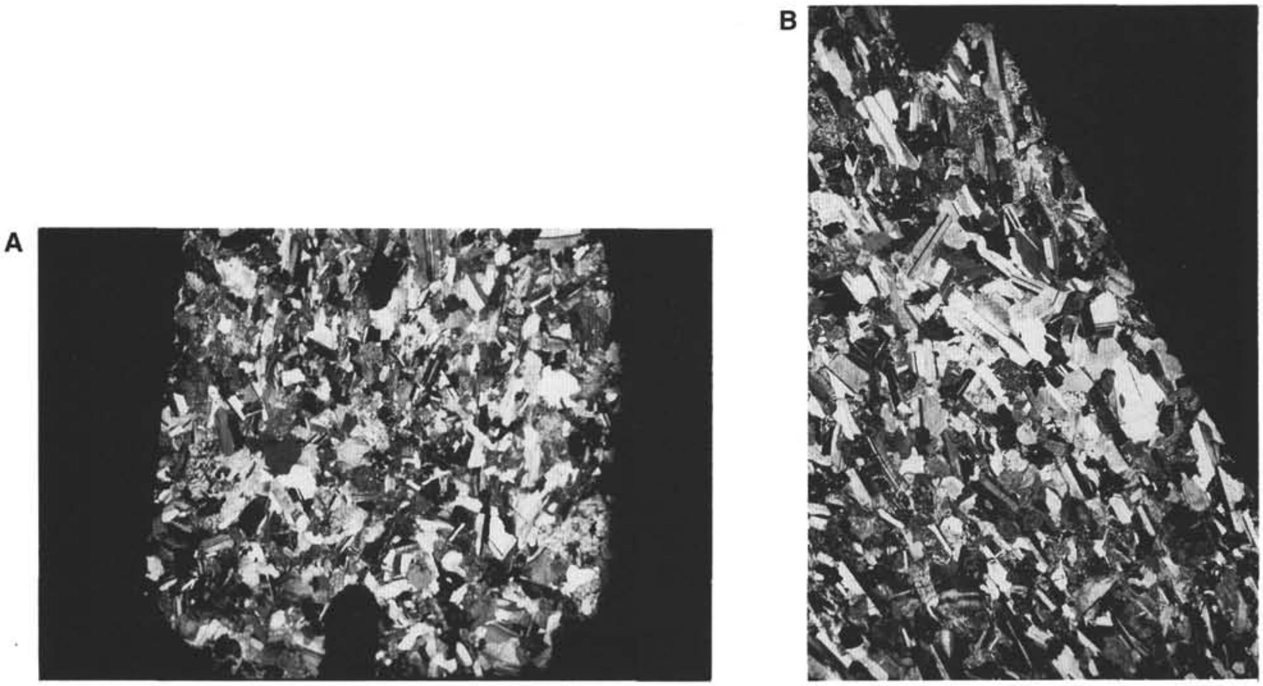

Figure 4. Photomicrographs of Sample 147-894G-12R-3 (Piece 8B, 142–150 cm) from which the detailed fabric determinations shown in Figure 5 were carried out. **A.** XY plane (parallel to the lineation in the plane of the foliation) and **B.** XZ plane (parallel to the lineation, perpendicular to the plane of the foliation). The preferred orientation of idiomorphic plagioclase, very marked in the XZ plane, is also obvious in the XY plane, emphasizing the strength of the lineation. Note the absence of curving deformation twins, undulose extinction, or recrystallized 120° triple junctions in all phases, implying that the fabric resulted from magmatic rather than solid-state flow. Field of view: Figure 4A = ~3.5 mm; Figure 4B = ~4.5 mm.

ture of 550°–580°C; hence, the direction of the remanence is likely to have been "fixed" relative to the magmatic fabrics at an early stage. Any subsequent tectonic rotation (as postulated for the region: MacLeod, Célérier, et al., this volume) will therefore affect both remanence direction and petrofabrics together, and is unlikely to modify the angular relationship between them. When considering the original orientations of the gabbro petrofabrics relative to the ridge reference frame, therefore, it is more useful to reorient them to the remanence direction than to their present-day geographical position: in this way all subsequent tectonic complexities (MacLeod, Célérier, et al., this volume) are taken into account.

We have made 45 measurements of foliations and 24 of lineations from macroscopic and microscopic observations of the Hole 894G cores. Of these, 19 are oriented fully with respect to the stable magnetic remanence direction to give both a foliation and lineation, and for a further five we have been able to determine a foliation only. In addition, we have taken one sample (147-894G-12R-3, Piece 8B) and carried out modeling and calculation of the anisotropy of its seismic velocity based upon its crystal fabric (Yaouancq, 1994); Richter et al. (this volume) studied 52 samples for anisotropies of magnetic susceptibility (AMS). A brief comparison is made here between these measurements and our petrofabric data.

