Shipboard Scientific Party²

HOLE 670A

Date occupied: 12 June 1986, 0130 L

Date departed: 16 June 1986, 1700 L

Time on hole: 4 days, 15 hr, 30 min

Position: 23°09.995'N, 45°01.930'W

Water depth (sea level; corrected m, echo-sounding): 3615.2

Water depth (rig floor; corrected m, echo-sounding): 3626.3

Bottom felt (m, drill pipe): 3625

Distance between rig floor and sea level (m): 11.1

Penetration (m): 92.5

Number of cores: 10

Total length of cored section (m): 92.5

Total core recovered (m): 6.52 (includes 1.5 m of drill cuttings)

Core recovery (%): 7.0

Sediment: washed through approximately 6.4 m of sediment

Basement:

Depth sub-bottom (m): approximately 6.4

Nature: serpentinized harzburgite, clinopyroxene-bearing harzburgite, serpentinites, minor amounts of hyaloclastites, and basalt in top of section

Velocity range (km/s): average velocity, 3.97

Principal results: JOIDES Resolution occupied Site 670 on the western flank of the Mid-Atlantic Ridge rift valley from 12 to 16 June 1986. The site was selected on the basis of survey work done concurrently by the ALVIN submersible, which had identified a body of serpen-

tinized peridotites several square kilometers large on the lower west wall of the median valley near 23°10'N. This seemed to be an ideal site to test unsupported spudding and coring capabilities in a different type of lithology, after the unsuccessful attempt on the gabbros of Site 669.

Hole 670A, at 23°09.9'N, 45°01.9'W, in 3625 m of water, was established using a positive-displacement coring motor (PDCM) and a television-sonar system for monitoring drilling operations. The serpentinite was overlain by about 5-7 m of sediment. The PDCM system was used to advance the hole 35.7 m into serpentinite before tripping to the surface. Recovery was 0.75 m. Using the television-sonar system, we then tripped a rotary coring system (RCB) into the hole, reentering a $1.2 - \times 2.5$ -m crater formed in the sediment by the PDCM. Eight cores were cut by the RCB, advancing the hole to a total depth of 92.5 mbsf and recovering 5.77 m of serpentinites. A total of 6.52 m of core was recovered from Hole 670A; recovery varied between 2% and 17%.

Drilling at Site 670 demonstrated the feasibility of spudding on a lightly sedimented surface, starting a hole using an unsupported PDCM, making a successful reentry without the aid of a reentry cone, and coring nearly 100 m in a body of serpentinized peridotites. In fault-dominated areas, such as fracture zones, the use of unsupported spudding techniques should allow the *in-situ* sampling of serpentinite outcrops to a depth of as much as 100 mbsf.

Hole 670A is one of the few sections of oceanic mantle drilled to date in the oceans. The rocks recovered are serpentinized uppermantle peridotites composing clinopyroxene-bearing harzburgites and abundant relicts of the four-phase primary assemblages (olivine, orthopyroxene, clinopyroxene, and chromium-spinel), showing a downward decrease in serpentinization, the first few meters being totally serpentinized. These mantle rocks exhibit a strong, high-temperature foliation of the primary phases, macroscopically marked by the flattening and stretching of the orthopyroxene porphyroclasts and chromite grains. The tectonic fabric developed in Hole 670A harzburgites shows that they were penetratively deformed by plastic flow at high temperature. Another prominent feature of these peridotites is the occurrence of abundant crosscutting veins of serpentine and calcite and the local development of serpentine breccias or shear zones. Physical and magnetic properties of these mantle rocks appear to be strongly dependent on the degree of serpentinization.

Several previously drilled holes near the Mid-Atlantic Ridge had yielded peridotite blocks and breccias interbedded with the lava flows of the upper crust. Site 670 offers a present-day example of how mantle rocks are exposed directly near the floor of the Mid-Atlantic Ridge rift valley. The mechanisms by which peridotite can be emplaced on the seafloor without basalt cover and immediately adjacent to an active, spreading volcanic axis remain unclear and obviously deserve further studies.

BACKGROUND AND OBJECTIVES

A body of serpentinized peridotite several square kilometers in area was discovered cropping out on the lower west wall of the median valley near $23^{\circ}10'$ N during the dive program conducted by the submersible ALVIN concurrently with Leg 109 drilling. The area consisted of moderately sedimented terrain of low relief and scattered outcrops.

The notice of this discovery, immediately transmitted to the *JOIDES Resolution*, raised considerable interest among the scientific party. Several previously drilled holes near the Mid-Atlantic Ridge (MAR) had recovered peridotite blocks and breccias interbedded within the lava flows of the upper crust or located just below them. This was true during DSDP Legs 37, 45,

¹ Bryan. W. B., Juteau, T., et al., 1988. *Proc. ODP, Init. Repts. (Pt. A)*, 106: College Station, TX (Ocean Drilling Program).

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and 82; for instance, boulders and cobbles of serpentinized peridotite were recovered about 100 m below the top of basement in DSDP Holes 395 and 395A, about 60 nmi west of the MARK area. The common occurrence of serpentinized peridotite blocks and breccias in Atlantic crust suggests that outcrops of upper-mantle material may occur within the MAR rift valley close to the axis of accretion. For the first time, we had the opportunity to study such an occurrence *in situ* on the inner floor of the rift valley.

Seismic-refraction data reported by Purdy and Detrick (1986) suggest the existence of a major structural discontinuity between $23^{\circ}08'$ N and $23^{\circ}18'$ N, separating normal layer 2 to the south from thinned layer 2 crust to the north in the floor of the median valley. In this "anomalous" zone, both the central valley axis and the western valley walls are deeper than normal (Fig. 1). The absence of distinct rift mountains to the west, the confused topography within the rift valley, and a reduction in amplitude of the central magnetic anomaly at this latitude suggest that this zone may represent a "zero-offset" transform or boundary between two distinct spreading-center cells (Purdy and Detrick, 1986).

Thus, it appeared that we had both scientific and technological reasons for drilling these peridotites:

1. We could learn more about the structures, petrology, and emplacement of these peridotites and have an opportunity to compare them with those drilled previously in other DSDP sites close to the Mid-Atlantic Ridge.

2. We had a potential opportunity to constrain better the tectonic history and accretion processes for that anomalous area. The mechanisms by which peridotite is emplaced and exposed without basalt cover adjacent to an active, spreading volcanic rift deserve detailed studies.

3. Investigations here could help clarify the possible influence of this material on the magnetic-anomaly shift on the west side of the valley.

4. From a technological point of view, this seemed to be an ideal place to test unsupported spudding and coring capabilities in another lithology typical of that likely to be encountered in future drilling in or near a major fracture zone.

Hole 670A was drilled on an eastwardly dipping gentle slope (Fig. 1B), almost midway between Sites 648 and 649, about 5 km west of the central volcanic axis of the median valley within this anomalous zone in the rift valley. Figure 2, based on the submersible observations (Karson et al., in press), shows a tentative interpretation of the tectonic setting of the peridotite body and Site 670.

OPERATIONS

Coring with an Unsupported Bottom-Hole Assembly

Site 670 was selected on the basis of survey work done by the ALVIN submersible, while logging was being done by the Leg 109 scientific party at Hole 395A. According to navigational coordinates determined by the ALVIN scientific party, the ship was located at Site 670 upon completion of operations at Hole 395A.

A PDCM established Hole 670A. Owing to the extensive bottom survey done by the ALVIN, conducting a site survey with the television-sonar system was not necessary. The drilling assembly was run into the hole, and the television-sonar system was lowered on the drill pipe. The bit was lowered to the seafloor, and a sonar reflector was released from the television frame at the desired drilling location.

Utilizing the television-sonar system for monitoring drilling operations, we efficiently spudded Hole 670A with the unsupported PDCM drilling assembly. Five to seven meters of sediment was penetrated before any weight was taken on the bit. The seafloor depth was established at 3625 m below rig floor (mbrf).

Drilling parameters were maintained as follows: 2000-4000-lb weight on the bit, 456 gal/min flow rate through the motor, 650 psi stand-pipe pressure, and 100-110-rpm bit speed. The PDCM ran effectively and provided adequate torque for coring the peridotite formation.

An interval from 0 to 35.7 mbsf was cored with the PDCM system. Core barrel number 1 (Core 109-670A-1D) was recovered without any mechanical problems with the core barrel or latch assembly. When the second core barrel was retrieved, two latch fingers were found to be broken off in the motor. The connection between the upper and lower core barrel had failed, also leaving the lower core barrel still in the motor. The PDCM drilling assembly was tripped out of the hole and laid down. A total of 0.75 m of core was recovered with the PDCM system in Hole 670A (Table 1).

A rotary-coring system (RCB) was picked up and tripped into the hole. Using the television-sonar system on the drill pipe, we successfully reentered Hole 670A. The crater was approximately 1.22×2.5 m and was filled with bentonite mud. Upon lowering the television-sonar system to the seafloor, we received a sonar return of the reflector. The crater of Hole 670A was then sighted with the television.

Reentry into Hole 670A was accomplished within 15 min. The bit was lowered 7 m into the hole and washed down to 12 mbsf with no weight on the bit. When coring passed 7 mbsf on the previous bit run, a 2000–4000-lb weight on the bit was required, a positive indication that the RCB was in the original borehole.

Eight cores were cut with the RCB in the hole interval from 0 to 92.5 mbsf. Total recovery for these eight coring runs with the RCB was 5.77 m. Recovery ranged from 2% to 17% (Table 1). The lower recovery rate with the proven RCB may be attributed to jamming of core rubble in the core catchers.

A total of 92.5 m of hole was cored in Hole 670A, and 6.52 m of core was recovered.

Conclusions

The PDCM has an adequate torque/weight ratio for spudding an unsupported hole into fractured basalt with voids (hollow pillows), which helps to provide adequate bit confinement (Hole 648A). The PDCM does not appear to have an adequate torque/weight ratio for drilling into a gabbro-type formation with an unsupported bottom-hole assembly (BHA) (Hole 669A). In softer formations (such as peridotite), where 2000-6000-lb weight on the bit is required, the PDCM unsupported spudding technique is effective (Hole 670A).

Before further deployment of the PDCM system, the corebarrel and latch system will require further development and strengthening. The core-barrel wall thickness will need to be increased significantly to obtain adequate strength in the corebarrel connections.

The PDCM concept has proven to be a viable means of establishing scientifically valuable boreholes in regions of the seafloor having < 40 m of sediment. Before the development of the PDCM unsupported coring system, attempts to spud with conventional rotary-coring systems repeatedly resulted in BHA failures.

To date, 14 holes, with no BHA failures, have been spudded during Legs 106 and 109 at Sites 648, 649, 669, and 670, using both the positive-displacement drilling motors and the positivedisplacement coring motors. The holes have been established in a wide range of rock types, which includes young fractured basalts, gabbro, peridotite, and hydrothermal sulfide sediments.



Figure 1. A. Location of Site 670 on the western flank of the Mid-Atlantic Ridge rift valley. B. Enlargement of Sea Beam bathymetric chart around Site 670 (rectangle in Fig. 1A). Sea Beam map after Detrick et al. (1985).



Figure 2. Schematic east-west geological cross section across the median valley, passing through Site 670. Symbols: 1-neovolcanic zone; 2-older basaltic rocks; 3-serpentinized peridotites; 4-main normal faults.



