28. TECTONICS OF HESS DEEP: A SYNTHESIS OF DRILLING RESULTS FROM LEG 147

C.J. MacLeod, B. Célérier, G.L. Früh-Green, and C.E. Manning

We present a synthesis of the tectonics of the Hess Deep rift valley, equatorial East Pacific Rise (EPR), as deduced from structural, paleomagnetic, petrological, geochemical, and borehole geophysical data acquired during Ocean Drilling Program (ODP) Leg 147. These data show that the crustal section and underlying shallow mantle lithologies now exposed in Hess Deep were formed by seafloor spreading at the north-south-trending EPR, were then transported eastward away from the EPR ridge axis, and were influenced by extensional tectonism caused by magmatic rifting in advance of the westward-propagating Cocos-Nazca spreading center.

Seawater influx into layer 3, the plutonic portion of the oceanic crust, commenced soon after crystallization, with pervasive influx of water along randomly oriented microfracture networks and grain boundaries, mostly at temperatures of 600°-750°C. This permeability was probably created by tensile brittle failure upon subsolidus cooling and thermal contraction of the gabbro, and must have been established within several tens of thousands of years after axial magma emplacement and within a few kilometers of the ridge axis. The upper plutonic section had cooled to a temperature of ~430°C, probably a few tens of kilometers from the EPR axis and tens to a couple of hundred thousand years after axial magmatism, it became influenced by the effects of Cocos-Nazca rifting, and a dense array of east-west tensile fractures developed. Widespread access of seawater to sub-Moho levels and consequent onset of serpentinization occurred at this time.

The ODP drill sites are located on an intra-rift horst block in the north of Hess Deep, and previous workers had speculated that serpentinite diapirism was responsible for the differential uplift of this block. However, textural evidence from the drill cores suggests that serpentinitization of the shallow mantle was a predominantly static phenomenon; hence, exhumation of the lower crust and shallow mantle appears to have taken place by block faulting rather than coherent diapirism. Uplift of the intra-rift ridge was accommodated on normal cataclastic shear zones, which contain low-temperature mineral assemblages (150°-250°C), implying that uplift occurred at a relatively late stage.

Petrological data from the drill sites, fully restored to geographical coordinates, show that the intra-rift ridge has suffered significant tectonic rotation, with both a northward component of tilt and a counter-clockwise vertical-axis component of rotation. We do not have sufficient evidence to constrain unequivocally the axis or axes of rotation, but argue that compound rotations are likely in such a complex tectonic setting. In conjunction with other geophysical evidence from the Hess Deep area, we tentatively conclude that a counter-clockwise vertical-axis tectonic rotation occurred at a very early stage, perhaps in the overlap basin of the duelling propagators at 2°N on the EPR. At a later stage, and associated with the opening of the Hess Deep rift, northward tilting appears to have occurred (about a subhorizontal axis), as a result of rotational normal faulting above a south-dipping detachment surface. Later, post-detachment normal faulting was probably responsible for the isolation and differential uplift of the intra-rift ridge.

BACKGROUND

Regional Setting

Hess Deep is a 5400-m-deep fault-bounded basin, located at 2°N, 101°W, close to the boundary between the Pacific, Cocos, and Nazca plates in the eastern equatorial Pacific Ocean. The EPR and Cocos-Nazca spreading axes do not physically meet at the triple junction; instead, a small microplate (the Galapagos microplate; Lonsdale, 1988) separates them (Fig. 1). The inferred position of the tip of the active Cocos-Nazca spreading ridge is some 60 km east of the present-day EPR axis (Fig. 2), and it is propagating westward at a rate comparable to the 65-km/m.y. half-spreading rate of the EPR (Lonsdale, 1977, 1988; Hey et al., 1977; Searle and Francheteau, 1986). The Hess Deep itself lies between the EPR and the Cocos-Nazca spreading ridge, and is a westward-migrating rift valley resulting from north-south extension of the EPR flank ahead of the magmatically active Cocos-Nazca ridge; it can thus be regarded as the "intra-rift tip" (Kleinrock and Hey, 1989) of the propagating Cocos-Nazca ridge. A major horst block, 8 km wide by 25 km long, flat-topped and east-west elongate, occurs between the Cocos-Nazca axis and the northern scarp that bounds the valley (Fig. 2).

Submersible studies have shown that substantial sections of approximately 1-m.y.-old oceanic crust and shallow mantle from the EPR are exposed in the Hess Deep rift valley (Francheteau et al., 1990, 1992; Karson et al., 1992). In particular, they show that the scarp that bounds the rift valley to the south and north expose complete, relatively fresh sections through volcanics, sheeted dikes, and high-level plutonics, and that the horst, or so-called "intra-rift ridge," and adjacent deep (the Hess Deep itself) are characterized by more tectonically disrupted sections of lavas, sheeted dikes, gabbros, and shallow-mantle peridotites (Fig. 3).