Results

Restored foliations in the gabbroic rocks are steeply dipping (mean 69°, with standard deviation of 14°) and their azimuths restore to a consistent, near north-south direction (Fig. 6A, B). This relationship holds for the data both before and after correction for magnetic inclination as well as declination; all figures given in this paper are fully corrected for inclination. Given the relatively small data set and difficulty in measuring such tiny samples the restored lineations show a remarkably consistent trend, plunging steeply north to northwestward (Fig. 6C; mean vector: 326.0 azimuth, 59.3° plunge, with cone of confidence $\alpha_{95} = 17.6°$ and concentration factor $k = 4.6$). No systematic changes in orientation were noted with stratigraphic position. The significance of these results are discussed further below.

OTHER PHYSICAL PROPERTIES

Seismic Anisotropy

The seismic properties of representative gabbronorite specimen 147-894G-12R-3, Piece 8B, have been calculated from the modal analysis, single-crystal elastic constants, density and crystallographic fabric of each phase (Mainprice, 1990; Yaouancq, 1994). This calculation provides information different from direct measurements of seismic velocities on specimens (Iturrino et al., this volume), in that it does not account for secondary alteration, but provides a three-dimensional representation of the seismic properties, and the geometrical relationships of the seismic anisotropy values V_{max} and V_{min} with the rock fabric. Comparison between Figures 5 and 7 shows that the seismic anisotropy of the gabbro is controlled by the plagioclase fabric: $V_{P_{max}}$ lies in the foliation (magmatic flow) plane, sub-parallel to the maximum of [010] pl, and the maximum birefringence of *S*-waves is perpendicular to the foliation plane. The seismic anisotropy is low, at 0.02%, reflecting the girdle distribution of the [010] crystallographic axis and predominantly linear fabric.

Anisotropy of Magnetic Susceptibility

The AMS of most rock-forming minerals is linked to the crystallographic lattice, such that the principal susceptibility axes parallel crystallographic axes. This allows magnetic susceptibility anisotropies to be used as an easy and sensitive way of measuring preferred

