64. BASEMENT ROCK SYNTHESIS: GEOCHEMISTRY, PETROLOGY, PHYSICAL PROPERTIES, AND PALEOMAGNETISM

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INTRODUCTION

The general objectives of Leg 34 were to: (1) study the oceanic crust, (2) study the metalliferous sediments, and (3) study the tectonic and sedimentary history of the Nazca plate. This chapter synthesizes results of shipboard and shore-based studies aimed at the first objective. These studies attempted to determine the age of oceanic crust at three sites and compare them with ages established from regional magnetics, paleontology, and the age-depth relationship. Sonic velocities were determined for comparison with regional seismic surveys. Paleomagnetic measurements of basement were made to establish latitudinal motions of the plate and to evaluate the origin of oceanic magnetic anomalies. The eruptive and cooling history of the crustal basalts were studied through petrographic and phase-chemical techniques. The chemical and isotopic character was determined to enable comparison with basalts produced on spreading ridges elsewhere, to evaluate possible changes of source mantle chemistry over the period of time (15-40 m.y.) represented at the three sites, and to add to our understanding of basalt-seawater exchange during alteration.

This Initial Report volume contains an unusually comprehensive collection of studies of basement rocks. This synthesis is drawn almost completely from these studies. I have not attempted to provide references for everything that appears in the synthesis; the reader is urged to consult the individual papers for details and first-hand interpretations.

RADIOMETRIC AGES

The age of ocean crust formation is usually inferred from the age of the overlying sediment. This is generally unsatisfactory since it does not help resolve the general question of the extent to which the oceanic crust is composed of igneous rocks intruded off the ridge at later times. Direct age determination of igneous crustal rocks has proved difficult because of the commonly altered nature of the rocks. The relative freshness of Leg 34 basalts thus makes them good candidates to evaluate the question of off-ridge volcanism.

K-Ar ages were measured on samples from Sites 319 and 321, and a fission track age on a glass sample from Site 320. Ages range from 8 to 24 m.y. at Site 319 and from 12 to 44 m.y. at Site 321. Much of this scatter in ages can be directly related to alteration, as, for example, in Seidemann's study (this volume) where several pairs of adjacent samples of variable alteration were analyzed. The altered portions gave significantly younger ages. Even considering samples identified as relatively fresh, the ages at Hole 319A range from 13 to 24 m.y., and there seems little basis for choosing one over another. In the two studies where Ar^{40}/Ar^{39} plateau ages were determined for Site 319, one gave 24 ±4 m.y. (Reynolds, this volume) and the other gave 17 m.y. (Hogan and Dymond, this volume). These are in fair agreement and suggest that the most probable age for Site 319 basement is in the range 17-24 m.y. Since alteration generally lowers apparent ages, it seems likely that the basement age at Site 319 is somewhat older than the basal sediment age (~15 m.y.). There may thus be a small time interval involved between the time of crust formation and the beginning of sediment accumulation. The radiometric age would also agree with the age of crust formation of 20-25 m.y. based on the Sclater depth-age curve.

At Site 320, a fission track age of 25 ±3 m.y. was obtained on fresh glass (Mitchell and Aumento, this volume). This age is slightly younger than the basal sediment age at this site, but the difference is probably not analytically significant.

At Site 321, conventional K-Ar ages on the freshest samples range from 27 to 44 m.y. Only one study produced a good plateau by Ar^{40}/Ar^{39} (Hogan and Dymond, this volume) with an age of 42 m.y. Thus the most probable basement age for Site 321 is in the range 40-45 m.y. which is in good agreement with those determined from the overlying sediments (39-40 m.y.), the Sclater age-depth curve (38 m.y.), and the well-defined magnetic anomaly pattern (39 m.y.).

Thus, at two sites, 319 and 321, it is fairly clear that we are not sampling off-ridge volcanism, but materials which were essentially produced on the ridge. The data, however, also illustrate the difficulties of dating ocean crust materials, and for sites where alteration is more pronounced than these, age data should be considered with considerable caution.