Tectonic disruption of the area is complex and cannot yet be deciphered unambiguously. Two alternative models for the formation of the intra-rift ridge within the Hess Deep rift valley have been proposed by Francheteau et al. (1990). One attributes formation of the ridge to diapiric uplift of serpentinized shallow mantle, the other to detachment faulting and block rotation on listric normal faults. These models, and possible alternatives, are discussed at the end of this paper in the light of the new information from Leg 147 presented here.
Present-day Tectonic Regime From Earthquake Focal Mechanisms

The position of Hess Deep, at the tip of a propagating rift and close to the margin of a microplate, suggests that the tectonic setting and history of the area is likely to be complex (see Lonsdale, 1988). Because constraints on the present tectonic regime may help understand the recent past regime, we made a search in the published literature and Harvard CMT database for available fault plane solutions within the area of latitude 0° to 8°N and longitude 105°E to 94°E. This yielded 14 events between 1969 and 1989, which are listed in Table 1. The P, B, and T axes of each of these events are taken as an approximate indication of the principal stress directions S₁, S₂, S₃ (the maximum, intermediate, and minimum principal stress directions, respectively), an assumption that is reasonable in the vast majority of situations (Célérier, 1988), but can result in angular errors of up to 90° (McKenzie, 1969) in unlikely cases. The axis with the largest plunge defines which of the principal stresses is vertical, and the orthogonal projection of the axis with the smallest plunge on the horizontal plane defines one of the horizontal principal stress directions, S_max or S_min (the maximum and minimum directions, respectively).

For all of the events documented in the Pacific-Cocos-Nazca triple junction area, one of the principal stress directions remains within 18° of the horizontal (Table 1), thus confirming that one principal stress direction is close to the vertical (Anderson, 1905). The resulting horizontal stress directions are mapped and displayed together with the seismic nodal planes on Figure 4.

Few intraplate events are recognized: three within the Pacific plate and only one within the Cocos plate. Despite the obvious complexity of the tectonic regime, events on the Pacific plate indicate a consistent northeast-southwest maximum horizontal principal stress direction, S_max (Figs. 4, 5). Seven events occur on the Cocos-Nazca plate boundary: four of them indicate a wrench regime and three of them a normal regime; the normal regime events are located in eastern part of the area of interest. The minimum horizontal principal stress direction varies from event to event but remains within 30° of the expected north-south extension direction suggested by the Cocos-Nazca ridge trend. To decide whether this variation of direction is real or due to the misidentification of the stress direction with the P, B, and T axis requires more data and stress inversion techniques (e.g., Angellier, 1984). Three events are located on the Galapagos-Nazca boundary (Fig. 4); two of these are normal events corresponding to the Dietz Deep extensional boundary, the other is a strike-slip event corresponding to the strike-slip rift discussed by Lonsdale (1988).

All indications of present-day stress direction are compiled in Figure 5, including (stress-induced?) borehole elongation data derived from the ODP drill sites (see below; Célérier et al., this volume). Both the focal mechanisms and the regional tectonics suggest that the state of stress around Hess Deep is heterogeneous and requires a finer scale study. The absolute plate directions from Hey et al. (1977) show no simple relationship with the compressional stress direction for our Pacific or Cocos data (Fig. 5). The minimum stress orientations are also compared with the preferential enlargement directions inferred from Hole 894G downhole logging data (Fig. 5; Célérier et al., this volume). These enlargement directions are poorly defined because of poor conditions in Hole 894G (see discussion in “Downhole Logging” section below); however, it is possible that the borehole enlargements trending approximately 030° reflect some influence of the 020°-030° Cocos-Nazca S_min direction that corresponds to the event closest to Hess Deep. Similarly, the 140°-170° azimuth enlargements could reflect the influence of the nearby Galapagos-Nazca strike-slip rift stress system or the Cocos-Nazca 140°-170° S_max direction farther east; however, this would imply that the 030° Cocos-Nazca S_min direction does not affect Hess Deep. In all cases, the inferred strike slip tectonic regime would have helped borehole failure by enhancing the horizontal principal stress differences.
from slow-spreading ridges (Southwest Indian Ridge, Hole 735B; Dick et al., 1991; Mid-Atlantic Ridge at Kane: Cannat, Karson, Miller, et al., 1995), within which ductile deformation is common.

In order to determine the original stratigraphic position of the Site 894 section, Dick and Natland (1994), Natland and Dick (this volume), and Pedersen et al. (this volume) compare the compositions of the drilled gabbros with samples recovered by submersible from the north wall of the Hess Deep rift valley. They show that the drilled gabbros are similar in composition to those from the upper part of the plutonic (“layer 3”) section, but that they are less evolved than the extremely fractionated lithologies recovered from slightly below the sheeted dike-gabbro transition. These highly fractionated rocks are interpreted by Dick and Natland (1994) as marking the position of the axial melt lens; hence the Site 894 section appears to be located slightly (tens to hundreds of meters) below this level, and at an original depth of crystallization of the gabbros of between 2 km and 3 km below the seafloor.

Rock Magnetism

Paleomagnetic measurements were made on drill core samples from Site 894 during Leg 147 (Gillis, Mével, Allan, et al., 1993) and post-cruise (Pariso et al., this volume; MacLeod, Manning, et al., this volume). Demagnetization of samples by either alternating field or thermal techniques led, in most cases, to the isolation of a stable remanent magnetization vector, carried by magnetite. This is assumed to be carried by small, secondary magnetite grains formed soon after crystallization of the gabbroic section, when it cooled to the Curie temperature of 550°–580°C (Gillis, Mével, Allan, et al., 1993; Pariso et al., this volume). Inclinations of stable remanence vectors from the Hole 894G average 39.1° downward (±17.6°; N = 29; Fig. 6), which is significantly different from that expected for the latitude of the drill site; assuming that the remanent magnetization was acquired in a geocentric dipole field, the inclination should be very shallow (+4.6°). This anomalous inclination is very unlikely to be a consequence of secular variations of the earth’s field, which should cause no more than 13° of angular dispersion (McFadden and Merrill, 1975) and should not be significant in such slowly cooled rocks; neither can it be due to a change in latitude of the site (e.g., Lonsdale, 1988), or caused by deviation of the borehole (which is inclined at only 4° from the vertical between 45 mbsf and 80 mbsf; Celérier et al., this volume). The steep inclinations are therefore most readily interpreted in terms of a tectonic tilting of the section, by approximately 35°, subsequent to acquisition of its remanent magnetization close to the axis of the EPR. Any vertical component of rotation is not constrained by the magnetic data alone; and because the latitude of the Leg 147 drill sites is so low the paleomagnetic data by themselves are insufficient to determine whether the section is normally or reversely polarized. The Shipboard Scientific Party inferred a reverse polarity, by assuming the intra-rift ridge section to be similar to the ~1 Ma ages of the north and south flanks of Hess Deep at the longitude of the drill sites (Gillis, Mével, Allan, et al., 1993); Gee et al. (1992), however, report normal polarities from some lower crustal samples recovered by the ALVIN submersible. The polarity, age of the site, and axis and magnitude of tectonic rotation are discussed further in later sections of this paper.

