Back–Arc Basin Lower Crust and Upper Mantle in the Northern Mariana Trough studied with "Shinkai 6500"

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Two dives of "Shinkai 6500" descended to depths of between 5,700 and 4,500m in the Central Graben of the Mariana Trough back-arc basin. The Central Graben is a zone of amagmatic extension that continues about 150km along strike and is defined bathymetrically by a series of basins lying along the rift zone. The dives (#358 & 359) examined rocks from the lowermost parts of a >3km high scarp on the eastern side of the southernmost and deepest basin. The dives discovered and sampled exposures of back-arc basin mantle (Dive 359) and sampled crustal materials from inferred debris flows (Dive 358) that originated higher up the scarp. Crustal units recovered during Dive 358 include variolitic basalt, diabase, and tonalite; fresh layered dunite-anorthosite-gabbro and totally serpentinized peridotite was also recovered. Dive 359 sampled partially serpentinized or otherwise altered (40 to 95%) harzburgite, along with subordinate lherzolite, pyroxenite, and dunite. Nine samples of gabbro were also recovered from 4 of the 6 sampling sites. We infer that the gabbroes represent dikes or sills intruded into the mantle peridotite. The petrologic Moho is inferred to be exposed at a water depth of about 4km. Further dives of "Shinkai 6500" and other studies are needed to fully understand the composition and structure of this possibly unique exposure of back–arc basin upper mantle and lower crust.

Key word : Mariana Trough, back-arc basin, Moho, uppre mantle, petrology

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1. Introduction

The Mariana Trough (Fig. 1A) is one of the best examples of an active back-arc basin (Fryer, 1995), with simple variations in extensional style along strike of the extension axis. Seafloor spreading occurs between 19°45'N and 14°N (Fig. 1B). At 18°N, where the Trough is widest, full spreading rates range between 3 and 4.4 cm/y (Hussong & Uyeda, 1981), similar to that of slow-spreading mid-ocean ridges (Fox & Gallo, 1984). North of 19°45'N and south 14°N, back-arc basin extension occurs by rifting (Martinez et al., 1995; Baker et al., 1996). Rifting north of 21°10'N is accompanied by igneous activity, but between 19°45'N and 21°10'N rifting is purely mechanical and has formed a series of asymmetric, fault-bounded deeps called the 'Central Graben' by Martinez et al. (1995). The southernmost of these contains the greatest depth in the Mariana Trough (∼5,700m) and exposes back-arc basin lower crust and upper mantle that was the target of two dives by "Shinkai 6500" during Dec. 1996. These exposures are of interest to a diverse group of earth scientists, because the lack of samples of back-arc basin oceanic crust has limited our understanding of back-arc basin lithospheric evolution as well as our ability to confidently infer the tectonic setting of ophiolites from their lower crustal and upper mantle components.

The structure of the Central Graben is poorly understood. We do not know the location of shallow earthquakes in the region, and no faults have been defined. Nevertheless, there is a low rate of sedimentation and we expect that bathymetry expresses structure. The overall structure is a complex graben that is composed of 4 asymmetric deeps (Fig. 1C). The southernmost (∼20°N) is a down- to-the east half-graben, as is the northernmost (∼21°N) and the easternmost of the central pair (∼20°35'N, 144°E). The westernmost of the central pair (∼20°35'N, 143°30') is a down-to-the west half graben, as is the narrow corridor that connects the southern and east-central graben. The structure is reminiscent of complex half-grabens that characterize continental rifts, such as the East African Rift Valley (Rosendahl, 1987). Similar structures have been documented for the earliest stages in the evolution of some back-arc basins such as the Sumisu Rift in the Bo-

nin arc (Taylor et al., 1991). Mutter & Karson (1992) argued that the exposure of lower crust and upper mantle results from movement on low-angle (∼30°) normal faults. This interpretation is consistent with the asymmetry observed for half-graben in the graben complex.