Core no.	Date (June 1986)	Time on deck	Total depths (m)	Sub-bottom depths (m)	Advanced (m)	Length cored (m)	Length recovered (m)	Recovery (%)
Hole 670A								
	12		3625-3631.4	0.0-6.4	6.4	0.0		
109-670A-1D	12	1730	3631.4-3641.8	6.4-16.8	10.4	10.4	0.18	1.7
109-670A-2D	13	2400	3641.8-3660.7	16.8-35.7	18.9	18.9	0.57	3.0
109-670A-3W	14	2330	3632-3651.3	7.0-26.3	0.0	19.3	0.24	
109-670A-4W	15	0730	3651.3-3670.2	26.3-45.2	9.5	18.9	0.20	2.1
109-670A-5R	15	1215	3670.2-3679.6	45.2-54.6	9.4	9.4	1.60	17
109-670A-6R	15	1715	3679.6-3689	54.6-64.0	9.4	9.4	0.40	4.3
109-670A-7R	15	1930	3689-3698.5	64.0-73.5	9.5	9.5	0.58	6.1
^a 109-670A-8R/W	16	0100	3698.5-3708	73.5-83.0	9.5	9.5	0.27	2.8
109-670A-9R	16	0645	3708-3717.5	83.0-92.5	9.5	9.5	0.98	10.3
^b 109-670A-10W	16	1000	3708-3714.5	83.0-89.5	0.0	6.5	1.50	

^a Cored from 3698.5 to 3701.6 m, washed from 3676 to 3701.6 m, cored from 3701.6 to 3708 m.

^b Drill cuttings.

Penetration rates varied considerably with the type of formation being cored or drilled.

From experiences at Hole 670A, establishment of future boreholes in selected formations having little or no sediment cover is feasible using the unsupported motor technology. After establishing the hole, investigators can reenter the borehole with one of the conventional rotary-coring systems and core to the desired depth.

LITHOSTRATIGRAPHY

Hole 670A is situated on an eastwardly dipping, gentle slope on the western flank of the median valley approximately halfway between Sites 648 and 649. About 6.4 m of soft, unconsolidated sediment was washed using the PDCM before drilling through a further 86.1 m of serpentinized peridotite.

A total of 6.52 m of serpentinized peridotite was recovered, including 1.5 m of drill cuttings. Recovery rates varied between 1.7% and 17% (Table 1). The average recovery rate was 7.0%. The poor recovery makes it difficult to establish a precise lithostratigraphic section through the basement. All the rocks recovered are variably serpentinized peridotites, ranging in degree of serpentinization from about 50% to 100%. Two main rock types can be recognized in hand specimen. These are (1) serpentinites with >75% serpentinization, which are dark bluish, veined, and exhibit relicts of orthopyroxene and chromite crystals; and (2) harzburgites, which are less serpentinized, greenish, and exhibit primary mantle deformation structures.

The section can be roughly divided into four units, as shown in Figure 3, from top to bottom: (1) Unit 1, down to 46 mbsf, composed of serpentinized harzburgites, the percentage of serpentinization decreasing downward; (2) Unit 2, from 46 to 52 mbsf, composed of dark serpentinites with distinctive tortoiseshell texture, >95% serpentinized; (3) Unit 3, from 52 to 66.5 mbsf, predominantly composed of greenish clinopyroxene-bearing harzburgites exhibiting a strong foliation defined by flattening and stretching of orthopyroxene porphyroclasts and chromite grains; and (4) Unit 4, from 66.5 mbsf to the bottom of the hole, composed of mixed samples of greenish porphyroclastic serpentinized harzburgites and dark serpentinites with distinct "megamesh" and/or veined textures. This unit also includes intervals of thick fractures filled with fibrous asbestos. The last core (Core 109-670A-10W) recovered 1.50 m of fine drill cuttings generally <1 cm long, consisting mainly of serpentine fragments. These appear to be derived from lithologies similar to those observed uphole.

PETROGRAPHY

The petrographic description of the rocks from Site 670 is divided into two sections. The first section describes the variably serpentinized peridotites that constitute the predominant rock type recovered from Hole 670A. The second section deals with basalt rubble, recovered in Cores 109-670A-1D, 109-670A-2D, and 109-670A-3W, that evidently fell into the hole during the drilling operations; these upper cores contain several pieces of this rubble.

Petrography of Ultramafic Rocks

Two lithologic types can be recognized within the ultramafic rocks recovered from Hole 670A: serpentinite in Units 2 and 4 (Fig. 3) and serpentinized harzburgite in Units 1 and 3. Modal data on the peridotites are presented in Table 2. Primary minerals are present in various stages of preservation; some are fresh



Figure 3. Proposed lithostratigraphy of Hole 670A. Stratigraphic position of each core is shown.

and some are pseudomorphs that allow identification of the primary mineralogy. Primary silicate minerals in the serpentinite were entirely replaced by serpentine + talc or by serpentine + talc + tremolite assemblages. These rocks may have been dunites. Olivine, orthopyroxene, clinopyroxene, and chrome spinel are present in various stages of preservation in the serpentinized harzburgite.

Serpentinized Harzburgite

Partly serpentinized harzburgite was recovered in several cores at Hole 670A. In contrast to the almost complete replacement of primary minerals in serpentinites recovered in Hole 670A (see next section), three- and four-phase primary mineral assemblages are preserved in the fresher harzburgites. The following samples contain less altered harzburgite: Core 109-670A-4W-1 (Pieces 3 and 4), Section 109-670A-5R-1 (Pieces 1 and 2); Section 109-670A-5R-2 (Pieces 9 through 19); Core 109-670A-6R-1 (Pieces 1 through 7); Core 109-670A-7R-1 (Pieces 1 through 5); Core 109670A-8R/W-1 (Pieces 1 through 5); Core 109-670A-9R-1 (Pieces 1 and 12). Most samples were recovered from Lithologic Unit 2, in the depth interval between 52 and 66.5 mbsf (Fig. 3). The petrography of the partly serpentinized harzburgites is described next, and a discussion of their significance is presented.

Modal Proportions

A modal analysis (1000 points counted on a 0.5-mm grid) of Sample 109-670A-4W-1, 19-21 cm, yields the following results: 45% serpentine, 35% olivine, 5% bastite, 8% orthopyroxene, 2% clinopyroxene, <1% tremolite, 1% spinel, 1% magnetite, and 3% talc. To reconstruct the primary, preserpentinization modal abundances of the harzburgites, the secondary minerals must be assigned to their precursor phases. Most of the serpentine occurs as a mesh-textured replacement of olivine, indicating that modal serpentine should be assigned to primary olivine in the reconstructed mode (see "Serpentinite" section, this chapter). Bastite, prismatic tremolite, and talc coronas replace or-

Sampl	e .	109-670 19-2	A-1D-1, 1 cm	109-670 45-4	0A-2D-1, 47 cm	109-670 12-1)A-3W-1, 14 cm	109-67 19-	0A-3W-1, 20 cm	109-670 19-2)A-4W-1, 21 cm	109-67 111-	0A-5R-1, 113 cm	109-670A 126-12	-5R-1, 8 cm	109-67 52-:	0A-5R-2, 54 cm	109-670 4-6	A-6R-1, cm	109-670 43-4	A-7R-1, 5 cm	109-670 107-1	0A-9R- 109 cm
Primary mineralog	y.																						
Olivine	present	0	80	0	88.5	0	70	0	3	35	85	0	05	0	00	0	> 90	20	85	0	80	0	00
Plagioclase	present	-	0	-	0	—	0	—	2-3	-	0	-	0	-	0		0		0	-	0	-	0
Clinopyroxene	present	<1	2	tr	1	-	0	-	4-5	2	3	-	0	-	0	-	0	2	2	-	?	-	?
Orthopyroxene	present	1	8	tr	10	0	28	-	0	8	11	0	4?	-	?	1	5-10	9	12		?	5	10
Spinel	present original	1	1	0.4	0.5	2	2	100	0	1	1	tr	1	< 0.5	1	< 0.5	< 0.5	<1	<1	tr	1		?
Glass	present original	_	0	-	0	-	0	0	90	-	0	-	0	- 	0	-	0	-	0	-	0	-	0
Secondary mineral	ogy																						
Serpentines:							4		2		-			121						1.0	20		
Lizardite		6	3	7	2 7.6	6	2		0		44	24	2 78	79		7	2 2	(2 54	1	0		5 9
Antigorite					-	- 9	_		0		-		10	8		1	5	-	-	2	0	1	12
Bastite		1	0	1	2	2	26		0		5		_	-			_		2	1	-		8
Iremolite			÷.		tr		_		0		<1		2				tr	-	-		5		30
Paraasite		2	12		_		_	1	0									_	_				
Talc			5		3	<	0.5		0		3		5	4	5		3	<	1		_		_
Chlorite			2						0					tr			2	-	_	1	0		30
Clays			_				_		5				_					_	_		-		_
Zeolites			0		0		0	3	30		0		0			24		-	2		-		22
Carbonates			1		tr		1		-										4		_		?
Magnetite			9		5		1		0		1		3	1			4.5		1		5		1
Iron hydroxide	S C		-		1				÷	2	_			_		03	-	-		-	-		
Sulfide									tr	2	-			tr		12		-	-	-	-	2	-

Table 2. Modal mineralogy of samples from Hole 670A.

Note: Modes are visual estimates of thin sections.

thopyroxene; thus, these minerals are assigned to orthopyroxene. Most magnetite occurs as a replacement for spinel and is assigned to that primary phase. The resulting estimate of primary modal proportions in the harzburgite is 85% olivine, 12% orthopyroxene, 2% clinopyroxene, and 1% spinel. If a change in volume accompanied serpentinization, this reconstructed mode will be in error, overestimating the modal abundance of olivine.

Textures

Textures of Hole 670A harzburgites fall in the porphyroclastic category defined for upper-mantle peridotites by Mercier and Nicolas (1975). This type of texture shows strained porphyroclasts of olivine, pyroxene, and spinel surrounded by a matrix of polygonal olivine having recrystallized grain boundaries.

Olivine

Olivine in Hole 670A harzburgites occurs as xenomorphic fragments (0.04–0.5 mm) embedded in a matrix of mesh-textured serpentine (Fig. 4). Isolated grains representing the remains of single olivine crystals have similar interference colors and extinguish simultaneously under crossed polarized light. These groups of crystals with a similar optical orientation are 0.8– 1.2 mm across, which gives an estimate of the original olivine



Figure 4. Small fragments of olivine surrounded by lizardite in left half of field of view. At lower left is a clinopyroxene porphyroclast with granulated margins. Sample 109-670A-6R-1, 4-6 cm. Plane polarized light. Field of view = 3 mm.

grain size. Undulatory extinction is common in olivine, and kink bands are observed in some grains. In one sample (109-670A-4W-1, 19-21 cm), a large proportion of the olivines are oriented with their optic axes perpendicular to the plane of the thin section. This indicates that olivine in this harzburgite has a preferred crystallographic orientation, with the *c* axes lying in the plane of the thin section. Olivine compositions of Fo₉₀ are estimated from conoscopic observations of centered optic axis figures.

Orthopyroxene

Orthopyroxene grains (0.8–8 mm) in the harzburgites are round to elliptical, or more rarely rectangular (Fig. 5). The long axes of elongate orthopyroxenes define a foliation that is inclined approximately 20° from horizontal (Fig. 6). Clinopyroxene exsolution lamellae are present in most orthopyroxenes and are preserved even in bastite pseudomorphs of orthopyroxene. Evidence of internal deformation is given by undulatory extinction, gently bent cleavage traces, and exsolution lamellae in orthopyroxene. Grain boundaries of larger orthopyroxenes may be granulated. Some small neoblasts of strain-free recrystallized orthopyroxene are found in the granulated zones. Some orthopyroxenes show faint pink pleochroism.