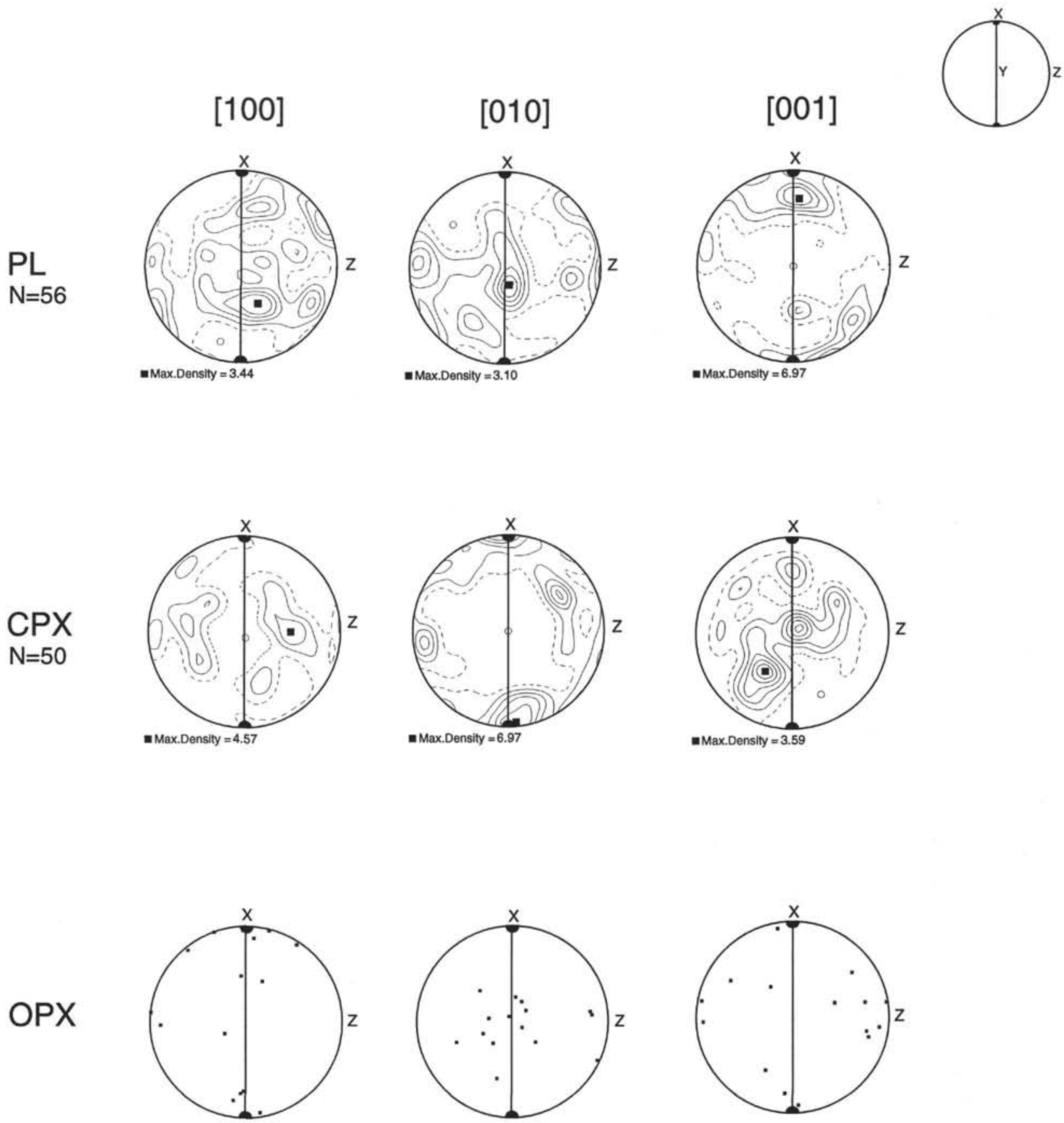

Figure 5. Crystallographic fabrics of the major phases in Sample 147-894G-12R-3 (Piece 8B, 142–150 cm). Note the strong crystallographic preferred orientation of plagioclase (PL), but lack of a strong fabric in the pyroxenes. This is primarily due to the coarse grain size of the pyroxenes, and thus insufficient number of grains on the scale of a thin section for a statistically significant number of crystallographic orientations to be measured. CPX = clinopyroxene; OPX = orthopyroxene.

crystallographic orientations in natural rocks, if it can be demonstrated that the magnetic fabric is due to minerals with a magnetocrystalline anisotropy (Hrouda and Schulman, 1990; Richter et al., 1993).

The magnetic susceptibility k_{ij} is the dimensionless proportionality factor between the magnitude of the induced magnetization J_i and the applied magnetic field strength H_j: $J_i = k_{ij} \cdot H_j$ where k_{ij} is a symmetrical second-rank tensor that can be visualized as an ellipsoid, with maximum, intermediate and minimum principal axes k_{max}, k_{int}, and k_{min}, respectively.

Richter et al. (this volume) studied the magnetic fabrics of 52 samples from Hole 894G. They show that the susceptibility of these rocks is dominated by magnetite (>95%), and that the AMS reflects the shape anisotropy of magnetite grains. Lower hemisphere equal-area stereographic projections of the principal axes of the AMS of 21 foliated gabbros are shown in Figure 8, restored to a common declination and inclination in the same way as the petrofabric measurements. It is immediately apparent (Fig. 8A) that the orientation of k_{max} (mean vector: 349.8° azimuth, 75.9° plunge, with α_{95} = 21.0° and k = 3.3), the maximum axis of the AMS ellipsoid, is identical to that of the lineation (statistically so at 95% confidence levels; cf. Fig. 6C). Axes k_{int} and k_{min} are both sub-horizontal but with a more scattered distribution, emphasizing the linear nature of the AMS fabric.