PETROLOGY AND GEOCHEMISTRY

The radiometric age data indicate fairly well that basalts from at least two of the three Leg 34 sites were produced at a spreading ridge. All of the chemical and isotopic data are in agreement with this, showing patterns at all three sites which are characteristic of mid-ocean ridge basalts (MORB). The basalts at all three sites are tholeiites of the "depleted" variety. That is, rare earth patterns show depletion of the light rare earths relative to the heavy rare earths; the elements Rb, Cs, and Ba are depleted relative to K (leading to K/Rb ratios of 800-2000, and K/Ba ratios of 70-300); Sr concentrations are low (80-140 ppm); and Sr^{87}/Sr^{86} isotopic ratios are low (0.7025-0.7028). This combination of chemical parameters uniquely distinguishes MORB from basalts of any other tectonic environment.

Within the general category of MORB, however, the Leg 34 samples show interesting and consistent differences among the three sites. Table 1 lists the average composition for each of the three sites. None of the samples contains more than 10% normative olivine, and all Site 319 samples are quartz-normative samples. These differences are also seen in the FeO/MgO ratios, with the upper basalts from Site 319 being least differentiated. The grouping of these basalts and some trends in their chemistry may be seen in Figure 1 and Figure 2. Thompson et al. (this volume) proposed a fivefold division of Leg 34 basalts, which is shown in Figures 1 and 2. For these elements (and most others), the upper part of the Site 319 basement appears most primitive or undifferentiated or unevolved, and the Site 321 basement appears the opposite. Both types are present at Site 320, though they are not so widely separated in composition. The lower part of the Site 319 basement falls in an intermediate position to these others. The high degree of Fe and Ti enrichment of Site 321 basalts (FeTi basalts) is evident from these figures.

There is no agreement as yet on the interpretation of the trends shown (Figures 1 and 2). Thompson et al. and others (this volume) show that the major element chemistry of group IV (and presumably group V) can be derived from group I by a fractional crystallization model involving removal of plagioclase, pyroxene, and minor olivine. Corliss et al. (this volume) suggest that the groups may reflect partial melting and source parameters rather than differentiation, since the intragroup trends for some elements do not coincide with the overall intergroup trend. The trace element and isotopic data cannot be explained solely by a differentiation process.

The lead isotope ratios of basalts from Sites 319 and 321 are very similar (Unruh and Tatsumoto, this volume), but the strontium isotope ratios are different at Sites 319 and 320. Also it is very difficult to produce large changes in trace element ratios such as La/Sm and K/Ba without large degrees of crystallization of minerals such as plagioclase, pyroxene, and olivine. On the other hand, the depletion of elements (i.e., Ni, Cr, and Co) in Site 321 rocks relative to Site 319 rocks probably requires some crystallization of olivine or pyroxene. Also, there is a small negative Eu anomaly at Site 321 which would be compatible with minor crystallization of plagioclase. Though a resolution of this problem must await further model studies, it seems that a "combination" model may be appropriate. In this model there would be variations in certain trace element and isotopic parameters (La/Sm, K/Ba, Sr^{87}/Sr^{86}) between the mantle sources from which Site 319 basalts and Site 321 basalts were derived, without large variations in major element composition. Then the observed variations in major element chemistry would be generated by crystallization processes, probably in shallow magma chambers under the ridge.