Figure 5. Large orthopyroxene porphyroclast at right and a smaller fragment of orthopyroxene in center of field of view. The smaller fragment probably derives from the porphyroclast. Fragments of olivine are at left. Sample 109-670-6R-1, 4-6 cm. Plane polarized light. Field of view = 3 mm.



Figure 6. Oriented Sample 109-670A-5R-2, 139–145 cm. The top of the sample is at the low end of the centimeter scale. Elliptical gray orthopy-roxene porphyroclasts are contained in a matrix of serpentinized olivine. A foliation is defined by the preferred dimensional orientation of the porphyroclast long axes and is inclined approximately 20° to the horizontal.

Clinopyroxene

Clinopyroxene grains (0.1–1.4 mm; Fig. 4) are rounded, some showing undulatory extinction, and commonly are gently warped. Grain boundary granulation affects some of the larger clinopyroxenes, and small clinopyroxene neoblasts appear in the granulated zones. Exsolution lamellae of orthopyroxene are found in clinopyroxene.

Spinel

In $30-\mu$ m-thick thin sections, spinel (0.04–3.0 mm) is reddish brown; in thinner sections it is brownish green to olive green. Spinel is blocky to elongate or elliptical. The long axes of elongate spinels define a foliation coplanar with that defined by orthopyroxene.

Constraints on Formation Conditions

The tectonite fabric developed in Hole 670A harzburgites shows that they were penetratively deformed at high temperatures. The preferred dimensional orientation of enstatite and spinel and the preferred crystallographic orientation of olivine probably resulted from a combination of plastic flow and syntectonic recrystallization under upper-mantle conditions (Casey et al., 1981). Similar fabrics have been produced experimentally at temperatures of 1000°-1150°C, pressures of 10-15 kbar, and strain rates of 10^{-6} to 10^{-7} s⁻¹ (Avé Lallemant, 1975). These types of petrofabrics also have been found in other studies of ocean-floor (Boudier, 1978) and ophiolitic (Casey et al., 1981) peridotites.

The primary mineral assemblage in fresh harzburgites of Hole 670A is olivine + orthopyroxene + clinopyroxene + spinel. Experiments on synthetic mantle compositions have shown that spinel peridotite is stable at pressures between approximately 10 and 20 kbar (Green and Ringwood, 1967; Presnall et al., 1979). Below 10 kbar, plagioclase replaces spinel as the stable aluminous phase, and plagioclase peridotite results (olivine + orthopyroxene + clinopyroxene + plagioclase). Concentrations of minor elements (e.g., chromium) can cause significant shifts in the pressure limits of these intervals. However, as a first approximation, these data suggest that equilibrium among the primary minerals in Hole 670A harzburgites was last established at pressures between 10 and 20 kbar, equivalent to depths of 30–60 km.

Discussion

Two general types of ultramafic rock were recovered from the seafloor, the most abundant being tectonites that are penetratively deformed and of presumed upper-mantle origin (Prinz et al., 1976; Bonatti and Hamlyn, 1981; Michael and Bonatti, 1985). In many places, the chemistry of ultramafic tectonites suggests that they are residues of partial melting and extraction of a basaltic melt from the suboceanic upper mantle. At present, such an origin appears likely for the Hole 670A peridotites. Ultramafic cumulates are less common (Hodges and Papike, 1976) and are primarily wehrlite and dunite rather than harzburgite. These rocks are thought to crystallize from basaltic magmas in the basal parts of spreading-ridge magma chambers.

Deformed ultramafic peridotites were recovered at DSDP Site 395, approximately 100 km west of Site 670A. Mineral compositions in these peridotites are olivine Mg/(Mg + Fe) = 89.9-91.3; orthopyroxene Mg⁺⁺ = 89.7-91.2; clinopyroxene Mg⁺⁺ = 90.7-91.9; and spinel Cr/(Cr + Al) = 28-43 (Arai and Fujii, 1979; Sinton, 1979). Given the well-known monotony of mineral compositions in residual mantle rocks, Hole 670A peridotites probably contain minerals with similar compositions.

Two samples, 109-670A-1D-1, 19-21 cm and 109-670A-2D-1, 45-47 cm, were analyzed for major and trace elements (Table 3). These analyses reflect both the primary geochemical characteristics and the serpentinization processes. The very low CaO and Al_2O_3 contents characteristic of these mantle rocks (Miyashiro et al., 1969) were lowered further during serpentinization. The TiO₂ is presumably preserved in the unaltered spinel crystals, and its abundance in the harzburgite is similar to the measured abundance of the less mobile trace elements, yttrium and zirconium, and the high nickel contents indicate that the Hole 670A harzburgites are depleted residues from prior melting events.

Table 3. Whole-rock analyses, Hole 670A.

Analysis	Sample 109-670A-1D-1, 19-21 cm	109-670A-2D-1, 45-47 cm
SiO ₂	44.57	44.10
TiO	0.05	0.06
Al ₂ Õ ₃	1.54	1.87
aFe2O2*	9.79	9.36
MnO	0.20	0.11
MgO	41.01	42.75
CaO	0.96	0.22
Na ₂ O	0.05	0.00
K ₂ Ő	0.02	0.00
P2O5	0.00	0.00
Total	98.17	98.47
^b Mg′ value	0.892	0.90
Rb	1.5	1.8
Sr	12	7.7
Y	0.8	0.6
Zr	3.6	1.7
Nb	1.3	1.4
Ni	2380	1985

⁴ Total Fe analyzed as Fe₂O₃.

^b Mg' value calculated from molar MgO/(MgO + FeO), whereas $Fe^{2+}/(Fe^{2+} + Fe^{3+}) \approx 0.9$.

SITE 670

Serpentinite

The serpentinite recovered in Cores 109-670A-5R, 109-670A-7R, and 109-670A-9R consists of 90%-95% serpentine minerals and 5-10 modal percent relict primary orthopyroxene and spinel porphyroclasts. The primary mineralogy was 90%-95% olivine, so the rock was probably a dunite that was altered extensively, because its fine grain size and polygonal texture provided pathways for fluid migration. Layers of equant chromite grains form seams at the top and bottom of Sample 109-670A-5R-1, 120-144 cm (Fig. 7) and may be relict chromite-rich layers of a dunite protolith.

The substantial variability in the macroscopic textures of the serpentinite is controlled by the proportion of alteration minerals. Fractures crosscut the serpentine and give rise to a characteristic tortoise-shell or "megamesh" texture (Figs. 7 through 9). The textural variability is controlled by two elements.

The first of these elements is a ring-shaped to ellipsoidal replacement texture, which is defined by variations in the proportions of alteration minerals in serpentine. The rings are formed by alternating lizardite-rich (black) and talc + antigorite-rich (light) bands. This replacement texture in Sample 109-670A-5R-1, 120-144 cm (Fig. 7) is defined by talc-rich central cores and alternating lizardite-rich and talc-rich layers; five alternating intervals can be seen in the rings of this sample. These rings were formed by fluid-wall-rock interactions, which produced variable percentages of serpentine and talc minerals in response to changes in the temperature and/or activities of CO2, H2O, and SiO₂ in the fluid phase. The conformity of the rings to the external fracture pattern indicates that the texture was formed by fluid infiltration along a replacement front that proceeded inward from the fractures. In some samples (109-670A-5R-2, 11-17 cm, Fig. 8), the latest stage of replacement involved the formation of lizardite, and the outer edge of the tortoise-shell texture is black. In other samples (109-670A-5R-1, 47-57 cm, Fig. 9), the lizardite boundary is thin, and a talc-rich assemblage dominates the texture. These complex variations in the replacement assemblage indicate substantial spatial variability in the metasomatic process that produced the tortoise-shell texture. Moreover, this replacement texture appeared secondarily after a pervasive serpentinization event that resulted in the formation of lizardite.

The second element that defines the tortoise-shell texture is a late-stage vein filling by antigorite and chrysotile on the fracture surfaces. The late-stage veining, which accompanied a late deformation of the serpentinite and is variably developed in the cored interval, is well developed in Sample 109-670A-5R-1, 47-57 cm (Fig. 9).

Complete textural gradation from ring-dominated (Fig. 8) to fracture-filling-dominated serpentinite occurs (Fig. 9). In some places, the lizardite that preceded the development of the tortoise-shell replacement is also preserved. A final stage of chrysotile veining cuts all the textural elements.

Serpentinites from Core 109-670A-7R-1 (Pieces 7A-7F) were disrupted by shearing and an accompanying higher grade metamorphism. This serpentinite is characterized by a cataclastic texture composed of lizardite, talc + antigorite and chrysotile domains, which have reaction overgrowths of tremolite + chlorite + carbonate. Centimeter-thick veins of massive serpentine (chrysotile?) define probable fault zones in this cataclasized zone.

Petrographic Features Observed in Thin Section

Preliminary macroscopic and thin-section petrography reveals a process of serpentinization that proceeded in at least four stages:

1. Pervasive serpentinization. The first stage of serpentinization, a pervasive hydration of the primary phases, is seen in



Figure 7. Tortoise-shell texture in serpentinite, Sample 109-670A-5R-1, 120-143 cm. Chromite-rich seams appear in the bottom and top parts of this core.



Figure 8. Ellipsoidal replacement texture in serpentinite, Sample 109-670A-5R-2, 10-17 cm. A delicately banded lizardite-rich outer rim dominates the texture. White ellipses are talc rich.

various states of advancement in the incompletely serpentinized harzburgites (see previous section). Olivine is the first phase to be completely replaced, then orthopyroxene, then clinopyroxene. Spinel is completely replaced in only one sample. The major serpentine group mineral formed during this stage is lizardite, replacing olivine and pyroxenes. Olivine pseudomorphs thus formed are characterized by polygonal mesh and hourglass textures centered on structureless cores of lizardite (Fig. 10). Magnetite seams, 0.1-0.3 mm thick, occur at the boundaries of the mesh-textured polygons, taken to represent the outlines of original olivine neoblasts 0.2-2.8 mm in diameter. Outer rims of these pseudomorphed neoblasts are composed of fibrous chrysotile, which is colorless to pale brown in plane light and has a distinctly higher birefringence than lizardite. Talc may also occur rimming the olivine pseudomorphs, forming coronas 0.1-0.4 mm thick. Talc is flaky in appearance and has a much higher birefringence than the other phases. The olivine pseudomorphs are cut by late-stage chrysotile veinlets with magnetite-rich seams in the wall rock. These veinlets may form an anastomosing network or may be deformed along shear zones.

Orthopyroxene and clinopyroxene are also pseudomorphed by a variety of lizardite termed bastite (Fig. 11). The bastite mimics the (001) cleavages of the pyroxenes and is pale browngreen in plane light. Bastite is commonly partly replaced by talc, which forms either coronas around the bastites or complex intergrowths within the bastites. The bastite content (as much as 26%) reflects the original total pyroxene content of the rock.

Spinel is partly altered around the margins and along cracks to an opaque secondary phase, probably magnetite or ferrite-



Figure 9. Tortoise-shell texture in Sample 109-670A-5R-1, 46-57 cm, in which talc-rich concentric rims dominate. Fractures were disrupted and filled by antigorite during late-stage deformation.

chromite, leaving red translucent cores of fresh spinel. In Sample 109-670A-5R-1, 111-113 cm, spinel replacement is complete.

2. Chrysotile formation. Extensive crystallization of chrysotile in tensional cracks and fissures characterizes this stage (Fig. 12). The fibrous chrysotile is commonly perpendicular to the fissure walls, indicating dilation of the fissures during crystallization (Riordon, 1955). Magnetite occurs as a coating or within the immediately adjacent wall rock. A few of the chrysotile veinlets are slightly sheared, so that the fibers are at acute angles to the veinlet walls.