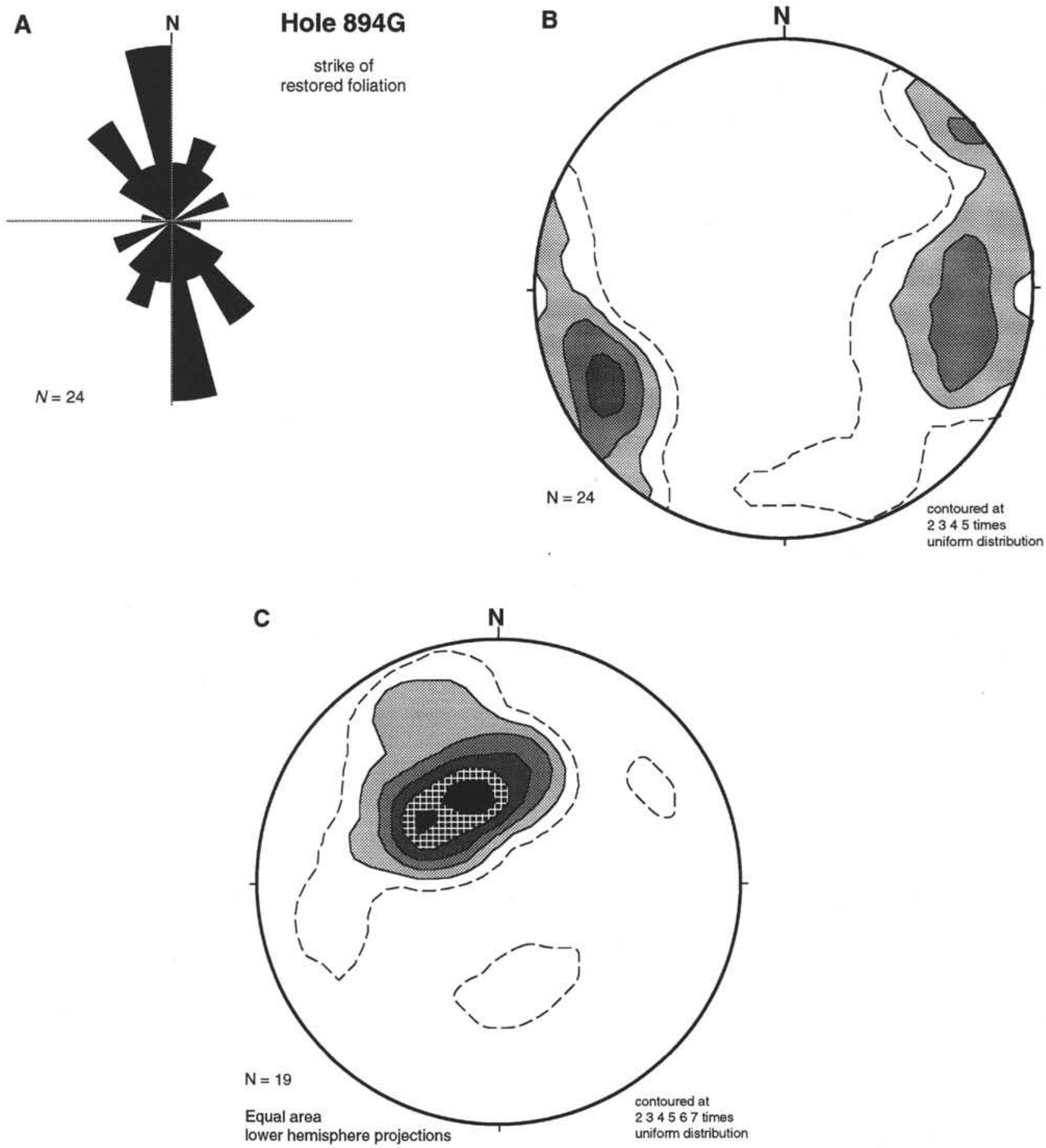

Figure 6. **A.** Bidirectional rose diagram of the restored strikes of foliation measurements from Hole 894G (reoriented assuming that the stable remanence vector of the sample plunges north, at an inclination of +4.6° (see text for methodology and justification). Note the strong preferred near-north-south trend, approximately parallel to the strike of the East Pacific Rise at which the rocks were formed. **B.** Contoured stereonet of pole to planes of the restored foliation measurements, showing the steep preferred dip of the foliations. **C.** Contoured stereonet of restored lineations. Note the strong, steeply northward-plunging preferred trend.

The AMS fabric represents the shape-preferred orientation of magnetite grains, and the steep plunge of k_{max} implies that the long axes of the grains parallel the macroscopic fabric defined by the preferred orientation of idiomorphic plagioclase crystals described above. This being so, the AMS fabric of the 31 gabbroic samples that were described as "isotropic-textured" in their shipboard description should logically be expected to show a random magnetic fabric. However, as can be seen from Figure 9, they in fact show an almost identical fabric, with k_{max} (Fig. 9A) steeply plunging and only slightly less well-clustered (mean vector k_{max} 284.0° azimuth, 68.6° plunge; α_{95} = 19.3° and k = 2.8) than the k_{max} of the "foliated gabbro" subset (Fig. 8A). This surprising result is most readily explained by suggesting that the gabbroic rocks throughout most of Hole 894G possess a magmatic flow fabric, whether or not a foliation was recognized in hand specimen (Richter et al., this volume). Given that we have found preferred crystallographic fabrics in all of the specimens examined in

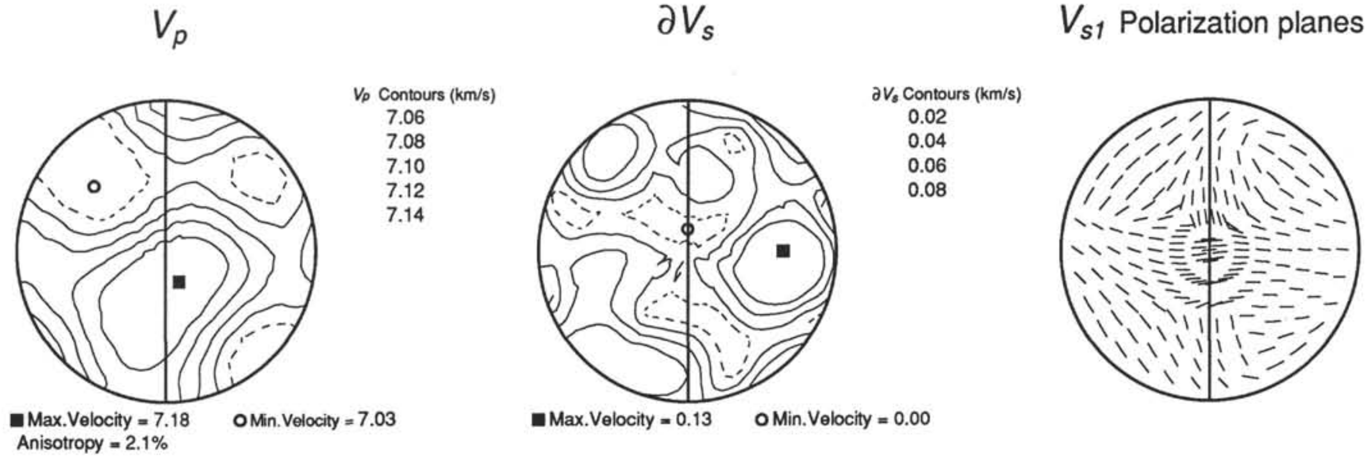

Figure 7. Anisotropy of seismic velocity in the plane Z, calculated for Sample 147-894G-12R-3, Piece 8B, 142–150 cm, following the method of Mainprice (1990). V_p = *P*-wave velocity; δV_s = *S*-wave birefringence, and V_{s1} = shear-wave polarization planes.

the laboratory, even when no foliation had been reported in the shipboard core descriptions, we believe that the apparent scarcity of flow fabrics in the Hole 894G section is simply a consequence of the difficulty in recognizing the foliation in the cores.