Another interesting aspect of the chemical data is the comparison of Leg 34 basalts with recent MORB dredged from active ridges. The field of MORB is outlined in Figures 1 and 2 along with fields representing selected previous DSDP legs. With respect to MORB, Leg 34 basalts (especially those from Site 321) appear more evolved or differentiated, for example, containing higher FeO (up to 15%), TiO_2, and P_2O_5. They all lie along similar trend lines, however, suggesting that the chemical variations in these basalts are produced by similar processes. FeTi basalts (such as those from Site 321) are not common on modern active ridges, but have been found in older crust on previous DSDP legs (for example, Legs 6, 9, 16, and 26). Kempe et al. (this volume) have noted the general tendency for drilled basalts to be more quartz normative than MORB from active ridges and suggest that highly fractionated basalt may be typical of older ridges. R. Hart (this volume) has shown by analysis of all DSDP basalt chemical data that there is clear evidence the older ridges produced basalt of different composition than active ridges. Some of this is an alteration effect and will be discussed later, but for some alteration-resistant elements (such as Ti) there is a clear correlation of concentration with age. The differences in major elements between Sites 319 and 321 are in this same direction, for basalts differing in age by 25 m.y.In this case, rocks from both sites are relatively unaltered, and it is clear that the differences are not alteration related. It is interesting to note that both Ti concentration (Nisbet and Pearce, 1974) and the fraction of normative quartz (Bass, 1971) have been correlated with spreading rate. This might suggest faster spreading rates during formation of Site 321 basalts.

Along with the bulk chemical data, a number of contributors to this volume have studied the petrography and mineral chemistry of these basalts. The basalts show a complete range in texture from glassy and variolitic basalt to medium-grained diabase; only a few 321 basalts are notably vesicular. Plagioclase and olivine are present as phenocrysts in basalts from Sites 319 and 320, and smectite occurs as pseudomorphs after olivine phenocrysts in those from Site 321. Clinopyroxene is present as microphenocrysts only in basalts from Sites 321 and 319 and is always accompanied by plagioclase and olivine. Clinopyroxene is reported as phenocrysts from other Leg 34 sites, but is probably large late ophitic grains in these cases. Titanomagnetite occurs in all samples; Cr-rich spinel is found only in Hole 320B (3-1, 120-125 cm, and 4-1, 144-147 cm). The general lack of spinel, normally an early crystallizing phase in basalts, supports the finding that most of the Leg 34 basalts have

TABLE 1
Comparison of Leg 34 Basalts With Fresh Ridge Basalts and Selected DSDP Basalts From Previous Legs

	Site 319	Site 320	Site 321	MORB[a]	DSDP[a]
SiO_2	49.78	50.40	49.72	49.92	49.09
TiO_2	1.81	1.72	2.28	1.46	1.55
Al_2O_3	14.36	14.98	13.18	16.08	15.48
Fe_2O_3	3.38	5.19	3.67	1.49	3.77
FeO	7.38	4.80	9.35	8.04	5.96
MnO	0.18	0.16	0.20	0.17	0.18
MgO	6.85	6.63	6.06	7.75	6.72
CaO	11.51	11.03	10.34	11.21	10.66
Na_2O	2.92	2.87	2.69	2.79	2.73
K_2O	0.19	0.21	0.21	0.17	0.58
P_2O_5	0.13	0.16	0.20	0.15	0.19
H_2O	1.15	2.21	1.71	0.77	2.65
No. of Samples	29	7	14	49	62

[a]Averages taken from R. Hart, this volume.