During the 1991 Tunes expedition aboard the R/V Thomas Washington, a single dredge haul (D45; 20°02.5'N, 144°04'E, 5,175–4,800 m depth) recovered a diverse suite of upper mantle and lower crustal rocks, including lherzolites, anorthositic and hornblende-rich gabbro, and felsic plutonic rocks. The crustal suite has the chemical and isotopic composition of back-arc basin crust, and ^{40}Ar-^{39}Ar analysis of a hornblende yielded an age of 1.8±0.6 Ma. Stern et al. (1996) interpreted the chemical, isotopic, and age data indicate that back-arc basin lithosphere formed magmatically about 1.8 Ma ago, perhaps by seafloor spreading, and was rifted sometime afterwards. This single dredge haul identified a valuable window into back-arc basin lower crust and upper mantle, but revealed nothing about the geologic relationships. Stern et al. (1996) concluded that the dredge collected samples from a talus pile at the base of the eastern scarp. A dredge haul from shallower portions (KH–84–1–23, 3,960–4,300 m; 20°07'N, 144°06'E) of the eastern scarp recovered tholeiitic basalts (Shibata and Segawa, 1985), suggesting that lower crustal and upper mantle exposures lie below 4 km. The purpose of "Shinkai 6500" Dives 358 and 359 was to examine the relationships along the scarp, with the twin objectives of 1) better understanding the igneous stratigraphy of the in situ ophiolite and 2) identifying and studying oceanic Moho on the ocean floor for the first time.

2. Field Studies

Dives 358 and 359 were conducted in the southernmost and deepest of the grabens (reaching depths of about 5,720m), which lies between 20°10'N and 19°50'N; we call this the 'Southern Basin'. We carried out a 50km by 60km bathymetric survey of the southernmost basin and the surrounding regions (Fig. 2). This survey revealed the asymmetric (down to the east) nature of the Southern Basin. This basin is linked with others to the north by a NNW-trending- and more sym-
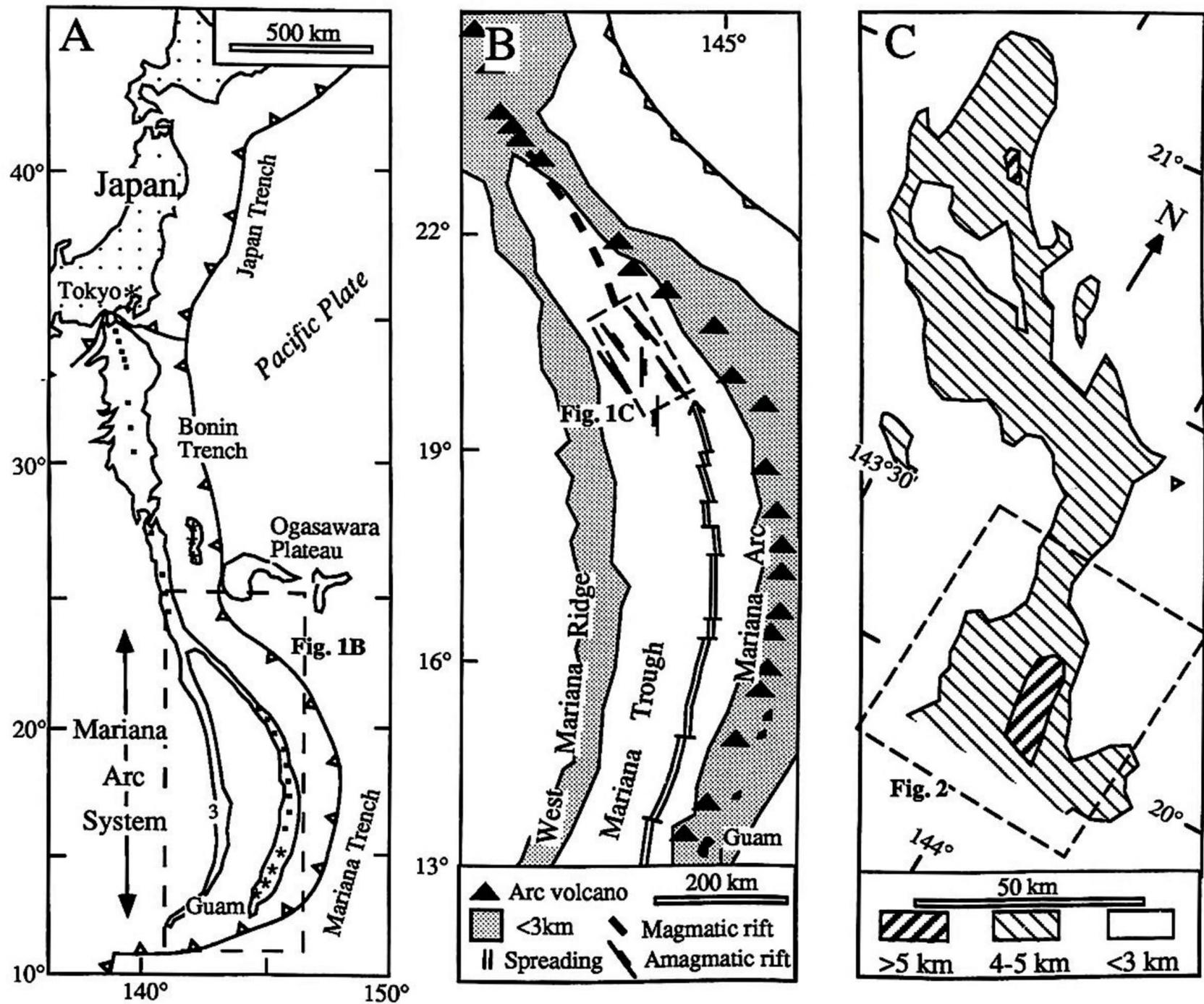
Fig. 1 Locality maps. (A) Location of the Mariana Arc system. Dashed box shows the location of Fig. 1B. (B) Location and principal tectonic elements of the Mariana Trough, showing regions affected by seafloor spreading and amagmatic and magmatic rifting. Dashed box shows the location of Fig. 1C. (C) Generalized bathymetry of the Central Graben and inferred boundary faults (modified after Stern *et al.*, 1996). Dashed box shows the location of Fig. 2.