DISCUSSION: IMPLICATIONS OF FABRICS

In the preceding sections we have demonstrated that most of the gabbronorites and gabbros from Hole 894G possess a viscous magmatic flow fabric defined by the preferred shape of early formed anisometric crystals. Although such fabrics are well known in on-land plutonic rocks (e.g., Wager and Deer, 1939, for the Skaergaard intrusion) they have not otherwise been recognized unambiguously from ocean-floor gabbros. Identical fabrics do, however, occur in layered and massive gabbros in the plutonic section of the Oman ophiolite (Nicolas et al., 1988; Benn and Allard, 1989; see below).

The mechanisms of formation of such fabrics in gabbroic rocks have been discussed in some detail by Benn and Allard (1989) and Nicolas (1992). Early formed crystals, principally anisometric plagioclase, behave as rigid strain markers, and are oriented by flow during or after growth. For high-melt fractions, the shape-preferred orientation of plagioclase crystals is dominantly controlled by their aspect ratio; at decreasing temperature and increasing solid suspension fraction, crystal interaction predominates. At a critical residual melt fraction estimated at approximately 30% (Van der Molen and Paterson, 1979), suspension-like flow behavior changes to one approaching solid-state flow (although Nicolas [1992] suggests that magmatic or suspension flow can continue at lower melt fractions because of lubrication by liquid films between particles); between 40% and 20% melt fraction effective viscosity increases by ten orders of magnitude (Wickham, 1987; Nicolas, 1992).

For the Hole 894G gabbros, restoration of the magmatic flow fabrics to geographical coordinates shows that their orientations are consistent throughout the drilled interval. Their north-south-trending foliations parallel the strike of the EPR axis, and the steep dips both of the foliation and lineation show that the magma flow direction was predominantly vertical. The linear character of the fabric is consistent with formation by the vertical flow of crystal mush (i.e., movement of liquid plus crystals), perhaps aided by the percolation of melt through a non-rigid matrix of crystal mush (i.e., ascent primarily of the interstitial liquid). The steep, apparently primary orientations of the fabric argue against a crystal settling origin (as proposed in the theoretical models of Henstock et al., 1993; Phipps Morgan and Chen, 1993; and Quick and Denlinger, 1993), but instead imply dynamic conditions in the mid-ocean-ridge magma chamber.

Recent geophysical evidence from the EPR shows that large, mainly molten magma chambers do not exist; instead, the region of melt is restricted to a small, sill-like "melt lens" located close to the boundary between the sheeted dikes and the plutonic complex (see review in Sinton and Detrick, 1992). This melt lens may be as thin as a few tens to hundreds of meters thick, less than 1–2 km wide, but persistent along the axis for hundreds of kilometers. Beneath the melt lens is a much larger seismic low-velocity zone that extends down to the base of the crust, at which level it is on the order of 10–12 km wide (Toomey et al., 1990). This zone is interpreted as hot rock, but largely solidified (not more than a few percent melt). The nature of the base of the melt lens is not well known, and slightly higher proportions of melt are admissible there, probably in the form of a crystal mush zone (Sinton and Detrick, 1992; Fig. 10). The fabrics in Hole 894G are readily interpretable in the context of this recent geophysical evidence, and, taken in conjunction with other observations from the drilling at Site 894, suggest that the following processes may be operative.

Batches of melt delivered to the base of the crust directly beneath the axis will rise because of their lower densities (Ryan, 1993). The fabrics we have observed here suggest that magma rise is predominantly vertical, in pipes or "diapirs." The magma may react with, remobilize and incorporate previously formed crystals (Bédard, 1993) as it ascends, but will also crystallize phases of its own. As crystallization proceeds and viscosity rises, convection will become inhibited. The remaining liquid will behave more like a closed system, becoming steadily more fractionated and precipitating progressively more albitic rims on plagioclase crystals (explaining the predominantly simple normal zoning patterns). Eventually, the proportion of crystals in the mush becomes too great for them to be carried by the liquid and they interact increasingly, to form a semi-rigid and then rigid matrix, with crystals locked in alignment parallel to the magma flow direction. Continued rise of the residual liquid continues by percolation, with intercumulus precipitation. Segregation or "filter-pressing" may form the coarse-grained pegmatitic gabbronorite veins described above and by Gillis, Mével, Allan, et al. (1993) (Fig. 3). These cross-cutting veins are not chilled, and their geochemistry shows them to have basaltic compositions (Gillis, Mével, Allan, et al., 1993; T.J. Falloon, pers. comm., 1994).