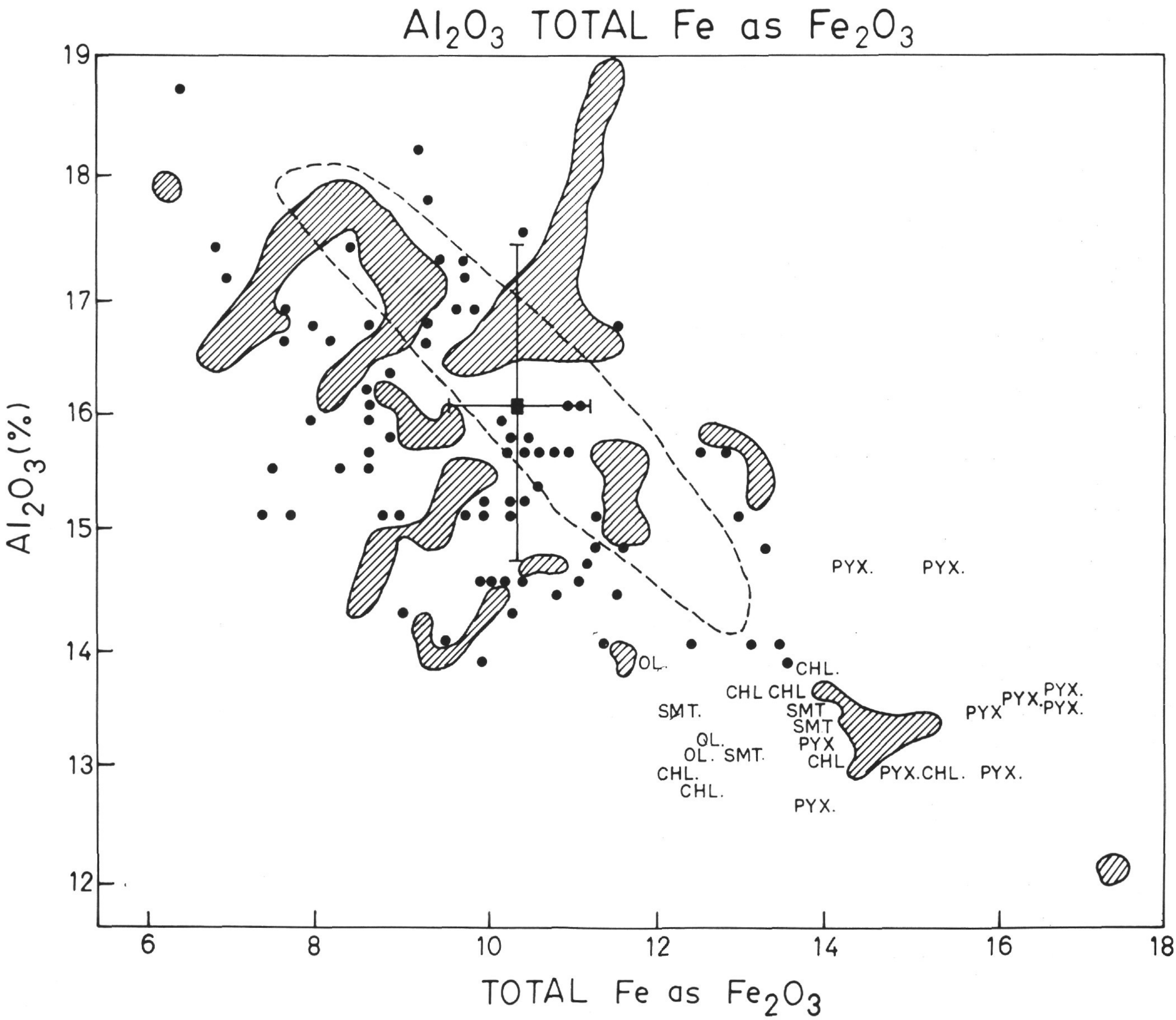

Figure 1. *Plot of Al_2O_3 versus total Fe for Leg 34 basalts, compared with the compositional field of dredged basalts and selected basalts from other DSDP legs (for details of sample selection for TOPS Group, see R. Hart, this volume). The Leg 34 basalts are divided into the five groups as designated by Thompson et al., this volume.*

been somewhat differentiated. The groundmass of all samples is made up of plagioclase, pyroxene, and magnetite, with considerable smectite alteration product. K-feldspar and quartz were reported as interstitial material in samples from Hole 319A (Bunch and LaBorde, this volume). Other minor phases reported are ilmenite, calcite, and sulfide.