Cataclastic Deformation

The only evidence for displacive deformation in Site 894 cores is the minor cataclasis observed in the 25-m section of Hole 894F and the uppermost 23 m of adjacent Hole 894G. This cataclastic material forms less than 1% of the total recovered core from the site. The cataclastically deformed zones are heterogeneous on a centimeter scale with respect to grain size and degree of alteration. The degree of deformation is also variable, ranging from distributed bands of protocataclastic gabbro through to foliated cataclasites and ultracataclasites with increasing strain. The cataclasites and ultracataclasites may be foliated, with “S-C” fabrics, Riedel shear arrays and offsets of brittlely disaggregated clasts indicating normal shear senses in every observed instance (Gillis, Mével, Allan, et al., 1993). Microscopically, the fabrics are characterized by grain size reduction by microcracking of primary igneous phases, producing sub-rounded to angular porphyroclasts set in a fine-grained clast-clay matrix dominated by corrensite, a regular layered chlorite-smectite mineral (Füh-green, Plas, and Dell’Angelo, this volume). The proportion of this matrix in-
Figure 3. Bathymetry and disposition of outcrop in the vicinity of the intra-rift ridge, Hess Deep, as deduced from submersible and dredging operations (after Francheteau et al., 1990).

Table 1. Compilation of fault plane solutions near the Pacific-Cocos-Nazca triple junction.

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Note: S1 is the index of that of the principal stress direction S1, S2, S3 that is closest to vertical; S2 is the index of that of the principal stress direction S1, S2, S3 that is closest to horizontal; S3-plunge is the plunge of the principal stress direction S1, S2, S3 that is closest to horizontal.
Figure 4. Cocos-Nazca-Pacific triple junction regional map (Mercator projection with Clarke's 1866 ellipsoid). Bathymetry contours at 3000 m are from Mammerickx and Smith (1994). Horizontal principal stress directions are inferred from the focal mechanisms given in Table 1 (maximum principal stress direction = $S_1$; intermediate principal stress direction = $S_2$; and minimum principal stress direction = $S_3$, corresponding to inward-pointing arrows, bar, and outward-pointing arrows, respectively). The nodal planes are shown together with the P, B, and T axes.
creases with increasing strain. Porphyroclasts include plagioclase (now completely altered), opaques, and amphibole, and also chlorite and prehnite. In a few instances, veins of chlorite-smectite were observed that had been sheared into the foliation. In turn, the cataclastic zones are cut by veins filled with chlorite/prehnite and zeolite/calcite, indicating that fluid infiltration continued after deformation. The presence of corrensite in the matrix of the cataclasites limits the maximum temperature of formation to less than 250°C, and oxygen isotope data (Früh-Green, Plas, and Dell'Angelo, this volume) suggest temperatures continuing down as low as 150°C.

**Veins and Fractures**

In marked contrast to the rarity of displacive deformation, brittle fracturing and fracture filling is extremely common in Site 894 cores. Manning and MacLeod (this volume) identify 1040 macroscopic veins in Hole 894G cores, at a density of 0.21 veins per meter. Virtually all nonmineralized fractures were observed. The mineralogies of vein fill in Hole 894G present a time-integrated record of the physico-chemical evolution of hydrothermal circulation in the upper part of the EPR (layer 3) plutonic section, documenting the cooling of the section from the moment of initial subsolidus penetration of seawater, through to its exhumation and exposure on the seafloor. Manning and MacLeod (this volume) recognize three principal mineralogical vein types in Hole 894G: amphibole veins, subdivided into microscopic and macroscopic types; chlorite veins, subdivided into chlorite–calc-silicate and chlorite–smectite subtypes; and zeolite–calcite veins.

**Microscopic Amphibole Veins**

Microscopic amphibole veins are the oldest veins recognized, and are responsible for grain-scale alteration of the gabbros, accounting for 10% to >50% of the modal mineralogy. They take the form of an interconnected network of tiny (average 17 µm wide) cracks filled by green, blue-green, and olive-green calcic amphibole, and occur pervasively throughout the Hole 894G section. Manning and MacLeod (this volume) show that more than 80% of grain boundaries were affected by the fluid flow at the time that this microfracture network was formed. They find that amphibole composition varies with the primary mineralogy of the vein wall, suggesting that material transport distances were short, and consistent with rapid reaction rates and low fluid fluxes. Presence of secondary clinopyroxene in association with the microscopic amphibole veins implies extremely high temperatures of metamorphism: Manning and MacLeod (this volume) calculate temperatures as high as 750°C, with most mineral compositions implying amphibolite facies temperatures of 600°C–750°C.