3. Antigorite formation. Localized shearing oblique to the primary foliation of the rock characterizes this stage. The development of irregular shear zones 0.5-1 cm thick is accompanied by wholesale recrystallization of lizardite and chrysotile to antigorite with subordinate talc and carbonate. Antigorite appears to replace chrysotile preferentially (Fig. 13). As much as 10% of the antigorite is in the form of plates, the remainder being made up of interlocking 0.3-0.6-mm flakes. No pseudomorphous texture can be distinguished in the antigorite. Talc, chlorite, and carbonate (magnesite?) are intimately intermixed with the antig-



Figure 10. Mesh and hourglass textures in Sample 109-670A-1D-1, 19–21 cm. Polygonal olivine pseudomorphs are lined by magnetite seams and talc coronas. Crossed polars. Field of view = 3 mm.

orite. The antigorite is commonly contorted, indicating reactivation of the shear planes. In some samples (e.g., 109-670A-5R-1, 111-113 cm, and 109-670A-9R-1, 107-109 cm) as much as 30% fibrous tremolite and as much as 30% colorless magnesium chlorite is present, replacing antigorite (Fig. 14).

4. Formation of second-generation chrysotile. This stage is characterized by late-stage tensional chrysotile veinlets, cutting all the previously described textures. About 10% of the chrysotile veinlets belong to this stage.

Discussion

Serpentinization of the peridotite recovered from Hole 670A is heterogeneous in its effects, and the degree of serpentinization may depend on the protolith composition. The initial stage of serpentinization (pervasive hydration) can be treated in terms of the transition from the anhydrous peridotite system to the hydrous system MgO-SiO₂-H₂O (Bowen and Tuttle, 1949; Deer et al., 1962; Winkler, 1976; Elthon, 1981; Bonatti and Hamlyn, 1981). The general form of the reaction is

$$\begin{array}{rl} (Mg,Fe)_2SiO_4 + (Mg,Fe)SiO_3 + 2H_2O \Leftrightarrow \\ & \text{olivine} & \text{enstatite} \\ Mg_3Si_2O_5(OH)_4 + Fe_3O_4 \ . & (1) \\ & \text{serpentine} & \text{magnetite} \end{array}$$

Figure 11. Bastite pseudomorph after pyroxene in Sample 109-670A-1D-1, 19-21 cm. Bastite preserves evidence of plastic deformation and is cut by parallel chrysotile and talc veinlets. The larger chrysotile veinlet contains well-developed transverse fibers. Crossed polars. Field of view = 2 mm.

Bowen and Tuttle (1949) demonstrated that this reaction takes place when $P_{H_{2O}} = P_{tot}$, at T <500°C. More recent work (reviewed in Winkler, 1976; Elthon, 1981) showed the serpentine assemblage to be stable to at least 325°C. Bastite and mesh-textured olivine pseudomorphed by lizardite are typical products of reaction number 1 (Miyashiro et al., 1969; Aumento and Loubat, 1971; Bonatti and Hamlyn; 1981). Lizardite is the common serpentine polymorph formed at this stage in oceanic serpentinites (Aumento, 1970; Aumento and Loubat, 1971; Bonatti et al., 1984).

Talc formation may be initiated when metamorphic fluid temperatures rise, causing previously formed serpentine to react to form talc (Deer et al., 1962; Elthon, 1981). Talc may also form by direct alteration of enstatite:

This reaction could explain the close association of serpentine and talc in pyroxene pseudomorphs (bastite). Although a temperature increase may be invoked to explain the formation of talc at the expense of serpentine (Winkler, 1976), the composi-

Figure 12. Mesh-textured olivine pseudomorphs cut by talc rims and veinlets, which are themselves cut by a striated chrysotile vein, Sample 109-670A-3W-1, 12–14 cm. This is a good example of a dilation fissure type of chrysotile vein. Crossed polars. Field of view = 2 mm.

tion of the metamorphic fluid is also critical in determining talc stability; therefore, to quantify the temperature at which the serpentine-to-talc transformation occurred is impossible. The high temperature limit of talc stability could also be raised if the CO_2 content of the fluid was high, as the presence of carbonate suggests:

$$2Mg_{3}Si_{2}O_{5}(OH)_{4} + 3CO_{2} \rightleftharpoons Mg_{3}Si_{4}O_{10}(OH)_{2} + serpentine talc$$

$$3MgCO_{3} + 3H_{2}O.$$
(3)
magnesite

Antigorite formation is related to shear deformation of the serpentinite. Antigorite forms mainly by replacement of chrysotile. This occurrence of antigorite is typical of serpentinized peridotites (Deer et al., 1962), particularly the association with shearing. Elthon (1981) suggested that both high pressure and temperature favor antigorite formation over the other serpentine polymorphs. Temperatures in the range of 325° - 500° C (probably near 400°C) and pressures <3 kbar are inferred for serpentinization that includes antigorite formation.

Tremolite $(Ca_2Mg_5Si_8O_{22}(OH)_2)$ is found in close association with antigorite and talc. The formation of tremolite is favored by a pyroxene-bearing protolith, a calcium-rich fluid, and high

Figure 13. Typical flaky interlocking texture exhibited by antigorite, Sample 109-670A-9R-1, 111-113 cm. Center of photograph shows antigorite invading and partly replacing chrysotile. Crossed polars. Field of view = 2 mm.

water/rock ratios (Elthon, 1981). Serpentinization of peridotite releases calcium from the rock (Miyashiro et al., 1969; Laurent, 1975; Bonatti et al., 1984) and could provide a source of calcium. The observed maximum of 30% tremolite (Sample 109-670A-9R-1, 107-109 cm) in the Hole 670A serpentinites suggests that the fluids were significantly enriched in calcium. Tremolite may also have formed as a result of temperatures exceeding the upper stability limit of antigorite (525°C at 3 kbar).

Petrography of Rubble Pieces Other than Serpentinized Peridotite

Some rock pieces recovered from Hole 670A that do not consist of serpentinized peridotite are considered to be rubble overlying the peridotite outcrop. Some of the orange-brown serpentinized peridotite pieces may be rubble, but these are described with the rest of the peridotites. All the nonserpentinite pieces >1 cm in size are briefly described in Table 4. Each piece is described separately because the pieces are possibly unrelated.

Sample 109-670A-3W-1, 0-8 cm

This piece of basalt, 8 cm long, is the largest of the nonserpentinite samples and is a sparsely to moderately (2%-3%) olivine-plagioclase phyric fine grained basalt having plagioclase phenocrysts up to 3 mm in size. About 2% of the rock is made up of miarolitic patches as much as 4 mm across. Vesicles are rare

Figure 14. Radiating well-crystallized acicular tremolite growing from the wall of a chrysotile vein. Tremolite replaces antigorite. Sample 109-670A-5R-1, 111-113 cm. Crossed polars. Field of view = 2 mm.

Table 4. List of nonserpentinite rubble pieces >1 cm.

Sample	Lithology	Features of interest (see text)
a,b109-670A-1D-1, 1-12	Cuttings, including basalt	Isolated aragonite crystals
^b 109-670A-1D, 16-18	Olivine microporphyritic basalt	Iron hydroxyoxide staining
a,c109-670A-2D-1, 4-6	Aphyric fine-grained basalt	Sediment encrusted
109-670A-2D-1, 29-32	Hyaloclastite	Partly palagonitized
109-670A-3W-1, 0-8	Olivine plagioclase phyric fine-grained basalt	Sediment encrusted; dark halos
a109-670A-3W-1, 19-28	Spherulitic glassy basalt	Alteration; zeolite veins
	Aphyric fine-grained basalt	Sediment encrusted; dark halo
	Aphyric fine-grained basalt	
	Aphyric very fine-grained basalt	Sediment injecting basalt
^{a,c} 109-670A-3W-1, 19-28	Basalt glass	Partly palagonitized

^a Denotes intervals to which a number of small rubble pieces were assigned.

^b Denotes lithology represented only in working half of core.

^c Denotes lithology represented only in archive half of core.

and <0.5 mm in diameter. All miaroles are coated with greenish or rusty-brown alteration products and black MnO₂(?) specks. Larger (up to 0.5 mm) aggregates of MnO₂(?) occur in miaroles next to the outer surface of the basalt. Slight humidification of the sawn surface reveals a complex, sinuous system of dark halos, mainly 1–2 mm thick (Fig. 15). A central dark zone evident

Figure 15. Complex dark halos in miarolitic basalt (Sample 109-670A-3W-1, 0-8 cm). Sample is encrusted with foraminiferal limestone (L) containing partly palagonitized glass fragments (G).

in the working half may have formed by the coalescence of inward-migrating halos. The halos appear to have developed parallel to the current boundaries of the sample and others by concentric spreading from larger miarolitic patches. In places, two halos are between the center and margins of the sample. This distribution of halos resembles the more complex type 2 halos in Hole 648B. The basalt is encrusted with pale-buff foraminiferal limestone as much as 5 mm thick (Fig. 15), which contains scattered glass shards as much as 3 mm in size, in various states of palagonitization. Some shards are completely altered to finely banded orange-red "palagonite," whereas others appear to be largely fresh.

Sample 109-670A-2D-1, 4-6 cm (Archive Half Only)

This 2-cm piece of aphyric fine-grained basalt is encrusted with carbonate sediment containing partly palagonitized glass shards. The sediment is further encrusted with sparse MnO_2 microconcretions.

Sample 109-670A-2D-1, 29-32 cm

This 3-cm piece of half-palagonitized hyaloclastite contains angular, fresh glass relicts as much as 6 mm long, set in an orange matrix of palagonite. The relicts are rimmed by concentrically banded palagonite, as much as 0.5 mm thick. No fresh glass is present.

Sample 109-670A-3W-1, 19-28 cm

A group of about 20 small rubble fragments is assigned to this interval. Most of the fragments are serpentinized peridotite, but five basaltic fragments also occur, all being different (Table 4). One of the aphyric fine-grained basalt pieces (2.5 cm in size) is partly encrusted with calcareous sediment, has a 2-mm-wide dark halo along one side, and has blue clay (cf. Site 648 chapter "Alteration" section, this volume) lining all the vesicles. The vesicles are as large as 0.5 mm and make up 2% of the rock.

A smaller (1-cm) piece of basalt appears to represent the contact of a flow with the calcareous sediment into which it was extruded. This basalt is very fine grained and is invaded by highly irregular "veins" of pale-gray sediment. From 0.1 to 0.3 mm adjacent to the sediment contacts, the basalt is glassy, suggesting quenching by the water-laden sediment. The sediment-filled "veins" are as much as 0.5 mm thick and penetrate at least 3 mm into the rock. The "veins" also expand into irregular masses as great as 0.2 mm across and have highly lobate basalt/sediment contacts that are convex toward the basalt. Vesicles about 0.2 mm in diameter occur entirely enclosed within the basalt, transgress the basalt/sediment contact, and also appear within the sediment, indicating that volatiles escaping from the basalt were partly trapped by the sediment. A few of the vesicles within the basalt are lined with blue clay. Vesicles within the sediment have an orange-red lining or, in the case of a vesicle at the basalt/sediment contact, a partial filling of microbotryoidal white carbonate. The sample is coated with a thin layer of red iron hydroxyoxide and encrusted with pale buff-colored foraminiferal limestone.