The pyroxenes (see Mazullo et al., this volume) from Leg 34 basalts are aluminous (up to 5.7%) augites (Wo_{46-36} En_{48-15} Fs_{6-49}) and pigeonites (Wo_{9-15} En_{69-57} Fs_{22-28}). The pigeonite occurs in samples from Sites 319 and 321, generally as discrete grains in the groundmass and as sectors within the augite crystals. The content of Al + Ti + Na + Fe^{3+} ranges from 5% to 26% in the augites and about 3% in the pigeonites. This content of "other" elements decreases in the augites from Sites 319 and 321 with crystallization (Fe enrichment), whereas it shows no clear trend during crystallization in the augites from Site 321. The augites from Site 319 are more calcic than those from Sites 320 and 321 and are more strongly zoned. The Site 321 pyroxenes, as might be expected in a FeTi basalt, tend to be lower in Al than the basalts from the other sites. However, they are also depleted in Ti, despite the high Ti content of the basalt in which they crystallized. It is possible that FeTi basalts may be recognized, even when extensively altered, through the chemistry of unaltered pyroxenes. The trend of variation in "other" elements in Site 321 pyroxenes suggests at least two separate periods of pyroxene growth. The general strong chemical zonation in pyroxenes from all sites is indicative of fairly rapid cooling.

The compositions of plagioclase phenocryst cores from Site 319 range from An_{60} to An_{80}; compositions are similar at Site 320, though the range is narrower (An_{70}-An_{76}); the compositions at Site 321 are considerably less calcic (An_{64}-An_{70}). There seems to be no overall