**Macroscopic Amphibole Veins**

Macroscopic amphibole-filled veins cross-cut their microscopic precursors in all cases. They are light green to blue in color, usually...
Zeolite-calcite Veins

Chlorite–Calc-silicate and Chlorite–Smectite Veins

Chlorite-bearing veins are by far the most common in Hole 894G, with 987 veins recorded (Manning and MacLeod, this volume). These veins are characterized by chlorite-lined vein walls and usually by vein centers filled either with calc-silicates (epidote and prehnite) or smectite. A distinction between the mineralogies of vein center-fill was made during description of the cores, but this is largely arbitrary: a continuum of compositions is recognized, with some veins containing calc-silicates and also clay minerals as a late-infilling phase. Chlorite–calc-silicate veins are, however, predominantly (though not exclusively) older than the chlorite–smectite veins. Chlorite veins of both types cut the amphibole veins where cross-cutting relationships are preserved. Brecciated wall-rock clasts and evidence for multiple generations of infill attest to repeated opening and filling, locally under high pore-fluid pressures.

Chlorite veins are characterized by continuous, straight-sided, planar features up to 3 mm in width, and are often associated with alteration halos of white albited plagioclase. They often form parallel sets of closely spaced veins cutting across the cores. Chlorite–calc-silicate veins (N = 404) are dark green to black in hand specimen, often with white prehnite centers. Chlorite–smectite veins (N = 583) are characterized by soft green, yellow or brown smectites in vein centers. The core is often broken across these planes of weakness. Late zeolites and calcite commonly fill residual pore space.

Temperature estimates for the formation of the chlorite–calc-silicate vein assemblage (Früh-Green, Plas, and Dell’Angelo, this volume) range as high as approximately 400°–450°C. Estimates of 300°–400°C are consistent with the assemblage chlorite + albite + actinolite in the alteration haloes. Veining and alteration must have continued down to 150°–250°C, as determined from the compositions of chlorite or calcite fill, but rarely both. Neither are common with 987 veins recorded (Manning and MacLeod, this volume).

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Operational difficulties and very poor hole conditions in all Leg 147 boreholes conspired to restrict downhole logging operations in Hess Deep to a short interval of Hole 894G (between 45 mbsf and 80 mbsf; Célérier et al., this volume). The Formation MicroScanner (FMS) downhole imaging tool was deployed in an attempt to map the distribution and orientation of fractures on the borehole wall, and to relate the structural information thus obtained to the vein orientation data (oriented relative to the magnetic remanence direction). The FMS tool generates electrical images of portions of the borehole wall, mapping out small-scale variations in resistivity as detected by a series of electrodes mounted on pads that are pressed against the wall (Ekstrom et al., 1987). The tool carries a three-axis magnetometer, thus allowing dip and strike features to be oriented reliably to geotaxonomic coordinates. Because the earth’s magnetic field typically contributes all but a few percent of the total field, directions determined by the downhole magnetometers are not normally affected significantly by rocks with moderate magnetic intensities (see Goldberg et al., 1992). The theoretical resolution of the FMS tool is approximately 0.5 cm although, in practice, considerably smaller features are discernible if the resistivity contrast is sufficiently large, as, for example, between a low resistivity water-filled fracture and a high resistivity lithified rock such as the gabbros encountered here.

The FMS data from Hole 894G are of very poor quality because of the extreme roughness and enlargement of the borehole. Nevertheless, MacLeod et al. (1995) and Célérier et al. (this volume) were successful in detecting a large number of low-resistivity, sub-planar to planar features on the FMS images. There is little doubt that these represent fractures, probably open and water-filled. In Figure 8, fractures are plotted as poles to planes in lower hemisphere, equal area stereographic projections, oriented relative to true north. These data yield a preferred pole to plane of 354.4°, 39.7° (N = 177), corresponding to a plane dipping at 50.3° southwards, with strike of 084.4° (Fig. 8). The marked preferred east-west strike is notable, being parallel to the trend of the Cocos-Nazca rift and of the intra-rift ridge at Site 894.

Core-log Integration

The veins measured in the core are predominantly planar (lined) fractures from the center of the borehole. The low-resistivity features identified on the FMS images are believed to be planar fractures on
the borehole wall. Because of the poor quality of the FMS images, it is not possible to match the features on a 1:1 basis; however, the FMS fracture data considered together may be compared with the core fracture (vein) data from the same (45–80 mbsf) depth interval (MacLeod et al., 1995, Célérier et al., this volume). The distributions of fractures on both cores and logs are very similar: both show marked preferred orientations, with similar dips, and a maximum strike direction ~15% of the total. There must be little doubt that the same features are being compared. The difference between the two is that whereas the FMS data are recorded relative to true north, the core data are measured relative to the stable magnetization direction, which was acquired when the gabbro section cooled, and which need not be north. Matching the two data sets (Fig. 9) implies that the stable magnetic remanence of the Hole 894G gabbros points toward the north-northwest. As discussed earlier, this cannot readily be explained in terms of secular variation, and is more readily explicable as a vertical-axis component of rotation either of ~30° counterclockwise (if normal polarity, i.e., declination points toward north) or ~150° clockwise (if the rocks are of reversed polarity). The former is obviously preferred in the absence of any other geological evidence for such large rotations, despite the previous inference of reversed polarity on the basis of its supposed ~1 Ma age (Gillis, Mével, Allan,
The core-log integration presented here, supported by
the preliminary findings of Gee et al. (1992), strongly suggests that
the Site 894 section is normally polarized, and hence acquired its
magnetization either during the Brunhes Chron (i.e., <0.73 Ma), or
Jaramillo (0.91–0.98 Ma), Olduvai (>1.6 Ma), or older subchrons.