Rocks and rock fabrics similar to those from Hole 894G are found in intermediate to higher levels of the plutonic sequence in the Oman ophiolite, which we believe to be a good analog of fast-spreading lithosphere. In Oman, sub-horizontal layered plutonic rocks near the base of the crust grade up into massive gabbros with magmatic foliations. These foliations are steeply dipping, have steep lineations, and trend parallel to the sheeted dike complex (Nicolas et al., 1988; Mac-

Leod and Rothery, 1992). They are directly comparable to those observed here from Hess Deep. MacLeod and Rothery (1992) traced these fabrics up into the gabbro-sheeted dike transition zone and interpreted them in terms of magma transport directly beneath the axis, associated with evacuation of the melt lens upon eruption. We predict that further study of these analogous fabrics in the Oman ophiolite (G. Yaouancq and C.J. MacLeod, unpubl. data), taking advantage of the three-dimensional outcrop and extending coverage to the whole of the upper plutonic section, rather than the 150 m available at Site 894, should test and greatly refine the hypotheses put forward here.

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Date of initial receipt: 8 August 1994
Date of acceptance: 27 April 1995
Ms 147SR-018

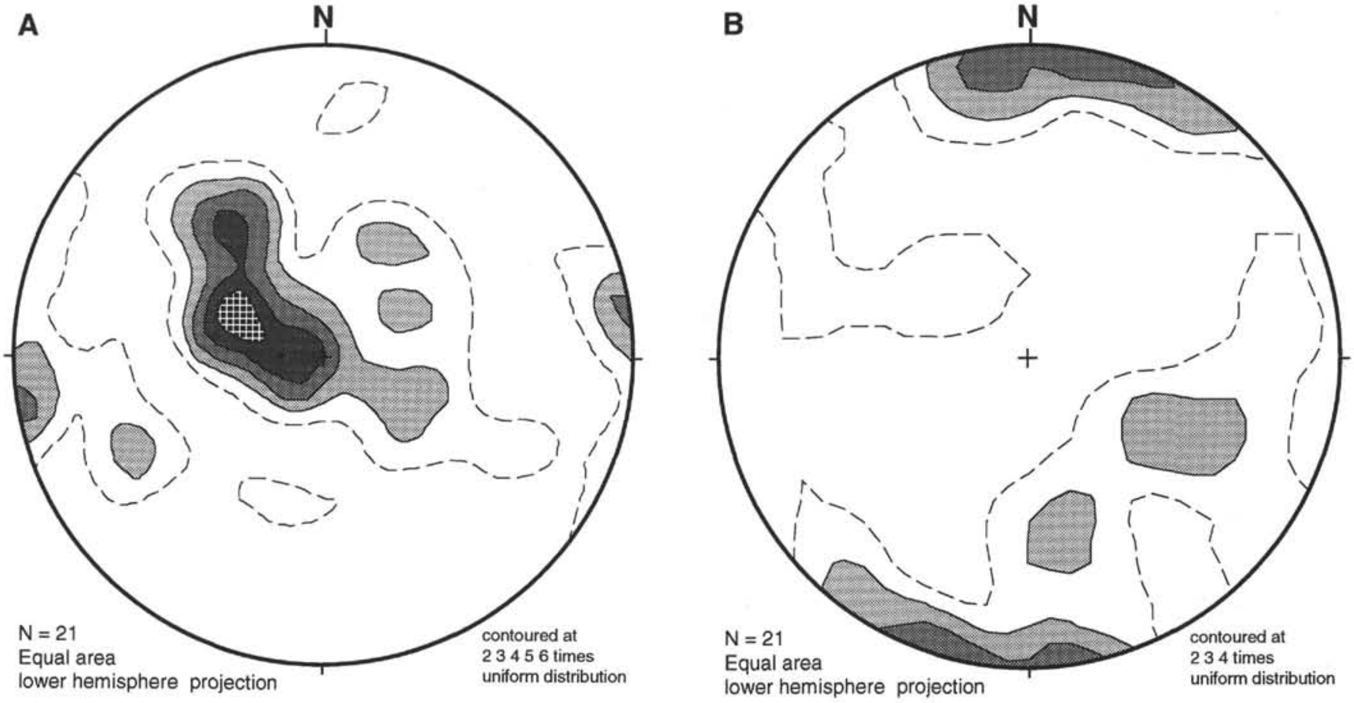


Figure 8. Orientation of the principal axes of the ellipsoid of the AMS of macroscopically foliated gabbro (*s.l.*) samples from Hole 894G, corrected for magnetic declination and inclination (from Richter et al., this volume). **A.** k_{max}. **B.** k_{int}. **C.** k_{min}. Note that k_{max} parallels the petrofabric lineation (Fig. 6C).