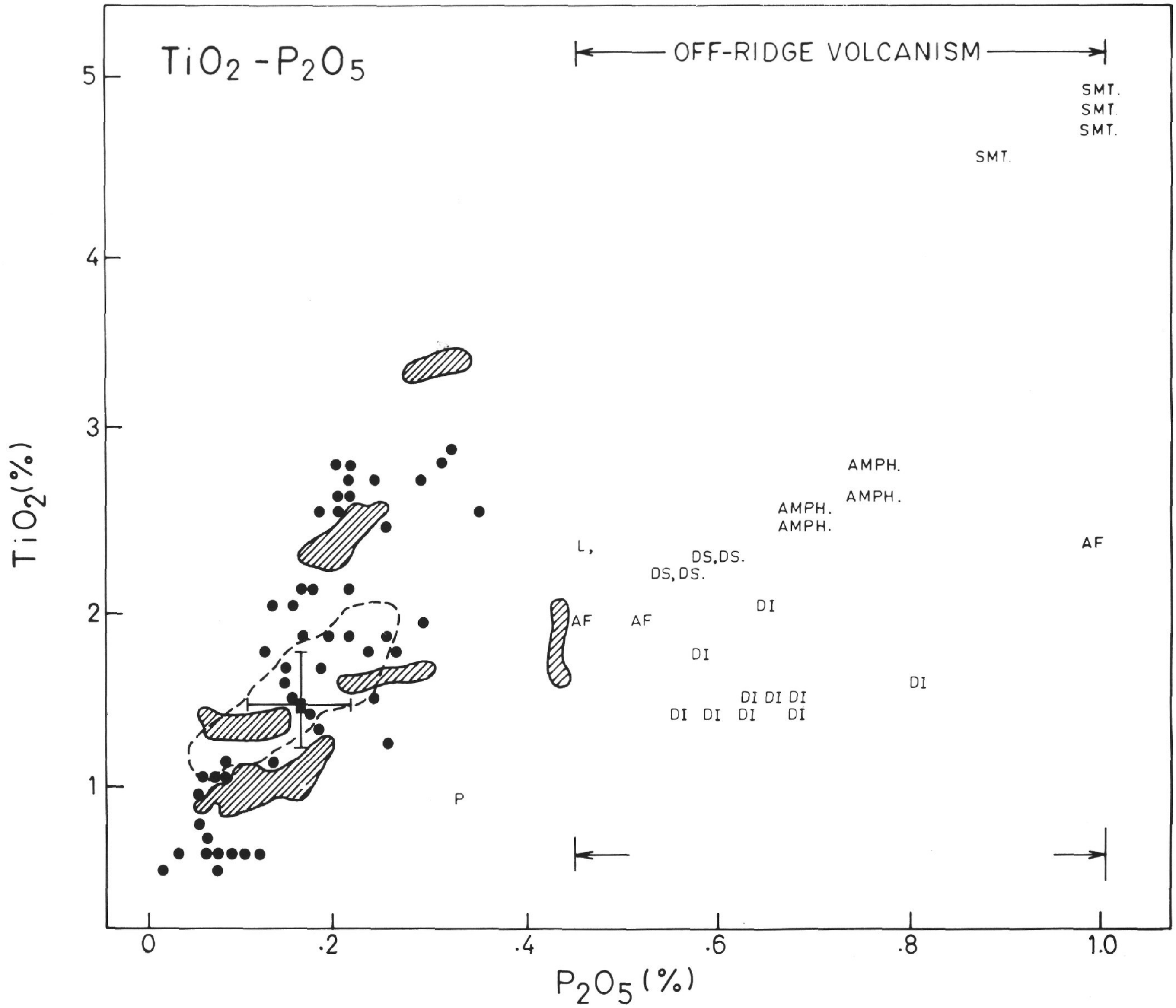

Figure 2. *Plot of TiO_2 versus P_2O_5 for Leg 34 basalts, compared with the compositional field of dredged basalts and selected basalts from other DSDP legs (for details of sample selection for TOPS Group, see R. Hart, this volume). The Leg 34 basalts are divided into the five groups as designated by Thompson et al., this volume.*

trend of phenocryst composition within different cooling units or as a function of depth within the core. However, the composition does vary from one cooling unit to another. Generally, the phenocryst rim compositions overlap the compositions of groundmass plagioclase. In most samples Fe and Fe/(Fe + Mg) increase in the plagioclase with increasing Na content (Sample 319A-6-1, 145-148 cm is one exception). As with the pyroxenes, the plagioclase data suggest several stages of crystallization with overall rapid cooling of the units.

Unaltered olivines are common only in rocks from Site 319, where their compositions range from Fo75 to Fo87. Some olivine settling is apparent in the thicker cooling units of Site 319, with unzoned olivine in the middle of the units and zoned olivines nearer the base.

ALTERATION

In most respects, the alteration of Leg 34 basalts appears to be a result of low temperature interaction with seawater. Muehlenbachs (this volume) found that the oxygen isotope ratio of fresh basalt glasses was in the normal range of MORB, whereas the holocrystalline rocks became increasingly higher in O^{18} content as a function of degree of alteration. Relatively pure smectites separated from two samples (319A-2-1, 135 cm and 321-14-3, 80-100 cm) gave O^{18} values of 25 per mil, about what would be expected for a clay mineral in equilibrium with cold seawater. Various rock samples ranged from 4% to 11% smectite content, based on a mixing model involving the O^{18} values of fresh glass and pure smectite. There is no overall difference in the degree of alteration between samples from Sites 319 and 321, despite the significant difference in age. Isotopic studies of calcite in alteration veins (Seyfried et al., this volume) point to a formation temperature for the calcite of about 7°C. In addition, absence of anhydrite in the veins limits the vein formation temperature to less than 60°C. Studies of sulfur isotopes (Field et al., this volume) in vein sulfides show a large range in isotopic composition and suggest complex relationships, but, if formed by reaction with seawater, would indicate temperatures of less than 150°C. Other evidence that seawater was involved in the alteration process is the increase of Sr^{87}/Sr^{86} ratio in altered relative to fresh basalt (S. Hart, this volume).

The general assemblage of vein minerals is smectite-calcite-sulfide-mica and hematite. The vein smectite is different in chemical composition from smectites in metalliferous sediments, but has sulfur, oxygen, and hydrogen isotope ratios similar to those of sedimentary smectites. The sulfides are marcasite and almost pure pyrite, with less than 1/10 the Cu found, for example, in pyrites associated with ophiolite ore bodies. The host rock next to veins does not show an appreciable increase in visible alteration as the veins are approached.