SITE 895
Lithostratigraphy

Site 895 is located 9 km to the east of Site 894, on the southern
slopes of the intra-rift ridge, on a small north-trending spur leading
up to the main part of the ridge (Gillis, Mével, Allan, et al., 1993). Six
holes were drilled at three locations, at depths of between 3820 m and
3692 m. Substantial penetration was made only at Holes 895C (37.9
m), 895D (93.7 m), and 895E (87.6 m). Serpentinized tectonite
harzburgites and dunites were the most abundant rock type recov-
ered, and were intercalated with troctolites, olivine gabbros, gabbros,
and minor basaltic dikes. Proportions of these rock types varied from
hole to hole, with harzburgites predominating in all holes except Hole
895E. In this hole dunite was the most common rock type recovered,
often associated with interstitial plagioclase and/or clinopyroxene.
Progressive increase in the proportion of these interstitial phases
leads to formation of troctolite and gabbro segregations in the cores;
these are interpreted as melt impregnation/percolation channelways
(Gillis, Mével, Allan, et al., 1993) located close to the crust-mantle
transition zone. Early, high-temperature, pervasive ductile deform-
ation fabrics are visible in harzburgites and dunites from Site 895.
These are shown by Boudier et al. (this volume) to have been formed
by flow under asthenospheric conditions beneath the EPR ridge axis.

Rock Magnetism

Inclinations of stable magnetic remanence directions from partially
serpentinized harzburgites and dunites at Site 895 are deviated signif-
ificantly away from the axial dipole inclination of +4.6° (Gillis,
Mével, Allan, et al., 1993; Kelso et al., this volume; MacLeod, Man-
nings, et al., this volume). As discussed earlier for Site 894, this is
most readily interpreted in terms of a tectonic rotation or rotations of
the samples subsequent to the acquisition of their primary remanen-
ces. Demagnetization characteristics of the peridotite samples indicate
that the magnetization is carried by magnetite, which was almost cer-
tainly formed during serpentinization. The median inclination for
Site 895 is 36° downward (Fig. 10), very similar to the mean inclina-
tion deduced from Site 894, and implying that Site 895 has also been
subjected to a rotation with horizontal-axis component of this magni-
tude. No logging of Site 895 was possible, and therefore no external
reference is available to constrain any vertical-axis component of ro-
tation; nevertheless, the implication of the Site 895 magnetic inclina-
tions is that the intra-rift ridge has been tilted northward (or rotated
with a component of northward tilt) in a relatively coherent manner.

Mean inclinations from Holes 895B, 895C, and 895E are similar
to the median inclination; the data from Hole 895D, however, are
widely dispersed, ranging from −60° to +60° (Kelso et al., this vol-
ume), thus biasing the mean for the site as a whole. This dispersion
of inclinations may indicate that Hole 895D was drilled through a
rubble pile (albeit one only slightly disrupted, because of the apparent
coherence of the stratigraphy of the section); alternatively, noting the
position of Hole 895D close to a break of slope at the foot of the intra-
Veins, Fractures, and Serpentinization

The shallow mantle sequences at Site 895 record multiple stages of fluid infiltration, brittle fracturing, and veining under greenschist to zeolite facies conditions (Früh-Green, Plas, and Lécuyer, this volume; Mével and Stamoudi, 1994, and this volume). Metamorphism is dominated by hydration reactions and static replacement, resulting in mineral pseudomorphs and coronitic textures. As in the Site 894 gabbro section, displacive deformation is rare and tends to be concentrated in local, 1–5-cm-wide, penetrative shear zones in the gabbroic rocks (Früh-Green, Plas, and Lécuyer, this volume). Brittle fracturing and fracture filling is observed throughout the Site 895 core, with a larger density of discrete veins occurring in the ultramafic lithologies.

The harzburgites and dunites at Site 895 are extensively serpentinized (50%–100%). Microscopically, these rocks are relatively undeformed and have typical pseudomorphic mesh-textures after olivine, indicating that the serpentinization process was essentially static. They are cut by multiple generations of fracture-filling veins. Lizardite and chrysotile are the dominate vein-filling minerals, with lesser amounts of chlorite, antigorite, magnetite, brucite, tremolite, talc, zeolite, and clay in varying proportions (Gillis, Mével, Allan, et al., 1993). Discrete fractures and microfractures filled with aragonite, commonly associated with incipient brecciation of the serpentinitized wall rock and an abundance of tremolite, represent the latest veining event. Vein morphologies vary from broad, planar, and continuous to thin, irregular, and discontinuous. Crack seal textures, indicative of multiple episodes of opening and mineralization, are often observed. In contrast to Site 894, no consistent relationships between vein mineralogy, morphology, relative age, and orientation (see below) were observed. On the basis of stable isotope data on bulk serpentine separates, vein serpentines, and serpentine-magnetite mineral pairs, Früh-Green, Plas, and Lécuyer (this volume) suggest that the main phase of serpentinization was related to veining and occurred at the relatively high temperatures of 400° ± 50°C. They argue that in addition to seawater, magmatic volatiles associated with late magmatic activity and possibly H₂ and CH₄ released during serpentinization were significant components of the hydrothermal fluids. Oxygen isotopes indicate the latest stage of veining occurred at ambient temperatures in the presence of pure seawater.