Thin sections were taken from one piece of this core interval because it contains zeolite veins. This pervasively altered rock appears to have been a glassy basalt with < 10% groundmass plagioclase and clinopyroxene microlites, about 3% euhedral to skeletal olivine, and plagioclase microphenocrysts as large as 0.2 mm. About 15% of the groundmass is in the form of spherulites that are 1–1.5 mm in diameter (Fig. 16), within which relict variolitic texture is locally developed. Some of the groundmass microlites are replaced by a pale-yellow-green, moderately birefringent clay mineral, possibly chlorite/smectite mixed-layer minerals replacing clinopyroxene. Other microlites and olivine

(and plagioclase) microphenocrysts are replaced by a zeolite having low birefringence. The spherulites and the enclosing groundmass are replaced by stubby, fibrous brownish crystals having high first-order interference colors and inclined extinction, tentatively identified as actinolite. The altered basalt is broken up by a network of zeolite veins as much as and exceeding 3 mm thick (Fig. 16). The vein-filling sequence is complex but appears to have five texturally distinguishable stages, one or more of which is commonly missing in any given part of a vein. The sequence established is as follows:

1. Isopachous, 10-15-µm-thick, pale-yellow-green clay same as that replacing "clinopyroxene" (frequently absent).

2. Slightly less isopachous, 10-30-µm-thick, clear, low-birefringent zeolite (infrequently absent).

3. Very fine-grained, almost isotropic zeolite with abundant inclusions.

4. Blocky, 0.1-0.7-mm zeolite crystals having abundant inclusions and $10-20-\mu$ m-diameter aggregates of clay resembling stage 1. This zeolite phase may also have a radiating appearance, crystals being as long as 1 mm (possibly stilbite).

5. Clear, blocky zeolite with at least two cleavages and complex twinning. Crystals are irregular in outline, as much as 1×1.5 mm, and commonly enclosed in stages 3 or 4 (possibly laumontite).

Stages 1, 2, 3, and 5 are illustrated in sequence in Figure 17. Rare grains of a yellow sulfide (chalcopyrite) as large as $20 \ \mu m$ occur in the coarser parts of the zeolite veins. A single grain of pyrite was noted in the groundmass of the basalt.

Summary

A variety of glassy and fine-grained basaltic rocks is among the components of the rubble overlying the serpentinized peridotite outcrop drilled at Hole 670A. Calcareous sediment that was locally sufficiently lithified to form adherent foraminiferal limestone encrusts some of the rubble. All rubble fragments are altered to varying degrees. Glasses are partly palagonitized, and basalts have undergone incipient low-temperature alteration (probably at ocean-bottom temperatures), except the zeolite-veined sample in 109-670A-3W-1, 19-20 cm. If actinolite is the principal secondary groundmass phase in this rock, then a two-stage

Figure 16. Altered glassy basalt from Sample 109-670A-3W-1, 19-28 cm, with spherulite (S). Groundmass replaced by actinolite(?). Plagioclase microlites (M) in spherulitic groundmass replaced by zeolite. Vesicles and veins filled with zeolites. Crossed polars. Field of view = 3 mm.

Figure 17. Typical sequence of vein-filling materials developed on altered glassy basalt. Phases numbered as in text. Clay mineral is I; texturally distinct zeolites are 2, 3, and 5. Sample 109-670A-3W-1, 19-20 cm. Plane polarized light. Field of view = 0.7 mm.

alteration history may be indicated. Zeolite facies alteration follows greenschist facies alteration.

Most previously studied samples of oceanic peridotite from the North Atlantic were collected from fracture zones (e.g., Michael and Bonatti, 1985). The increased exposure of mantle lithologies at fracture zones may be related to the ease at which water can penetrate to deeper structural levels. Water in the deeper parts of fracture zones may come into contact with mantle minerals at elevated temperatures, causing serpentinization of the mantle rocks. The volume increase and density decrease (3.3 g/cm^{-3} in fresh peridotite and 2.6 g/cm^{-3} in serpentinite) that accompanies serpentinization will then cause diapiric rise of the partly serpentinized peridotites to shallower levels (Francis, 1981).

One of the most intriguing aspects of the Hole 670A harzburgites is their presence in the Mid-Atlantic Ridge axial valley, approximately 30 km south of the Kane Fracture Zone. We present two explanations for exposure of peridotites in the median valley. Their high structural stand may be related to serpentine diapirism. Penetration of water into deeper structural levels might occur along normal faults that parallel the axial valley trend (Francis, 1981). The serpentine-filled fractures encountered in lithologic Unit 4 (see Fig. 3) may represent part of such a fault. Reaction of water penetrating along such a fault with mantle minerals at approximately 500°C will produce the secondary mineral assemblage observed in Hole 670A peridotites (i.e., mostly serpentine + talc; Miyashiro et al., 1969). Volume expansion occurring as a consequence of this process might cause the serpentinized peridotite to rise to high structural levels. For the serpentine diapir to rise, its overall density need only be less than that of the surrounding unserpentinized mantle rocks. Large pockets of relatively unserpentinized peridotite might be entrained and preserved in the inner parts of the rising diapir. The relatively fresh harzburgites recovered from Hole 670A may be samples of this entrained material.

À limitation of the aforementioned process is that it can occur only off-axis where temperatures fall to 500°C. At a "normal" axis of divergence, temperatures in the upper mantle far exceed the stability limit of serpentine. An alternative model is required to explain the existence of serpentinites in the axial zone of spreading ridges. We suggest that the direct exposure of upwelling mantle material may occur in areas where volcanism is episodic or absent. This situation might exist at slow-spreading centers where magma chambers are ephemeral or discontinuous. As long as convective divergence continues, upwelling mantle material rises to the surface and is transported off-axis by seafloor spreading. Prolonged divergence without volcanic activity might produce an exposed strip of mantle striking parallel to the axial valley. Circulation of seawater through the exposed mantle could cause near-surface, in-situ serpentinization, which is likely to be more static than diapiric upwelling and might explain the nearly perfect preservation of the delicate tortoiseshell textures described earlier. At some later time, magmatism might be reactivated, and all or part of the serpentinized peridotite could be covered by basalt. This process might explain the occurrence of peridotites capped by basalts at Site 395.

PALEOMAGNETICS

Some serpentinized peridotites exposed on land have high intensities of magnetization that compare to those of basaltic rocks. Magnetite grains precipitated during serpentinization cause this magnetization, which can produce detectable magnetic anomalies around the serpentinized body. Magnetic anomalies were observed along some large active faults in Japan, where the exposure of the serpentinite can be seen. A serpentinized body exposed on the oceanic crust may disturb magnetic lineations observed at the sea surface.

One purpose of the paleomagnetic study of the serpentinized peridotites from Hole 670A is to estimate the effect of the body on the magnetic anomalies. The natural remanent magnetization (NRM) intensity, the inclination, and the susceptibility of these rocks yield such information. The other purpose is to observe the rotation or the displacement of the body after the acquisition of remanence. This investigation is needed to clarify the origin of the serpentinite body observed on the west side of the median valley, far from the fracture zone. Such information can be obtained from the stable inclinations exhibited by the oriented core samples. Unfortunately, the recovery was poor, and the oriented pieces very few; but an insight into the nature of the serpentinized body can be obtained.

Samples and Experimental Procedure

For the paleomagnetic study, 10 minicore samples of serpentinized harzburgite or serpentinite were taken from the recovered cores in Hole 670A. The procedure for the paleomagnetic study is described in the summary of the Site 648 chapter (this volume). All the samples were progressively demagnetized by alternating fields until the intensity became <10% of the original intensity. The NRM intensity and inclination and the quality of the orientation of these samples are summarized in Table 5. The demagnetization steps are listed in Table 6. From the demagnetization experiments, median destructive field (MDF) and stable inclinations were obtained. Magnetic initial susceptibility was also measured, and Q-ratio (Königsberger ratio) was calculated by using the present field intensity of 0.4 Oe. These results are listed in Table 7 and discussed in the following part of this section.

The lithological unit from which the paleomagnetic samples were taken is indicated in Table 5. Since the degree of serpentinization can cause a large change in magnetic properties, samples from Units 1 and 3 and from Units 2 and 4 are compared; magnetic parameters are averaged over all the samples; samples from

Table 5	5. Natural	remanent	magnetization	properties of	peridotite samp	ples.

	Sub-bottom	NRM			
Sample	depth (m)	Intensity (10 ⁻⁶ emu/cm ³)	Inclination (degrees)	Lithological unit	Orientation
109-670A-1D-1, 19-21	8.59	4010	-9.0	1	no
109-670A-2D-1, 45-47	29.88	1992	54.6	1	no
109-670A-3W-1, 12-14	14.72	4310	24.6	1	no
109-670A-4W-1, 19-21	36.56	231	5.1	1	poor
109-670A-5R-1, 111-113	48.68	3703	29.2	2	good
109-670A-5R-1, 126-128	49.14	8257	51.9	2	good
109-670A-5R-2, 52-54	51.53	1333	2.9	2	poor
109-670A-6R-1, 4-6	55.20	145	28.7	3	poor
109-670A-7R-1, 43-45	67.49	7197	71.5	4	no
109-670A-9R-1, 107-109	91.84	44	68.3	4	poor

Table 6. Demagnetization steps, Hole 670A.

Natural remanent magnetization	Circular standard deviation	Intensity	Declination	Inclination
Sample 109-670	A-1D-1, 19-2	21		
	1.9	4009.76	309.8	-9.0
50	1.7	4390.39	311.5	-7.8
100	1.7	4999.44	312.0	-8.5
150	1.6	5141.54	313.5	-9.1
200	1.4	5076.56	313.7	-9.2
300	1.3	4184.41	313.4	-9.6
400	0.9	2947.94	312.7	-9.8
500	1.0	1821.94	310.9	-9.4
600	1.4	1005.05	308.3	-8.8
800	2.1 4.5	504.41 232.08	302.5 284.6	-11.2 -26.5
Sample 109-670	A-2D-1, 45-4	47		
	2.9	1992.08	337.5	54.6
20	2.5	1637.10	344.0	49.2
50	1.6	1292.24	342.6	45.5
100	1.5	918.74	342.0	45.3
150	1.4	710.11	344.2	46.8
200	1.8	573.89	344.6	47.9
300	2.1	384.70	343.3	48.9
400	1.8	207.13	341.7	48.1
800	7.5	28.64	319.6	28.1
Sample 109-670	A-3W-1, 12-	14		
	2.1	4309.74	167.9	24.6
20	2.3	4246.41	166.4	25.0
50	2.1	4004.57	165.4	26.0
100	1.9	3464.19	164.2	26.5
150	1.5	2853.77	163.8	24.8
200	1./	2380.99	161.0	23.5
300	1.5	1/34.97	167.4	23.3
600	2.5	573.08	164.0	26.6
800	3.0	286.41	169.8	24.4
Sample 109-670	A-4W-1, 19-3	21		
	1.8	231.45	154.9	5.1
20	0.9	209.27	185.2	-1.6
30	1.3	219.32	199.1	-7.6
40	1.4	222.59	204.4	-4.3
50	1.2	224.63	208.3	-4.8
70	1.2	200.73	211.3	-7.0
150	2.0	126 34	214.0	- 3.8
200	1.6	89.50	216.7	-39
300	2.4	47.58	211.1	-2.6
400	2.9	33.84	207.3	-1.4
600	3.5	22.45	210.7	0.6
800	2.7	15.10	203.8	2.2
Sample 109-670	A-5R-1, 111-	113		
	1.8	3703.20	325.4	29.2
20	1.6	2860.02	317.1	17.7
30	1.0	1029 14	318.0	5./
50	1.0	1560 25	317.1	2.0
70	1.6	981 59	315.8	-17
100	1.4	489.36	313.8	-4.4
130	1.6	266.47	311.6	-4.7
160	1.3	161.97	317.7	- 5.8
200	1.9	118.17	304.5	- 5.4
250	3.9	70.99	309.4	-3.6
300	3.8	41.62	305.3	1.9
400	7.5	34.17	287.2	6.7

Table 6 (continued).