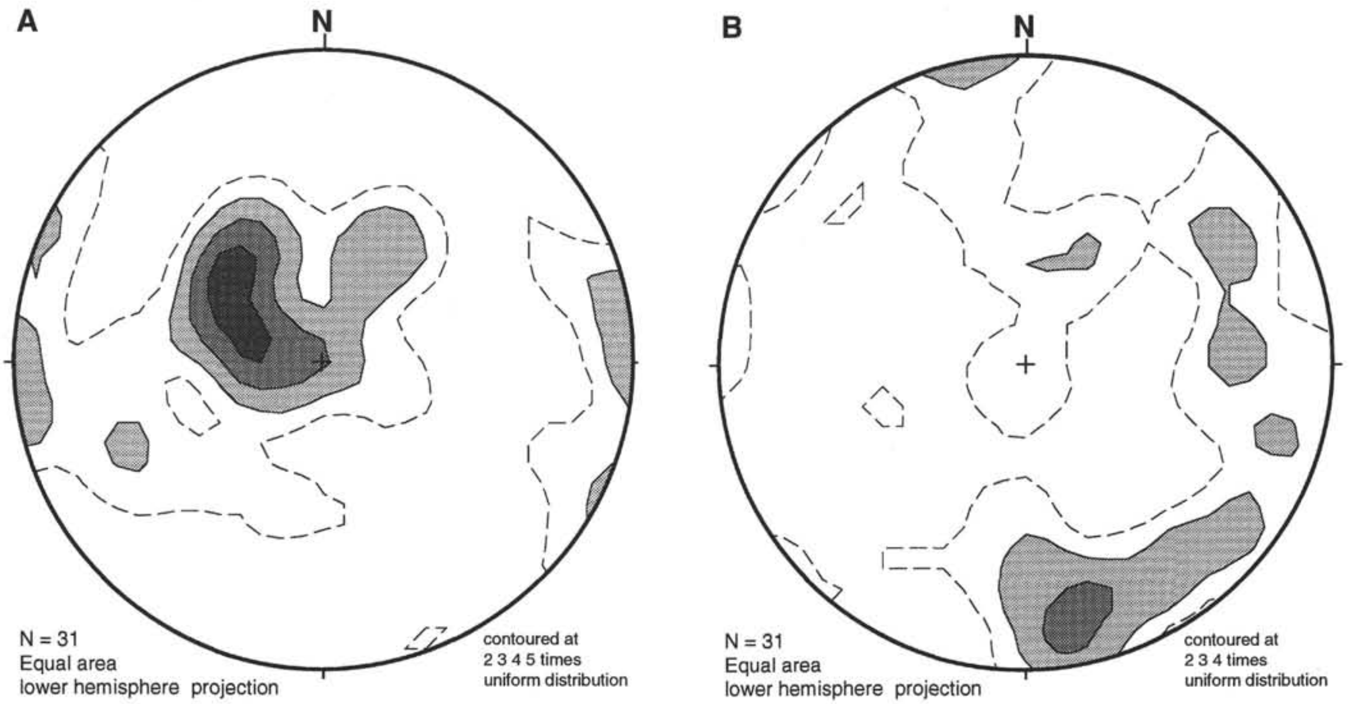


Figure 9. Orientation of the principal axes of the ellipsoid of the AMS of macroscopically isotropic gabbro (*s.l.*) samples from Hole 894G, corrected for magnetic declination and inclination (from Richter et al., this volume): **A.** k_{max}. **B.** k_{int}. **C.** k_{min}. Note the close similarity between the fabrics of these supposedly isotropic rocks and the foliated samples (Fig. 8), suggesting that all samples have a similar fabric irrespective of whether a foliation was identified macroscopically.

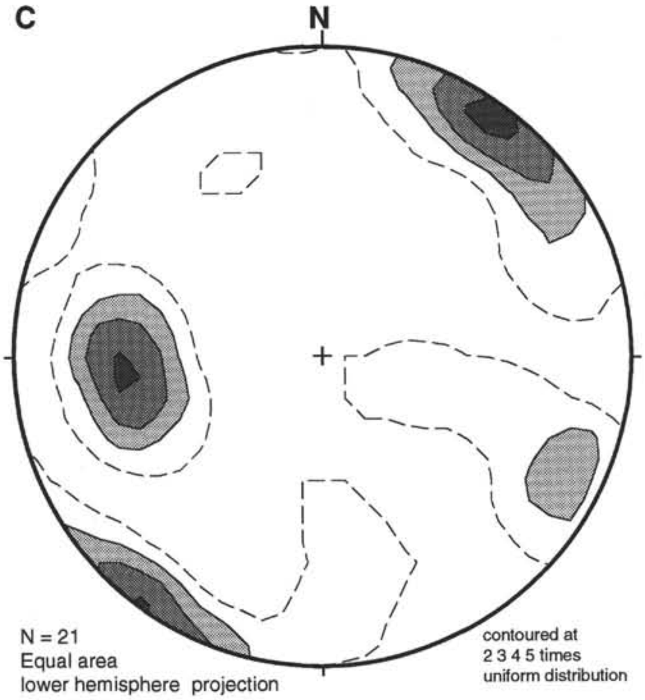
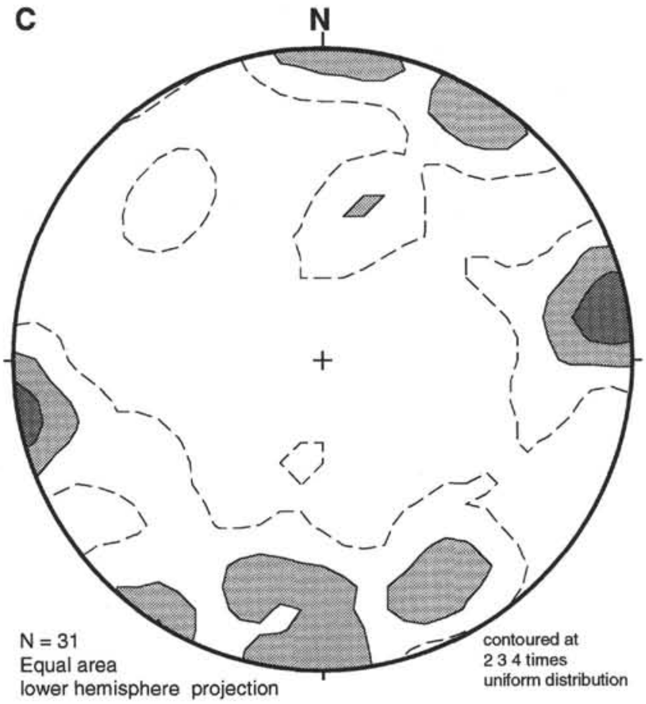