In the tectonite and gabbroic rocks within the peridotites, progressive, static alteration from greenschist to zeolite facies conditions is documented by presence of distinct coronas, pseudomorphic textures, and vein infill. The less altered samples contain olivine, diopside, anorthite, tremolite, chlorite, and prehnite. Incipient rodingitization is associated with an increase in the amounts of prehnite, hydrogrossular, zeolites (predominantly thomsonite), smectitic clays, mica, and Al and Fe hydroxides. The extent of alteration and distribution of lower temperature mineral assemblages is related to an increase in the density of mineral-filled microfractures and macroscopic veins (Früh-Green, Plas, and Lécuyer, this volume). Veins in the mafic lithologies vary from discontinuous, filled microfractures to discrete networks of veins up to 1 cm thick. Filled microfractures are most common and form sinuous, anastomosing networks with variable thickness, length, and mineralogies. Both monomineralic and composite, zoned veins and veinlets are observed. Vein fillings include diopside, chlorite, tremolite, calcic plagioclase, prehnite, talc, serpentine, magnetite, zeolite, clays, rare epidote and calcite. Multiple, cross-cutting fracture filling phases are common, with variable infill mineralogies depending on the host mineral that is cut. The mineral assemblages in the mafic rocks and veins are more diagnostic of alteration temperatures than those in the peridotites: Früh-Green, Plas, and Lécuyer (this volume) and Mével and Stamoudi (this volume) estimate temperatures initially as high as 450°–600°C, but that most alteration (and greatest flux of seawater) occurred when temperatures were in the approximate range 350°–400°C. These authors consider this main alteration "event" to be synchronous with the principal period of fracturing and chlorite vein formation at Site 894.
Veins Orientations

Orientations of veins at Site 895 restored relative to the stable magnetic remanence direction and inclination ($N = 187$) are significantly more scattered than at Site 894, with larger numbers of shallowly dipping veins and vein networks (Fig. 11; see also Gillis, Mével, Allan, et al., 1993). Note that data corrected only in declination are even more scattered because of the near-random inclinations of samples from Hole 895D. A preference is observed among steeply dipping veins for a general west-northwest orientation relative to the magnetic declination direction. This is directly comparable with the Hole 894G veins restored in the same way. Although much of the veining at Site 895 is probably caused as a result of volume changes associated with serpentinization, the presence of a significant number
of veins parallel to the dominant chlorite vein set in Hole 894G suggests that some role for far-field tectonic stresses in allowing initial water access is likely.

**DISCUSSION**

**Tectonic Evolution of Intra-rift Ridge**

**Exhumation of Mid-crustal Levels**

Leg 147 drilling verified the first-order hypothesis that the crustal section and underlying shallow mantle lithologies now exposed in Hess Deep were formed by seafloor spreading at the north-south trending EPR. This lithosphere was transported eastward away from the EPR ridge axis and became influenced by extensional tectonism caused by amagmatic rifting in advance of the westward-propagating Cocos-Nazca spreading center. The combined structural, borehole geophysical, paleomagnetic, petrological, and geochemical studies from Leg 147 operations summarized here contribute significantly to our understanding of the general processes by which the above occurred.

Seawater influx into layer 3, the plutonic portion of the oceanic crust, commenced soon after crystallization, and while the host was at a very high temperature (estimated at up to 750°C; Manning and MacLeod, this volume). Pervasive influx of water along randomly oriented microcrack networks and grain boundaries gave rise to significant mineralogical and isotopic alteration of the section, mostly at temperatures of 600°–750°C (Manning and MacLeod, this volume; Lécuyer et al., this volume). This permeability was probably created by tensile brittle failure upon subsolidus cooling and thermal contraction of the gabbro as it was transported away from the ridge axis (e.g., Lister, 1974). Comparison with numerical simulations of heat flow and material transport (e.g., Phillips Morgan and Chen, 1993; Henstock et al., 1993) suggests that this early fracture permeability must have been established within several tens of thousands of years after axial magma emplacement and within a few kilometers of the ridge axis (here spreading at 65 km/yr half rate) (Manning and MacLeod, this volume).

At the point at which the upper plutonic section had cooled to the upper greenschist facies (a temperature of approximately 450°C) it became influenced for the first time by the effects of Cocos-Nazca rifting. Development of a dense array of east-west, steeply dipping, tensile (mode I) fractures occurred almost certainly in response to the north-south, far-field extensional stresses expected for Cocos-Nazca spreading. The moment at which this changeover occurred is less well constrained by theoretical studies than for the higher-temperature veining; however, it may be estimated at several to tens of kilometers away from the axis, and tens to a couple of hundred thousand years after axial magnatism. This is roughly comparable to the distance east of the present-day EPR axis that the first east-west lineaments are observed today (approximately 25 km, from GLORIA sidescan sonar records: Searle and Francheteau, 1986).

The observation of lower-temperature phases in the centers of veins whose walls are lined by higher-temperature phases suggests that the east-west fractures were not sealed, but maintained their permeability, presumably upon continued extensional deformation. All subsequent fluid circulation and cooling of the section (documented down to approximately 150°C) appears to have been controlled strongly by this permeable fracture network.

Cataclastic shear zones (east-west striking, moderately southward-dipping, and with normal senses of motion) are almost certainly related to the differential uplift of intra-rift ridge. Metamorphic temperatures in the range 150°C to no more than 250°C indicate that the cataclastic deformation occurred relatively late in the history of the EPR gabbros. Eckhardt and Puchelt (this volume) suggest a minimum unroofing age of 50 ka for the inter-rift ridge, based upon the observed thickness of sediment and known sedimentation rates for the area. A recent microearthquake study of the Hess Deep area indicates that the intra-rift ridge is seismically very active (Porras et al., 1995).