Natural remanent magnetization	Circular standard deviation	Intensity	Declination	Inclinatior
Sample 109-670	A-5R-1, 126-	-128		
	1.3	8256.97	108.2	51.9
10	1.3	6634.01	104.8	47.5
20	1.9	4840.20	100.7	29.7
30	1.5	3682.97	100.0	27.6
50	2.0	2458.66	99.0	14.1
70	2.7	1492.31	97.2	8.9
100	4.1	/03.3/	97.5	5.4
200	10.5	201 78	98.4	7.7
250	11.2	159.93	97.3	6.4
300	11.3	139.23	95.8	9.1
400	12.8	126.32	96.1	8.9
600	13.5	91.44	94.5	18.3
Sample 109-670.	A-5R-2, 52-5	54		
10	3.3	1332.56	351.0	2.9
20	2.0	1429.42	333.0	- 3.3
30	3.0	1151 93	317.8	- 23 5
50	2.7	898.64	316.5	-27.9
70	2.2	610.56	313.7	- 31.4
100	2.7	304.36	310.3	- 33.0
150	3.3	137.53	308.5	- 29.8
200	2.7	67.79	315.3	-29.1
250	4.4	43.09	304.8	-21.4
300 400	3.3 8.4	27.91 10.25	315.9 324.3	- 17.3 18.3
Sample 109-670/	A-6R-1, 4-6			
	3.7	145.25	153.1	28.7
10	3.0	132.92	150.2	24.7
20	2.7	134.18	146.8	18.8
30	2.8	132.38	148.5	21.2
50	2.8	134.51	147.1	19.1
70	2.7	120.33	148.8	17.7
100	2.0	90.99	145.4	14.5
200	2.0	33.87	149.1	14.2
250	2.1	20.07	150.7	6.3
300	1.3	11.12	155.7	-1.0
400	2.3	4.96	161.9	-29.1
Sample 109-6704	A-7R-1, 43-4	5		
	2.4	7197.01	309.3	71.5
10	2.1	6038.91	312.1	72.7
30	0.5	3973.12	323.6	69.3
100	1.0	476.00	333.3	47.5
150	4.8	182.24	353.3	37.2
200	6.2	89.88	342.8	28.1
300	8.7	37.56	318.9	18.9
400	6.7	18.93	75.0	53.6
600	5.6	24.68	268.5	37.9
ample 109-670A	A-9R-1, 107-	109	07.1	<i>(</i> 0.2
10	2.1	43.91 39.12	86.1 91.7	68.3 69.9
20	1.0	37.17	96.8	70.9
30	1.6	35.97	98.5	71.3
50	0.3	34.04	107.6	72.1
70	0.6	33.12	111.6	72.1
100	1.3	32.27	114.9	72.3
150	1.2	30.15	117.5	72.7
200	1.2	29.24	123.0	73.0
400	2.3	20.17	127.5	71.0
500	2.4	20.44	142 3	71.6
600	3.4	18.12	139.4	71.4
800	4.2	15.83	145.8	69.8
000				

Table 7. Magnetic properties of peridotite samples.

Sample	Sub-bottom depth (m)	NRM intensity (10 ⁻⁶ emu/cm ³)	MDF (Oe)	Stable inclination (degrees)	Susceptibility (10 ⁻⁶ G/Oe)	Q-ratio (H = 0.4 Oe)
109-670A-1D-1, 19-21	8.59	4010	484	-8.9	3548	2.83
109-670A-2D-1, 45-47	29.88	1992	90	45.8	2172	2.29
109-670A-3W-1, 12-14	14.72	4310	226	25.8	2639	4.08
109-670A-4W-1, 19-21	36.56	231	161	-4.8	412	1.40
109-670A-5R-1, 111-113	48.68	3703	41	-2.0	8787	1.05
109-670A-5R-1, 126-128	49.14	8257	25	4.5	8796	2.35
109-670A-5R-2, 52-54	51.53	1333	66	-29.2	4487	0.74
109-670A-6R-1, 4-6	55.20	145	128	16.9	328	1.11
109-670A-7R-1, 43-45	67.49	7197	34	-13.8	8521	2.11
109-670A-9R-1, 107-109	91.84	44	450	74.7	36	3.06

Units 1 and 3 and samples from Units 2 and 4 are summarized in Table 8.

NRM Intensity

The NRM intensity varies from 44 to $8257 \times 10^{-6} \text{ emu/cm}^3$ (Table 7), spanning more than two orders of magnitude difference among the 10 samples. Since the original peridotites do not contain magnetite, all the magnetic properties arise from the serpentinization. The variation of the magnetization reflects the degree of the serpentinization. The increase in the magnetization intensity is to be expected because of the precipitation of magnetite from the serpentinization of olivine, although some other factors, such as original olivine content or later alteration, would modify the intensity. As evident from Table 8, Units 2 and 4 are characterized by higher intensity, compared with Units 1 and 3. This can be explained by the difference in the degree of serpentinization; Units 1 and 3 are more highly serpentinized. Because the serpentinization occurs under 500°C, which is less than the Curie temperature of magnetite, the origin of the remanence may be chemical remanent magnetization (CRM) or partial thermo-remanent magnetization (PTRM).

Figure 18A shows the depth variation of the NRM intensity. Through Unit 1, the intensity decreases with depth. This feature may be attributed to the decrease in degree of serpentinization with depth, although the number of samples studied is not enough for a detailed discussion. The samples from Units 2 and 4 have very high intensity, though the scattering is also high. In contrast, Samples 109-670A-4R-1, 19-21 cm, and 109-670A-6R-1, 4-6 cm, from the lower part of Unit 1 and the upper part of Unit 3 have very low intensities of magnetization. Microscopic study indicates that the degree of serpentinization in these samples is relatively low. The lowest intensity was observed in Sample 109-670A-9R-1, 107-109 cm. Because this minicore sample was taken from a serpentine-chlorite-tremolite vein, the vein fill does not contain the magnetic minerals.

The high intensity exhibited by the serpentinized peridotite compares to the mean intensity of basalt samples from Hole 648B and also to the intensity expected in the source layer of the magnetic lineation. Most of the basalt samples recovered from DSDP and ODP holes have a magnetization intensity much

Table 8. Mean characteristics of magnetic parameters.

	All sa (N =	mples = 10)	nples Units 10) (N		Units 2 and 4 (N = 4)	
NRM intensity (10 ⁻⁶ emu/cm ³)	3122.2	2919.0	1788.7	1975.1	5122.5	3188.7
MDF (Oe)	170.5	168.4	256.5	169.4	41.5	17.6
Susceptibility (10 ⁻⁶ G/Oe)	3972.6	3559.9	1522.5	1458.8	7647.8	2111.0
Q-ratio	2.10	1.05	2.46	1.10	1.56	0.79

Figure 18. Depth plots of NRM intensity and stable inclination of the serpentinized peridotite from Hole 670A. A. NRM intensity. B. Stable inclination.

smaller than this. Hence, depending on the thickness or extent of the body, the serpentinized peridotite can affect the magnetic anomalies. The magnetic field caused by a highly serpentinized body 500 m thick compares to the amplitude of the magnetic lineations observed at sea level.

Stable Inclination

Unfortunately, most of the present samples are not oriented or are poorly oriented. Only two samples (109-670A-5R-1, 111-113 cm, and 109-670A-5R-1, 126-128 cm), both from Unit 2, give a reasonable orientation. These two samples show very shallow inclinations of -2.0° and 4.5° , respectively. Including three other poorly oriented samples, the mean inclination is -6.3° . Although the number of samples is far from sufficient, this very shallow inclination value of the serpentinite body compared with the present field direction can be inferred from the present observation. No systematic variation with depth is observed in Figure 18B. The origin of the shallow inclination is not obvious; in some oriented samples, horizontal foliations, probably caused by horizontal extension, are observed. If magnetite grains precipitate along the foliation, they may cause the magnetic anisotropy. The magnetic anisotropy affects the magnetization direction and can be one explanation for the nearly horizontal stable inclination. However, the rotation of the serpentinite body after it acquired remanence is another possible explanation. In either case, the use of serpentinite for the paleomagnetic study is rather discouraging.

MDF and Demagnetization Characteristics

Highly serpentinized samples from Units 2 and 4 give MDF values <70 Oe, whereas other samples show higher MDF values (Table 7). MDF values are plotted vs. depth in Figure 19A. The low MDF in the highly serpentinized samples may indicate large magnetite grain sizes as observed in the samples from Units 2 and 4. However, such a tendency is not obvious within Unit 1, where a decrease in the degree of serpentinization with depth can be seen.

Very high MDF values observed in Samples 109-670A-1D-1, 19-21 cm, and 109-670A-9R-1, 107-109 cm, need some explanation. As evident from the demagnetization steps shown in Table 6, the magnetization of Sample 109-670A-1D-1, 19-21 cm, is composed of two components. The directions of these two components are almost antipodal with each other, causing the observed high MDF. The magnetic minerals that carry these two components may be magnetite grains with two different grainsize distributions. Microscope study indicates that two types of magnetite grains exist within these samples; one exists within the serpentinized region, and the other exists along the boundaries of the veins intruding into the serpentinized areas. These two grain populations might have caused the observed two components; the origin of each component is currently unclear. One possibility is that these components represent different polarities of the Earth's magnetic field. This type of the demagnetization curve is common in reversely magnetized rock samples. The soft component is commonly viscous remanent magnetization acquired by the present field.

Figure 19. Depth plots of median destructive field (MDF) and susceptibility of the serpentinized peridotite from Hole 670A. A. MDF. B. Susceptibility.

Susceptibility

Susceptibility of the 10 samples ranges from 36×10^{-6} G/ Oe to 8796×10^{-6} G/Oe (Table 7). The variation is closely correlated with that of the NRM intensity. High susceptibility is observed in Units 2 and 4; the degree of serpentinization is high in these units. A gradual decrease in the susceptibility with depth can be seen in Unit 1 (Fig. 19B), mainly because of a change in the content of magnetite grains.

The mean susceptibility of the basalts from Hole 648B is 1270×10^{-6} G/Oe, and the susceptibility of samples from other sites on the ocean floor is comparable to or smaller than this value. For example, the mean susceptibility of the dredged samples from the FAMOUS area is about 300×10^{-6} G/Oe. Compared with the susceptibilities in oceanic basalt, the susceptibility of the present serpentinized peridotite has much higher values. As shown in Table 8, the mean and the standard deviations of the susceptibilities of all the samples are 3973×10^{-6} G/Oe and 3560×10^{-6} G/Oe, respectively. For the highly serpentinized samples from Units 2 and 4, the mean value is 7649×10^{-6} G/Oe. The high susceptibility in these serpentinized peridotites can be explained by the presence of a large amount of magnetic minerals in these rocks.

Q-Ratio (Königsberger Ratio)

Q-ratio varies from 0.74 to 4.8 (Table 7), much smaller (about one order of magnitude) than that of oceanic basalts. The difference between the samples from Units 1 and 3 and the samples from Units 2 and 4 is not evident, in contrast to differences between other magnetic properties, such as the NRM intensity and the susceptibility. The observed low Q-ratio indicates that the induced magnetization of the serpentinized peridotites causes the appreciable magnetic anomalies as well as the remanent magnetization.