Although all of the Leg 34 basalts contain smectite alteration, the chemistry is relatively unaffected by this alteration. The Fe_2O_3 contents and Fe_2O_3/FeO ratios (Table 1) are higher than in fresh MORB, but are still low compared to most DSDP basalts. Similarly, the water contents reflect some alteration (total H_2O averaging 1.0% at Site 319, 1.6% at Site 320, and 1.2% at Site 321), but are significantly lower than those of most other DSDP basalts. Definite alteration effects show up in some of the trace element contents; for example, Li contents are high in the more altered samples (Thompson et al., this volume), and Rb and Cs contents and Sr isotope ratios are high in one altered sample compared to adjacent fresh glass (S. Hart, this volume).

There are a number of perplexing problems concerning the state of alteration of the Leg 34 basalts. For example, these basalts are relatively fresh compared to other DSDP basalts of similar age, and, while this was initially taken as possible evidence for younger off-ridge volcanism, the radiometric age data clearly show that the basalts drilled on Leg 34 were formed essentially on a spreading ridge. A related problem is why the Site 321 basalts, which are 25 m.y. older than the Site 319 basalts, are not appreciably more altered than the Site 319 basalts. One possible explanation is that the extent of alteration is limited by the amount of easily altered material (glass, olivine, etc) which is present. If coarse-grained rocks (such as those from Sites 319 and 321) have less of this "alterable" material, then rocks from previous DSDP legs, which are mostly finer grained, would show more alteration effects. This anomaly could also be explained by assuming that alteration of ridge basalts occurs rapidly and is slowed down after being covered with sediment. There is some evidence that alteration occurs rapidly—for example, the U-Pb isochron age for Site 321 basalts, which probably dates the time of U addition to the basalt during seawater alteration (Unruh and Tatsumoto, this volume), is about 40 m.y., in reasonable agreement with the formation age for these basalts. Furthermore, there is a suggestion at Site 319 of an age gap between the age of formation and age of first sedimentation of as much as 5 m.y., thus allowing more time for alteration to progress at Site 319 relative to that at Site 321. While this is a possible explanation for the similar states of alteration at Sites 319 and 321, it does not explain the lower degree of alteration at both sites compared to other DSDP sites of similar age. Also, the analysis of alteration effects at previous DSDP sites (R. Hart, this volume) in terms of variables such as age, sediment thickness, bottom relief and water depth suggests that sediment cover does not inhibit alteration, and that the combined effect of water depth and sediment thickness (both of which are time related) may even enhance alteration. There appears also to be a topographic effect, in the sense that alteration progresses more rapidly in areas of high relief. If the Leg 34 sites were of unusually low relief compared to other DSDP sites, some of the above anomalies might be reconciled, but this does not appear to be the case to any significant degree. It is true that the Site 319 and 321 sections contain numerous massive basalt cooling units, and these may tend, not only to slow alteration within the unit, but also to protect the underlying basalt from full interaction with circulating seawater. At this stage we have not investigated the alteration at other DSDP sites with respect to the lithology of the basalt sequences. It is apparent that the nature of the alteration process in the oceanic crust is rather imperfectly understood and is in need of more intensive study.

MAGNETIC PROPERTIES

Eight different groups were involved in the measurement of magnetic properties on Leg 34 basalts. Only the highlights of these studies will be given here, as a comprehensive summary of the magnetic work has been prepared by Ade-Hall and Johnson (Review of Magnetic Properties, this volume).

In terms of magnetic properties, two basic types of materials were identified. One was massive coarse-grained basalt containing fairly large (15-30μ) stoichiometric or little oxidized titanomagnetite. The other was fine-grained pillow basalt containing altered, highly cation-deficient titanomagnetite. When altered, the magnetic properties of the first type would approach those of the second type. The first type of basalt is characterized by strong remanence (up to 0.01 Gauss), strong induced magnetization (approaching the intensity of the remanence component), and an ability to acquire large viscous magnetizations. In situ magnetization of this material will be dominantly viscous, having the direction of the ambient field. The second type of basalt is characterized by weak remanence (0.001-0.002 Gauss), distinctly weaker induced magnetization, and poor ability to acquire viscous magnetization. The in situ magnetization of this material will be dominated by the remanent magnetization and thus will have either the direction of the original magnetizing field or some combination of directions depending on later chemical remagnetizations. There is no apparent trend in the magnetic properties of these two types of basalt with age, at least over the 25-m.y. age difference represented by Sites 319 and 321.