**Exhumation of the Shallow Mantle**

The processes leading to exposure of the sub-EPR shallow mantle are not as well constrained as for mid-crustal levels. Nevertheless, Früh-Green, Plas, and Lécuyer (this volume) and Mével and Stamosdi (1994, and this volume) document minor amounts of early alteration at temperatures of 450°C to 600°C, followed by larger scale influx of seawater down to Moho level and consequent widespread serpentinization, probably at 350°–400°C. This was almost certainly aided, if not caused, by a system of deep, east-west fractures associated with Cocos-Nazca rifting, probably at a similar time to that inferred above for the crustal section, and at a distance estimated at approximately 30 km from the EPR axis (Mével and Stamosdi, 1994).

In the peridotites, further permeability was created by volume changes associated with serpentinization, which near-random process gives rise to a much greater variability in observed vein orientations.

Previous workers (Francheteau et al., 1990) hypothesized that serpentine diapirism was responsible for uplift of the intra-rift ridge, and that serpentinized peridotite samples recovered by submersible from the vicinity of Site 895 were partly responsible. However, the preservation of pseudomorphic mesh textures in all serpentinized ultramafic lithologies observed during Leg 147 operations, and of a coherent mantle fabric overprinted by the serpentinization (Boudier et al., this volume), suggests that the serpentinization was a predominantly static phenomenon. Exhumation of the shallow mantle on the seaﬂoor is therefore likely to have been by faulting of coherent blocks rather than incoherent diapirs. This is supported by velocity data from beneath the intra-rift ridge (Wiggins et al., 1993), which suggest that high velocities typical of mafic lower crustal rocks (and hence not serpentinite) underlie the ridge.

**Origin of Tectonic Rotations**

The anomalously low directions of restored paleomagnetic data from the Leg 147 drill sites provide convincing evidence for the tectonic rotation of lower crustal and shallow mantle lithologies exposed on the intra-rift ridge within Hess Deep. Oriented samples of sheeted dikes from the northern and southern walls of Hess Deep, collected by Hurst et al. (1994) using the ALVIN submersible, indicate that some rotation has also occurred at upper crustal levels elsewhere within the rift valley. These dike samples, too, show anomalously steep inclinations (mostly positive), and have declinations that lie predominantly within the southeastern quadrant.

The anomalous magnetic inclination data from the two ODP drill sites imply that the intra-rift ridge has been subjected to a horizontal-axis component of tectonic rotation of approximately 30°–40° toward the north, probably as a relatively coherent block. Comparison of core and downhole logs allows us to identify a 30° counterclockwise horizontal-axis component of rotation at Site 894. It is not possible to determine unequivocally whether the vertical and horizontal components of rotation here identified are part of a single rotation inclined about an inclined axis, or whether they result from composite rotation episodes. It is not possible, either, to find a uniquely constrained rotation axis without other, external structural criteria. On purely geometrical grounds, assuming the minimum possible amount of rotation about a single axis that can account for the difference between the expected and observed directions of the magnetic vector, a rotation of approximately 30° counterclockwise, about a moderately east-plunging axis, can be derived (Fig. 12). We doubt whether this axis has any geological significance; it certainly does not accord with the kinematic information from veins and cataclasites from Site 894.
dated this. What we do not know for certain is the original orientation required shortly after cooling, and that the chlorite veins certainly post-
generically incapable of accommodating further strain (cf. Nur et
al., 1986).

In this scenario the high-angle normal fault (now forming the southern
isolation and uplift of the intra-rift ridge was most likely to have been
lower-angle detachment surface, as proposed by Francheteau et al.

crustal and shallow mantle section occurred above a south-dipping
Hess Deep rifting. A possible cross-section drawn across the intra-rift
ridge, incorporating the tectonic tilting and not requiring serpentinite
serpentinization (interpreted above as relating to the influx of wa-
ture, given this complexity, it is equally likely that the dikes may also
have suffered compound rotations, and a similar history of early ver-
tation to their inferred present-day orientation are not uniquely constrained;
hence, if a single tectonic rotation is responsible, its axis must lie on the
great circle outlined by the dashed line. The minimum rotation required to
move the remanence direction from its original to its present position may be
calculated as approximately 44° clockwise about a moderately eastward-
plunging axis (indicated by the white square). See text for discussion.

(for pure normal slip on east-west striking structures). To accommo-
date such a rotation a highly oblique slip direction would be imparted
on planes with this orientation, and this is not observed.

If certain assumptions are made, however, some constraint can be
placed on the tectonic processes that gave rise to the rotation or rota-
tion. This constraint comes from a consideration of the timing of rota-
ation. At Site 895, the peridotites must have acquired their rema-
nance upon serpentinization (and consequent liberation of magnetite; Kelso et al., this volume); hence the tilting of the section
to the mean +40° inclinations) must necessarily have post-dated
the serpentinization (interpreted above as relating to the influx of water
to Moho levels at the time of Cocos-Nazca rifting). The northward
tilting or component of tilting of the intra-rift ridge may therefore be
related to the predominantly extensional tectonics associated with
Hess Deep rifting. A possible cross-section drawn across the intra-rift
ridge, incorporating the tectonic tilting and not requiring serpentinite
diapirism, is presented in Figure 13C. Northward rotation of the
crustal and shallow mantle section occurred above a south-dipping
low-angle detachment surface, as proposed by Francheteau et al.
(1990, their model “B”; Fig. 13B); however, we instead propose that
isolation and uplift of the intra-rift ridge was most likely to have been
achieved by down-to-the-south displacement of the detachment by a
later, high-angle normal fault, possibly aided by footwall uplift. In
this scenario the high-angle normal fault (now forming the southern
scarp of the intra-rift ridge) would have been initiated upon the con-
tinuation of Cocos-Nazca rifting after the detachment had become
geostructurally incapable of accommodating further strain (cf. Nur et
al., 1986).