Figure 8 (continued).



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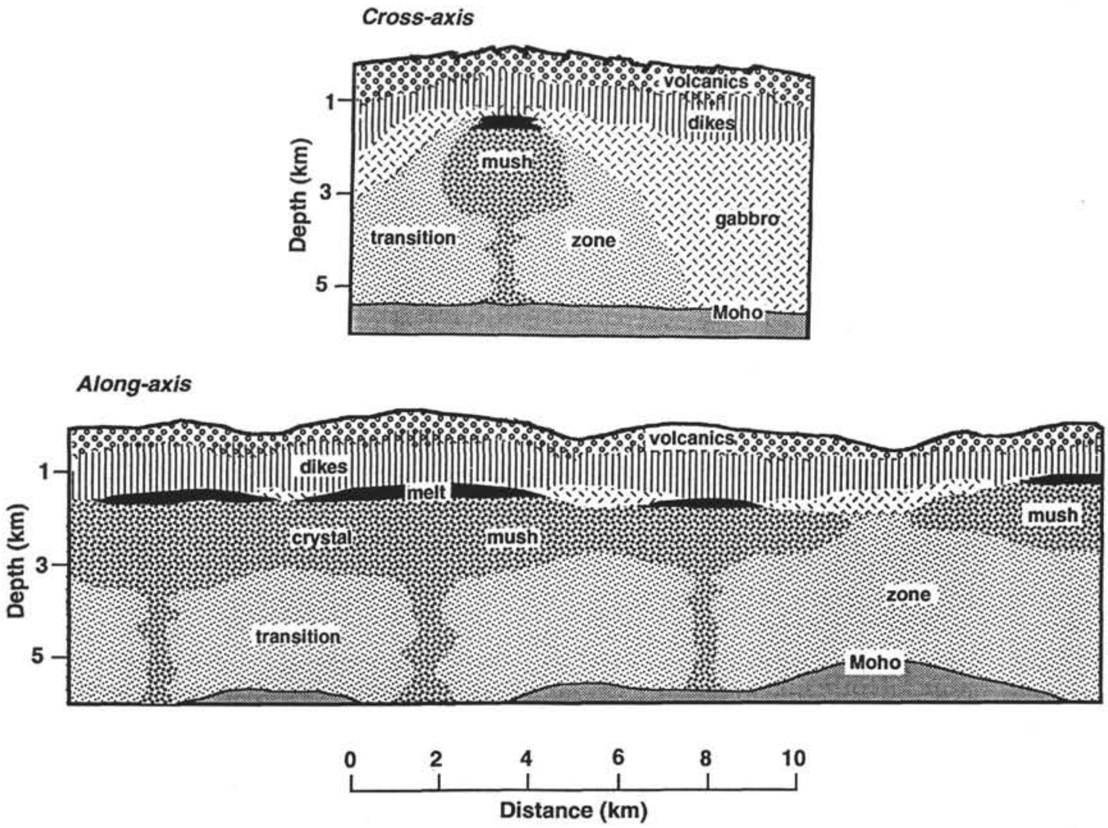

Figure 10. Interpretative model (although compatible with recent geophysical evidence) proposed by Sinton and Detrick (1992) for the morphology of the axial magma chamber, and structure of oceanic Layer 3, at a fast-spreading ridge such as the EPR. In this model (discussed in the text) a small, perched melt lens (in black) overlies a partially molten crystal mush zone within a much larger, hot but largely solid "transition zone." In this scenario the steep, ridge-parallel magmatic flow fabrics with vertical lineations documented in the sub-melt lens gabbros at Site 894 are formed by magma ascent and orientation of cumulus crystals in the sub-lens mush zone.