metric- corridor. This 'Northern Corridor' is about 10 km wide and about 4,000 to 4,500m deep.

Yamazaki and Stern (in press) report the results of magnetic surveys over the Southern Basin and Northern Corridor. The data indicate the fault scarp on the east side of the Southern Basin lacks a significant magnetic anomaly, in spite being over 3km high. This indicates that very weakly magnetized rocks make up the eastern wall, an interpretation that agrees with the results of Dive 359 which discovered exposed mantle on the lower slopes. Mantle peridotite is generally considered to have weak magnetization. The Southern Basin may have formed by 'Basin and Range' faulting, along a low-angle normal fault that dips to the west (Stern *et al.*, 1996). Several ENE-WSW trending cross-faults may be small

and incompletely developed accommodation zones such as those characteristic of the East African Rift (Rosendahl, 1987).

Dive 358 started near the maximum depth in the Southern Basin, beginning at 5,711m and climbing to 4,713m; about 2.6km of horizontal distance was covered. The traversed slope displayed a surface of mud and blocks of different sizes and lithologies. We interpret this as a debris-flow deposit, except for a possible outcrop at 5,100m. Most rocks collected during Dive 358 are from the crust: tonalite, diabase, altered basalt and minor gabbro make up 12 of 14 samples; only samples of serpentinite were obtained. Noncalcareous clay was also sampled. We conclude that these rocks were transported by submarine landslide from shallower
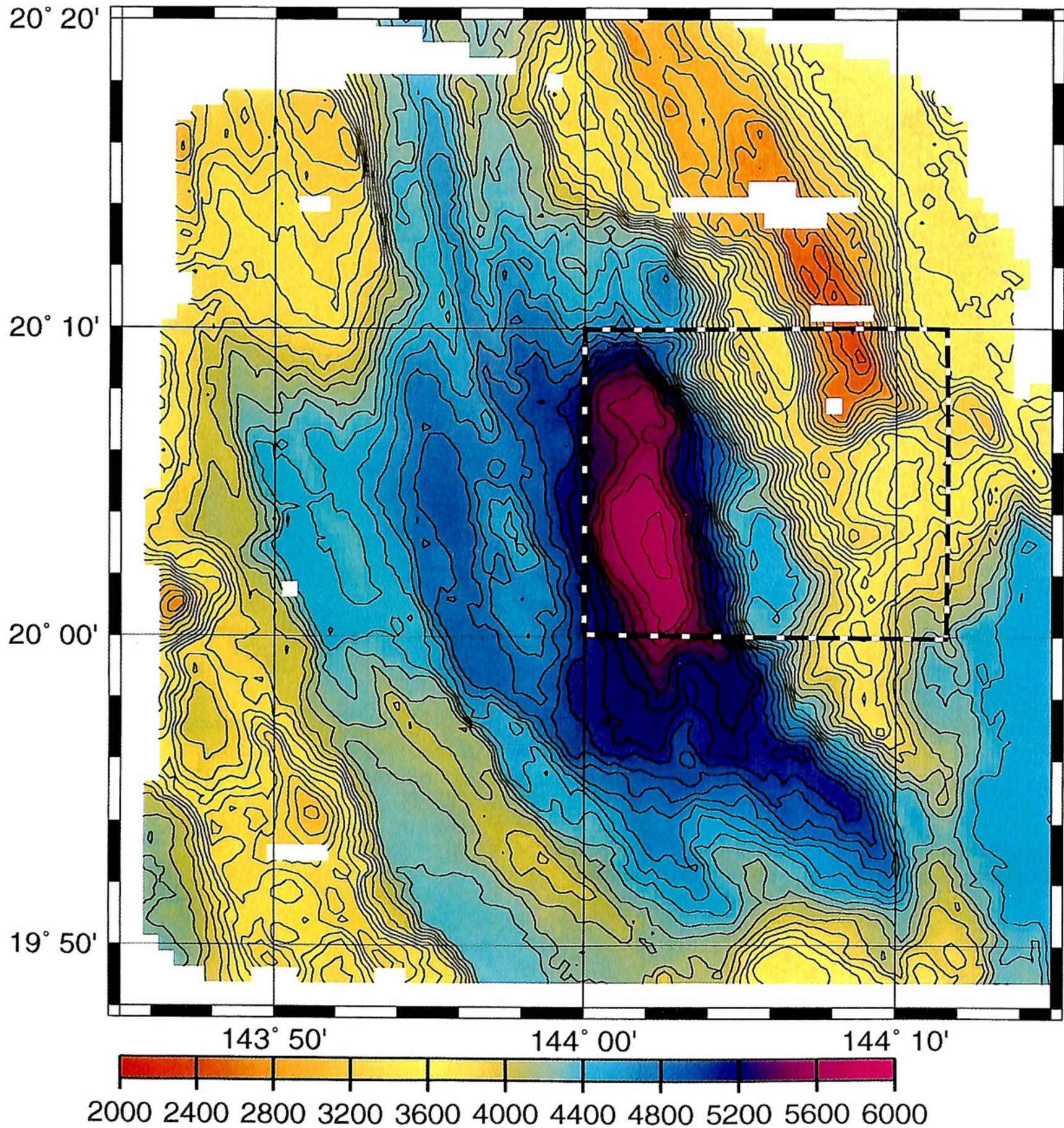
Fig. 2   Bathymetry of the Southern Basin as obtained by surveying aboard R/V "Yokosuka". Box in black shows the location of Fig. 3.

parts of the scarp, as shown on Fig. 3. Typical views of the bottom during this dive are shown in Fig. 4.

The location of Dive 359 was chosen to maximize the likelihood of recovering peridotites and so was moved about 2km south of the Dive 358 track to a position very near that of the Tunes 7 D45 dredge. This dive began shallower in an effort to avoid talus at the base of the scarp, at a depth of 5,200m. About 700m vertical and