At Site 894 we know that the stable magnetic remanence was ac-
quired shortly after cooling, and that the chlorite veins certainly post-
dated this. What we do not know for certain is the original orientation

of the chlorite veins. If the assumption is made that the chlorite vein
set was formed with an east-west strike (i.e., the same as observed at
the present day from the FMS data), which is reasonable in the con-
text of Cocos-Nazca-Hess Deep rifting, then the vertical axis compo-
nent of rotation must have predated chlorite vein formation; the dif-
fERENCE in azimuth between the vein strikes and the magnetic decli-
nation direction is ~60°, and this should not change during rotation.

Taking the above arguments to their logical conclusion, we are
left with the premise that a ~30° counterclockwise vertical axis rota-
tion occurred at a very early stage (within a few kilometers to tens of
kilometers of the ridge axis; see above), prior to formation of the
chlorite vein set (which records temperatures of up to 450°C). This
was followed by a later (post-serpentinization) northward tilting of
the whole intra-rift ridge by 30°-40° (when the mantle section was
cooler than 350°-400°C). While this model might appear to be con-
trived, there is some geological evidence in its favor. As outlined
above, the cataclasites and mode I veins imply pure normal extension
across the Cocos-Nazca-Hess Deep rift, rather than the oblique ex-
tension required if both vertical and horizontal components were to
be accommodated about a single, inclined axis such as that calculated
above (see Fig. 12). Furthermore, substantial areas of north-north-
west-oriented abyssal hill fabrics may be identified on multibeam
bathymetry and GLORIA data in the overlap basin between the “du-
elling” overlapping spreading centers at the present-day EPR due
west of Hess Deep and, moreover, in several relict areas of north-
northwest striking abyssal hill lineations stranded within Hess Deep
itself (Fig. 2). These north-northwest–trending areas have been inter-
preted by Lonsdale (1988, 1989) as remnants of originally north-
south EPR seafloor that were rotated counterclockwise by the well-
known process of lithospheric transfer in the overlap basin between
the duelling, right-stepping overlapping spreading centers/propagat-
ing rifts on the EPR at 2°N, directly west of Hess Deep.

We tentatively conclude that a two-stage model is appropriate to
explain the anomalous magnetization directions identified from the
restored Leg 147 paleomagnetic data. A very early counterclockwise
rotation of approximately 30° about a steeply plunging axis is
thought to have taken place as a result of spreading-related complex-
ities at the EPR axis. At a later stage, when the lithosphere now ex-
posed on the intra-rift ridge had been transported eastward some tens
of kilometers into the Hess Deep rift, it was tilted toward the north,
probably above a south-dipping detachment fault. Uplift, exposure of
the lower crust and shallow mantle and isolation of the horst block
within the rift valley was probably effected by post-detachment nor-
mal faulting. Serpentinite diapirism need not have played a signifi-
cant role.

With the complex geometry of rifting in Hess Deep it is improba-
brable that the model proposed here for the intra-rift ridge can be applied
directly to the sheeted dikes sampled by Karson et al. (1992) and
Hurst et al. (1994) from the north and south walls of Hess Deep; how-
ever, given this complexity, it is equally likely that the dikes may also
have suffered compound rotations, and a similar history of early ver-
tical-axis rotation close to the EPR followed by later deformation
associated with Hess Deep rifting could provide an alternative equally
table to the models discussed by Hurst et al. (1994).

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Tectonics of Hess Deep

**Figure 13.** Interpretative two-dimensional sections across the central to northern part of Hess Deep, at longitude 101°32'W. (A) and (B) are from Francheteau et al. (1990); (C) is proposed here on the basis of structural and paleomagnetic data from Leg 147. All sections are drawn with no vertical exaggeration, use realistic oceanic crustal thicknesses, and account for the observed topography and surface geology (as determined from submersible traverses; Francheteau et al., 1990). Model (A) implies that basal crustal layers have been uplifted by serpentine diapirism and isostatic readjustment, whereas model (B) invokes low-angle normal faulting and rotation above a low-angle detachment, with only limited serpentine diapirism to explain uplift of the intra-rift ridge. The model preferred here (C) is a variation of model (B) in that it, too, invokes northward rotation (from Leg 147 paleomagnetic data) and southward translation of crustal blocks above a low-angle detachment horizon; however, because of the evidence for static serpentinization at Site 895 (this paper) and high velocities below the intra-rift ridge (Wiggins et al., 1993), diapirism is not believed to be the principal mechanism responsible for uplift of the ridge. Isolation and uplift of the intra-rift ridge can instead be achieved by internal deformation of the supra-detachment fault blocks (probably greater than shown here) and either "breakaway" of the fault block to the south of the ridge by means of relief on the detachment or, more likely, by later high-angle normal faulting (the intra-rift ridge is still seismically very active [Porras et al., 1995]). Uplift of the intra-rift ridge may have been aided by flexure upon unloading of the footwall; any buoyancy-related effects are likely to be in the form of uplift of coherent fault blocks only. Note that balancing of the cross-section is not necessarily required because of the likelihood of some strike-slip movement of lithospheric material into or out of the plane of the section.