The net magnetization of a basement section will thus depend on the relative proportions of these two types of basalt. In general, these basalt types do not have sufficient magnetic intensity to generate the observed oceanic magnetic anomalies in a layer as thin as 500 meters; a thickness closer to most of layer 2 would be required. Fine-grained but fresh basalt, which is only found very close to spreading centers, is the only known type of submarine igneous rock capable of generating typical anomaly amplitudes with layer thicknesses of as little as 500 meters.

At all three Leg 34 sites, the major control of magnetic properties is related to low temperature oxidation of titanomagnetite. With few exceptions, there is no evidence in the titanomagnetites of Leg 34 basalts for high temperature oxidation. The low temperature oxidation produces cation-deficient titanomagnetites, and there is a strong correlation between degree of cation deficiency and a decrease in NRM intensity, initial susceptibility, and saturation magnetization.

In principle, cleaned NRM inclinations on basalt can be used to estimate latitudinal motions of the Nazca plate. However, the internal consistency of cleaned paleomagnetic inclinations at each site suggests that only short time intervals (perhaps 1000 yr or less) are represented by the recovered sections. At Sites 320 and 321, the basalt inclinations are in good agreement with the inclinations measured for the basal sediments, suggesting a reasonable estimate for the geomagnetic latitude. In contrast, at Site 319, the basalt inclination is significantly different from the basal sediment and may reflect either cooling of the basalt during atypical geomagnetic field conditions or a tectonic rotation of the section. In any case, plate motion cannot reasonably be obtained from the Site 319 results. Overall analysis of the paleomagnetic inclination data suggests a minimum latitudinal motion of the Nazca plate of 5° or less over the last 40 m.y. This result is consistent with the present due-eastward absolute motion of the plate.

PHYSICAL PROPERTIES

Acoustic velocities were measured by two groups (Salisbury and Christensen, this volume; Schreiber, this volume) by somewhat different techniques, with results only slightly different. The range of values observed at the three sites for compressional and shear velocities, and bulk density are as follows:

	V_p	V_s	P
319	5.9-6.3	3.2-3.5	2.85-3.01
320	5.3-6.1	2.9-3.3	2.72-2.90
321	5.3-6.1	2.9-3.3	2.72-2.95

These velocities are given for a pressure of 600 bars; the compressional velocities are in general a few percent higher than the values measured onboard at 1 atmosphere using the Hamilton frame.

Compared to other DSDP basalts, the Leg 34 basalts show unusually high velocities and densities, with a fairly narrow range of values. This is consistent with the general observation that the Leg 34 basalts are relatively fresh, as both velocity and density decrease markedly during submarine weathering. There is no clearcut correlation with age between the three sites; the variations in velocity and density tend more to reflect variations in grain size, glass content, vesicularity, and alteration. V_p appears to increase slightly with depth at Site 320; no variation with depth is observed at the other sites. This is unlike many other DSDP sites, where fairly strong velocity gradients with depth have been observed.

No seismic refraction profiles have yet been published for the area of the Leg 34 sites. General layer 2 velocities (V_p) on the Nazca plate tend to be considerably lower, however, than the velocities measured in the laboratory. This may be due to the presence of interlayered sediments, pillow lava, and rubble zones, etc. in layer 2 which are poorly recovered during drilling, thus are unrepresented in the samples which are taken for laboratory measurement.

Electrical resistivities were measured on Leg 34 basalts by Drury (this volume). The resistivities are notably lower than other DSDP basalts for a given porosity; this is again probably related to the less-altered nature of the Leg 34 basalts. In general, oceanic basalts have much lower resistivities than continental basalts when measured under conditions of P, T, and water saturation appropriate to the ocean floor. In the Leg 34 samples, the resistivity increases with increasing pressure, suggesting that pore fluid conduction is important.

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