1.8km horizontal distance was traversed. Most of this was over rugged rock exposures, either in-place exposures or house-sized or larger fallen blocks. Several narrow, sediment-covered benches suggests that faulting is accomplished by a series of parallel, down-dropped blocks that have been displaced along steeply west-dipping normal faults. All outcrops were massive, with no obvious indications of low angle shear zones or
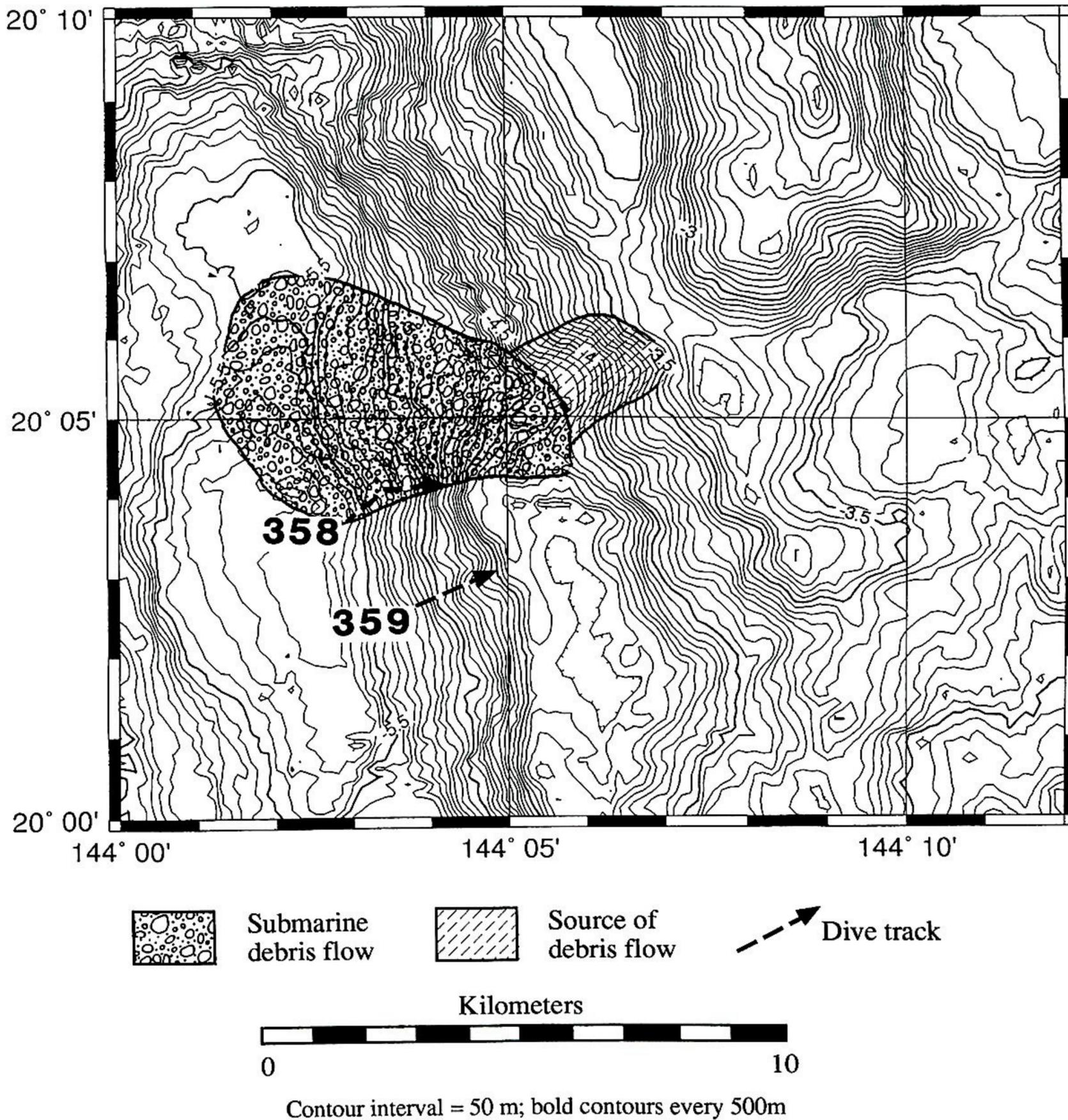
Fig. 3 Bathymetry and geologic interpretation of the eastern scarp of the Southern Basin, in the vicinity of "Shinkai 6500" dives 358 and 359. Note that the outlines of the debris flow and its source are largely speculative, but are consistent with Dive 358 results and seafloor morphology.

faults. Towards the end of the dive, we encountered several nearly vertical cliffs, several tens of meters high. Little Mn-encrustation was observed, and several outcrops displayed a well-developed sub-horizontal fabric, which probably reflects preferred zones of serpentinization in peridotites (Fig. 5A). Occasional distinct layering could be discerned in more massive rocks, which we interpret to be due to sills, 50cm to 1 m thick, intruding less serpentinized peridotite (Fig. 5B).