Discussion

Present measurements indicate that the intensity of the magnetization and the magnetic susceptibility in the serpentinized peridotite are high. The intensity compares to that of oceanic basalts obtained either by dredging or drilling; the susceptibility of the serpentinized peridotites is much higher than that of most basalt rocks. Compared with those of basalts, the scatter of these magnetic parameters of the serpentinized peridotites is also high. The variation of these parameters with the degree of serpentinization was also confirmed by these measurements. An increase in magnetic mineral content with serpentinization causes the variation. However, it is not appropriate to apply the present results to all the serpentinized bodies observed on the seafloor. Magnetic properties can easily be changed by many factors, such as the original olivine content, the temperature, and the water content during the serpentinization. Later alteration also causes a large change in the magnetic properties. Cretaceous serpentinized peridotites recovered during ODP Leg 103 show smaller intensities of magnetization (by a factor of about 2 or 3) (Boillot, Winterer, Meyer, et al., 1987). Other magnetic properties of these rocks are not reported. Since these results indicate the importance of the serpentinized peridotites as a source of the magnetic anomalies, more systematic study of these rocks must be done to understand the validity of the original Vine-Mathews hypothesis.

The shallow inclination of the magnetization in the samples is not easy to explain. It may indicate a subsequent rotation of the serpentinized body or may be magnetic anisotropies caused by the deformation of the body. The rotation should have occurred after the acquisition of the remanence, that is, after the completion of the serpentinization. On the other hand, the deformation could have occurred either after or before the acquisition of the remanence. Anisotropic texture produced by the deformation before the precipitation of magnetites can cause such an anisotropy. To clarify these possibilities, more detailed magnetic studies are required.

Conclusions

Ten serpentinized peridotite samples were paleomagnetically processed and found to have very high intensities of magnetization and magnetic susceptibility. Higher intensity and higher susceptibility are observed in the samples with the highest degree of serpentinization. The NRM intensity is high enough to affect the magnetic anomalies observed at sea surface if the thickness of the serpentinized body is more than a few hundred meters. The few oriented samples showed a very shallow, stable inclination. Currently, the cause of the shallow inclination is not apparent.

PHYSICAL PROPERTIES

The 10 paleomagnetic samples (see previous section) were also used for a standard suite of physical-properties determinations.

The methods used to determine bulk density, saturated sonic velocity, and porosity are described in detail in the Site 648 chapter "Physical Properties" section (this volume) and will not be repeated here. Sonic velocity and GRAPE density of the dried samples were not determined owing to time constraints.

Results

These samples are less dense, have lower sonic velocities, and are more porous than the basalts from Sites 648 and 669. Average bulk density is 2.564 g/cm^3 , and average porosity is 9.9%, yielding an average grain density of 2.726 g/cm^3 . The average velocity is 3.97 km/s. The data are summarized in Table 9.

A review of Table 9 shows no obvious correlation between any of the physical properties. This is not surprising because correlations between, for example, density and porosity require constant mineralogy. Similarly, the inverse correlation between sonic velocity and porosity generally holds only for rocks of similar chemical composition.

However, a detailed comparison between these properties and sample petrology reveals that some relationships hold for this set of samples. These rocks fall into two general families: (A) serpentinites, dark with >90% serpentine pseudomorphing olivine, spinels generally oxidized to magnetite, and crosscutting chrysotile veins; and (B) partly serpentinized harzburgites, pale green with large (>1 cm) orthopyroxene grains and minor amounts of clinopyroxene and spinel. Several rocks (C) are intermediate between these two end-members. One anomalous sample (D) is mainly fibrous antigorite and tremolite. These classifications are noted in Table 9.

The data, in light of these petrographic differences, reveal some interesting relationships. The serpentinites (which are the most intensely altered) have the lowest density, the harzburgites the highest, whereas the intermediate samples have intermediate densities. One exception is Sample 109-670A-2D-1, 45-47 cm, which is anomalous probably because of additional low-temperature alteration in contact with seawater. Modal mineralogy does not control sonic velocity, although the fibrous antigorite/tremolite has the highest velocity. Similarly, no relationship between porosity and modal mineralogy exists.

The grain density of serpentine is approximately 2.55 g/cm³, whereas olivine, orthopyroxene, and clinopyroxene have densities near 3.3 g/cm³. Modal estimates of the concentration of unaltered material in these samples range from about 30% for Sample 109-670A-6R-1, 4-6 cm, to <5% (Table 2). According to these densities and the modal proportions, the grain density of Sample 109-670A-6R-1D, 4-6 cm, should be 2.775 g/cm³. The computed grain density for this sample is 2.82 g/cm³, slightly greater than its expected value, suggesting that the porosity may be underestimated. This is not unlikely, as these samples probably contain some trapped fluids, which could not be fully removed by shipboard techniques in the time available.

Figures 20 through 22 show velocity, density, and porosity as a function of sample depth. Separating these samples into lithostratigraphic units on the basis of their physical properties is not a straightforward process. The boundaries between the four identified units are at 46, 52, and 66.5 mbsf (Fig. 3). Unit 2 is characterized by uniformly low density; two of the samples also have low velocities. The upper sample from Unit 3 has high density and velocity, whereas the lower sample is less dense. Unit 1 has intermediate velocities, trending downward as the serpentinization decreases. The decrease in serpentinization is associated with an increased porosity, which explains this effect. The lowermost unit is represented by only a single sample, which, although it may represent the competent materials within this unit, cannot be used to infer the average properties.

Conclusions

The 10 samples studied are highly heterogeneous. Although they are characterized by uniformly low velocities and densities, variations in petrology and alteration control their properties. However, within individual units, the properties can be related to recognizable changes in alteration and mineralogy, and the expected relationships between porosity, density, and velocity can be observed.

Table 9. Computed values of physical properties of core samples from Hole 670A. Letters refer to categories described in the text.

Sample	Туре	Bulk density (g/cm ³)	Grain density (g/cm ³)	Porosity (%)	Sonic velocity (km/s)
109-670A-1D-1, 19-21 cm	С	2.590	-	_	—
109-670A-2D-1, 45-47 cm	aC	2.506	—		3.99
109-670A-3W-1, 12-14 cm	С	2.555	2.711	9.2	4.10
109-670A-4W-1, 19-21 cm	B	2.605	2.789	10.4	3.68
109-670A-5R-1, 111-113 cm	A	2.520	2.760	13.8	3.60
109-670A-5R-1, 126-128 cm	A	2.533	2.652	7.3	3.66
109-670A-5R-2, 52-54 cm	A	2.537	2.708	10.1	4.09
109-670A-6R-1, 4-6 cm	В	2.660	2.821	9.0	4.05
109-670A-7R-1, 43-45 cm	A	2.523	2.659	8.3	3.63
109-670A-9R-1, 107-109 cm	D	2.542	2.705	9.7	4.90
Average		2.564	2.726	9.9	3.97

^a Altered in contact with seawater.

Figure 20. Velocity as a function of depth, samples from Hole 670A.

THERMAL CONDUCTIVITY

The thermal conductivity of 12 samples of serpentinites and serpentinized harzburgites from Hole 670A was measured with the Thermcon half-space needle device, as outlined in detail in

Figure 22. Porosity as a function of depth, samples from Hole 670A.

the "Thermal Conductivity" section of Site 648 chapter (this volume). Table 10 shows the results of Hole 670A measurements. The thermal conductivities measured range from 2.12 to 3.06 W/m \times °C with a mean of 2.71 W/m \times °C for the serpentinites, and from 2.05 to 2.40 W/m \times °C with a mean of 2.29 W/m \times °C for the harzburgites. Compared with that of the basalts, the conductivities measured on these rock samples are distinctly higher. Thermal conductivities of the serpentinite samples show a relatively high variation. From a preliminary comparison of these thermal-conductivity measurements with the results of the physical-properties measurements ("Physical Properties" section, this chapter), no indication of a significant correlation was obtained.

SUMMARY AND CONCLUSIONS

Hole 670A was a twofold success:

First, from a technological point of view, it demonstrated the feasibility of the following operations:

1. Spudding over a slightly sedimented area.

Starting a hole with the aid of a PDCM in the underlying serpentinite basement.

3. Changing the bit and making a successful reentry in the hole in <15 min (time between the first image of the seafloor given by the television camera and the actual penetration of the BHA inside the hole).

4. Coring close to 100 mbsf with the classical rotary system.

The unsupported coring conditions did not allow a good recovery; we got 1.7% to 17% recovery, enough, however, for fulfilling scientific purposes. Used in fault-dominated and rough areas, such as fracture zones, the unsupported spudding technology should allow us to get *in-situ* samples of serpentinized peridotite outcrops as deep as 100 mbsf and even deeper if casing is set in the hole. A low recovery will probably be normal in such drilling conditions, but the recovered material will be at

Table 10. Results of thermal-conductivity	measurements on	a serpen-
tinites and harzburgites, Hole 670A.		

Section	Distance from top of section (cm)	Thermal conductivity (W/m × °C)			
		2.52	(2.93)		
109-0707119-1 (0)	10-25	2 51	(2.81)		
		2.52	(2.93)		
		1		2.52	(2.82)
109-670A-5R-1 (H) 109-670A-5R-1 (S) 109-670A-5R-1 (S)	8-15	1.98	(2.11)		
		2.12	(2.22)		
				2.05	(2.17)
	57-58	3.03	(3.05)		
		3.05	(3.51)		
		3.04	(3.43)		
		3.03	(3.61)		
	12027022227	00000	122712425	3.03	(3.40)
	110-120	2.74	(2.84)		
		2.74	(2.91)		
109-670A-5R-1 (S)				2.74	(2.88)
	123-143	3.07	(3.54)		
		3.04	(3.33)		
				3.06	(3.44)
109-670A-5R-2 (S)	18-26	2.95	(2.88)		
		3.00	(3.12)		
109-670A-5R-2 (S)	10.01			2.98	(3.00)
	49-51	2.40	(2.35)		
		2.47	(2.74)		
109-670A-5R-2 (H)	1000000	2002		2.44	(2.55)
	105-112	2.42	(2.80)		
		2.37	(2.52)		
				2.40	(2.66)
109-6/0A-5K-2 (H)	139-145	2.35	(2.63)		
		2.31	(2.17)		
109-670A-6R-1 (H)				2.33	(2.40)
	0-8	2.40	(2.34)		
		2.34	(2.90)		
100 (201 20 11 20				2.39	(2.62)
109-670A-7R-1A (H)	42-46	2.75	(3.21)		
		2.81	(3.45)		
100 (7 01 0 0 1 (77)				2.78	(3.33)
109-670A-9R-1 (H)	104-116	2.09	(2.17)		
		2.14	(2.36)		
				2.12	(2.26)

S = serpentinites.

H = harzburgites.

least partly oriented and much less altered than any dredged material of the same nature.

The contrasting degrees of success we met with in Holes 669A and 670A demonstrate that mantle peridotites are easier to drill with mud motors than are the hard gabbros of layer 3; this is probably mainly due to the well-known lubricating properties of the serpentine minerals. More experience is certainly needed to test and improve the feasibility of drilling gabbros during spudding attempts.

Second, from a scientific point of view, Hole 670A yielded one of the very few sections of oceanic upper mantle ever drilled, 92.5 m being cored in the serpentinized peridotite basement. Serpentinized peridotites were met in several crustal sections during Legs 37, 45, and 82, for instance, but always as layers of rubble blocks interbedded with basaltic flows. Only the section of serpentinized peridotites recovered in Hole 637A during Leg 103 on the Galicia Bank can be compared to the Hole 670A section (Boillot, Winterer, Meyer, et al., 1987, Site 637 chapter).

In Hole 637A, 73.6 m of peridotites was cored beneath a cover of 212 m of Neogene sediments. Both sections have several common characteristics: (1) They are made of clinopyroxene-bearing harzburgites. (2) They show a downward decreasing

degree of serpentinization, the first few meters being totally serpentinized. (3) Several serpentinite shear zones appear at different levels in the sections. (4) Both sections exhibit a strong foliation of the primary phases, macroscopically marked by the flattening and stretching of pale whitish orthopyroxene porphyroclasts and black chromite grains; this foliation has a rather flat, gentle dip: about 20° in the few oriented samples of our section and 30° in Hole 637A (in which, however, the foliation steepens to 75° near the bottom of the hole). (5) Another prominent feature of these peridotites is the occurrence of abundant crosscutting veins of serpentine and calcite with complicated patterns and chronological relationships and the local development of serpentine breccias. (6) Physical and magnetic properties of these mantle rocks appear to be strongly dependent on the degree of serpentinization of the initial peridotite. In both sections, the inclination of the magnetic vector seems to be influenced by the internal mantle deformation structures.

The poor recovery in Hole 670A, 1.7%-17%, compared with about 50% in Hole 637A (which was cored with the classical rotary system under >200 m of sediment), is partly compensated by the quality of some of the harzburgite samples, several of them having <50% serpentine.

The material from the upper-mantle section so far obtained in Hole 670A appears adequate for the following shore-based studies:

1. Primary mineralogy and geochemistry: microprobe analyses of the four primary phases (olivine, orthopyroxene, clinopyroxene, and spinel) and X-ray fluorescence and neutron activity analyses of the whole rocks; geothermometry, geobarometry, degree of partial melting, parental relationships with the Kane Fracture Zone basalts.

2. Structural study of the high-temperature mantle deformations: U-stage fabrics of the freshest harzburgites; evaluation of the stress/strain pattern and conditions of the deformation (plastic flow vs. flattening by uniaxial vertical compression).

3. Physical and magnetic properties of the peridotite body: density, porosity, susceptibility, and NRM variations vs. degree of serpentinization; influence of a peridotite outcrop on the pattern of the sea-surface magnetic anomalies.

4. Secondary mineralogy: microprobe, X-ray diffraction, and scanning-electron-microscope analyses of the serpentine and associated phases (carbonates, etc.); oxygen-isotope studies; structural and chronological study of the vein net and concentric alteration aureoles; mechanisms of serpentinization at different scales; static vs. dynamic (shear zones) serpentinization at different scales; isovolumetric vs. nonisovolumetric serpentinization; local and global geochemical budget of serpentinization.

Many fundamental problems raised by the existence of this serpentinized mantle body on the western flank of the rift valley, about 50 km from the Kane Fracture Zone intersection, should be addressed by these shore-based studies and we hope also by future diving and drilling programs.

REFERENCES

- Arai, S., and Fujii, T., 1979. Petrology of ultramafic rocks from Site 395. In Melson, W. G., Rabinowitz, P. D., et al., Init. Repts. DSDP, 45: Washington (U.S. Govt. Printing Office), 587-594.
- Aumento, F., 1970. Serpentine mineralogy of ultramafic intrusives in Canada and on the Mid-Atlantic Ridge. Geol. Surv. Can. Comm., 69-53.
- Aumento, F., and Loubat, H., 1971. The Mid-Atlantic Ridge near 45°N. XVI. Serpentinised ultramafic intrusions. Can. J. Earth Sci., 8:631– 633.
- Avé Lallemant, H. G., 1975. Mechanisms of preferred orientations of olivine in tectonite peridotite. *Geology*, 3:653-656.
- Boillot, G., Winterer, E. L., Meyer, A. W., et al., 1987. Proc., Init. Repts., (Pt. A), ODP, 103 College Station, TX (Ocean Drilling Program).

- Bonatti, E., and Hamlyn, P. R., 1981. Oceanic ultramafic rocks. In Emiliani, C. (Ed.), The Sea, The Oceanic Lithosphere (vol. 7): New York (Wiley), 241-283.
- Bonatti, E., Lawrence, J. R., and Morandi, N., 1984. Serpentinization of ocean-floor peridotites. *Earth Planet. Sci. Lett.*, 70:88-94.
- Boudier, F., 1978. Structure and petrology of the Lanzo peridotite massif, Piedmont Alps. Geol. Soc. Am. Bull., 89:1574-1591.
- Bowen, N. L., and Tuttle, O. F., 1949. The system MgO-SiO₂-H₂O. Geol. Soc. Amer. Bull., 60:439-460.
- Casey, J. F., Dewey, J. F., Fox, P. J., Karson, J. A., and Rosencrantz, E., 1981. Heterogeneous nature of the oceanic crust and upper mantle: a perspective from the Bay of Islands ophiolite complex. *In Emi*liani, C. (Ed.), *The Sea, The Oceanic Lithosphere* (vol. 7): New York (Wiley), 305-338.
- Deer, W. A., Howie, R. A., and Zussman, J., 1962. An Introduction to the Rock-Forming Minerals, Sheet Silicates (vol. 3): London (Longman).
- Detrick, R. S., Ryan, W.B.F., Mayer, L., Fox, P. J., Kong, L., Manchester, K., Kastens, K., Karson, J., and Pockalny, R., 1985. Mid-Atlantic Ridge/Kane Fracture Zone final site survey report. *Joint Oceanographic Institutions*.
- Elthon, D., 1981. Metamorphism in oceanic spreading centers. In Emiliani, C. (Ed.), The Sea, The Oceanic Lithosphere (vol. 7): New York (Wiley), 285-303.
- Francis, T.J.G., 1981. Serpentinization faults and their role in the tectonics of slow spreading ridges. J. Geophys. Res., 86:11616–11622.
- Green, D. H., and Ringwood, A. E., 1967. The genesis of basalt magmas. Contrib. Mineral. Petrol., 15:104-167.
- Hodges, F. N., and Papike, J. J., 1976. DSDP Site 334: magmatic cumulates from oceanic layer 3. J. Geophys. Res., 81:4135-4151.
- Karson, J. A., Thompson, G., Humphris, S., Edmond, J. N., Bryan, W. B., Winters, A. T., Brown, J. R., Pockalny, R. A., Casey, J. F.,

Campbell, A. C., Klinkhammer, G. P., Palmer, M. R., Kinzler, R., and Sulanowska, N. N., in press. Along-strike variations in seafloor spreading in the MARK area. *Nature*.

- Laurent, R., 1975. Petrology of Alpine-type serpentinites of Asbestos and Thetford Mines, Quebec. Schweiz. Mineral. Petrog. Mitt., 55: 431-455.
- Mercier, J.-C.C., and Nicolas, A., 1975. Textures and fabrics of uppermantle peridotites as illustrated by xenoliths from basalts. J. Petrol., 16:454-487.
- Michael, P. J., and Bonatti, E., 1985. Peridotite composition from the North Atlantic: regional and tectonic variations and implications for partial melting. *Earth Planet. Sci. Lett.*, 73:91-104.
- Miyashiro, A., Shido, F., and Ewing, M., 1969. Composition and origin of serpentinites from the Mid-Atlantic Ridge near 24° and 20° north latitude. *Contrib. Mineral. Petrol.*, 23:117-127.
- Presnall, D. C., Dixon, J. R., O'Donnell, T. H., and Dixon, S. A., 1979. Generation of mid-ocean ridge tholeiites. J. Petrol., 20:3-35.
- Prinz, M., Keil, K., Green, J. A., Reid, A. M., Bonatti, E., and Honnorez, J., 1976. Ultramafic and mafic dredge samples from the equatorial Mid-Atlantic Ridge and fracture zones. J. Geophys. Res., 81: 4087-4103.
- Purdy, G. M., and Detrick, R. S., 1986. Crustal structure of the Mid-Atlantic Ridge at 23°N from seismic refraction studies. J. Geophys. Res., 91:3734-3762.
- Riordon, P. H., 1955. The genesis of asbestos in ultrabasic rocks. Econ. Geol., 50:50–65.
- Sinton, J., 1979. Petrology of (alpine type) peridotites from Site 395, DSDP Leg 45. In Melson, W. G., Rabinowitz, P. D., et al., Init. Repts. DSDP, 45: Washington (U.S. Govt. Printing Office), 595-602.
- Winkler, H.G.F., 1976. Petrogenesis of Metamorphic Rocks (4th ed.): New York (Springer-Verlag).

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109-670A-2D-1

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109-670A-4W-1

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109-670A-7R-1

109-670A-7R-1

UNIT 4: SERPENTINITE

Pieces 6-13

COLOR: Black and white mottled.

LAYERING: Not apparent.

DEFORMATION: Possible shear zones between Pieces 7A and 7C and between 13B and 13D; parts of Piece 6 were embedded in sheared matrix material. Material was removed and placed with Pieces 7B, 13C, and 6B, respectively.

Piece 6: Serpentine-rich material consisting of massive light green fibers surrounding pieces. Pieces 7A and 7C: Separated by a massive serpentine vein approximately 1.5 cm thick consisting of light green serpentine needles >1 cm in length; both pieces contain talc + serpentine-rich layer on one side which defines the boundary of the shear zone.

Piece 13: Massive serpentine-rich zones between Pieces 13A, 13B, and 13D, similar to those found between 7A and 7C.

No apparent foliation defined by elongate minerals.

PRIMARY MINERALOGY:

Olivine - Mode: 95%.

Crystal size: Indeterminate in hand specimen.

- Crystal shape: Cannot be determined in hand specimen.
- Preferred orientation: Not apparent.

Percent replacement: 100% with serpentine, talc, and magnetite.

Orthopyroxene - Mode: 4-5%.

Crystal size: 2-6 mm.

Crystal shape: Round.

Preferred orientation: Not apparent.

Percent replacement: As much as 90% with serpentine + talc.

Spinel - Mode: 1-<1%.

Crystal size: <1 mm.

Crystal shape: Round to elliptical.

Preferred orientation: Piece 10 defined by long axes of elliptical spinel grains.

Percent replacement: As much as 10%, rimmed with magnetite.

Clinopyroxene (Piece 9) - Mode: <1%.

Crystal size: 4 mm.

Crystal shape: Round.

Preferred orientation: Not apparent.

Percent replacement: 0%, fresh.

SECONDARY MINERALOGY:

Total percent: As much as 99%.

Texture: Olivine replaced by alternating bands of dark and light secondary phases, orthopyroxene

pseudomorphed by bastite and rimmed by talc, spinel rimmed by magnetite.

Percent vein material: As much as 5% in rock pieces, 1 mm to 2 cm thick.

Vein material: White talc veins as wide as 1 mm, blue-green opaline serpentine veins 2 mm wide, rich veins in Pieces 6–7 and 13 (see deformation section for description).

NOTE: Shading on graphic representation denotes freeze-dried vein material in correct stratigraphic position.

109-670A-8R-1

SITE 670

Shipboard Studies Graphic Representation Piece Number Orientation cm 0-50 -100 -

CORE/SECTION

10-1

109-670A-10W-1

DRILL CUTTINGS: SERPENTINITE, HARZBURGITE, HYALOCLASTITE, BASALT, AND SERPENTINE MINERALS

109-670A-10W-2

5 DRILL CUTTINGS: SERPENTINITE, HARZBURGITE, HYALOCLASTITE, BASALT, AND

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