3. Description of Samples

Fourteen igneous samples were collected from 4 sites on Dive 358, while 23 igneous samples were collected during Dive 359. Although the dive tracks are separated by only 2km apart, and in spite of the fact that Dive 358 began a half-kilometer deepper than Dive 359, a useful generalization is that Dive 358 recovered crustal rocks whereas Dive 359 recovered mostly mantle samples (Table 1). The fact that crustal rocks are found at greater
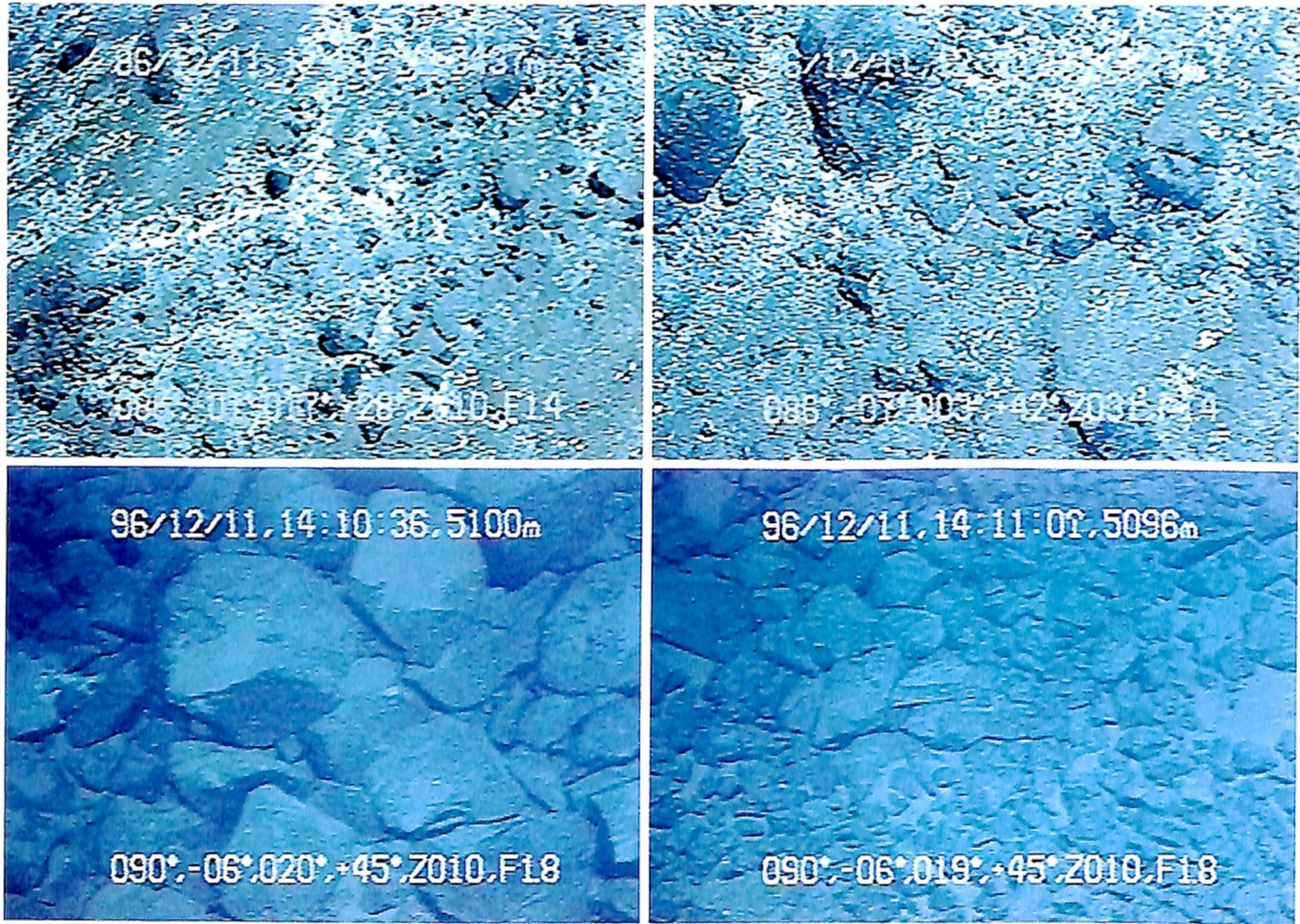
Fig. 4　Images captured from video during Dive 358, showing matrix-supported debris flow (upper scenes) and clast-supported debris flow material (lower scenes).

depth than mantle rocks is consistent with the interpretation that the former were transported from higher up by debris flow. Representative photomicrographs of samples collected during Dives 358 and 359 are shown in Fig. 6.
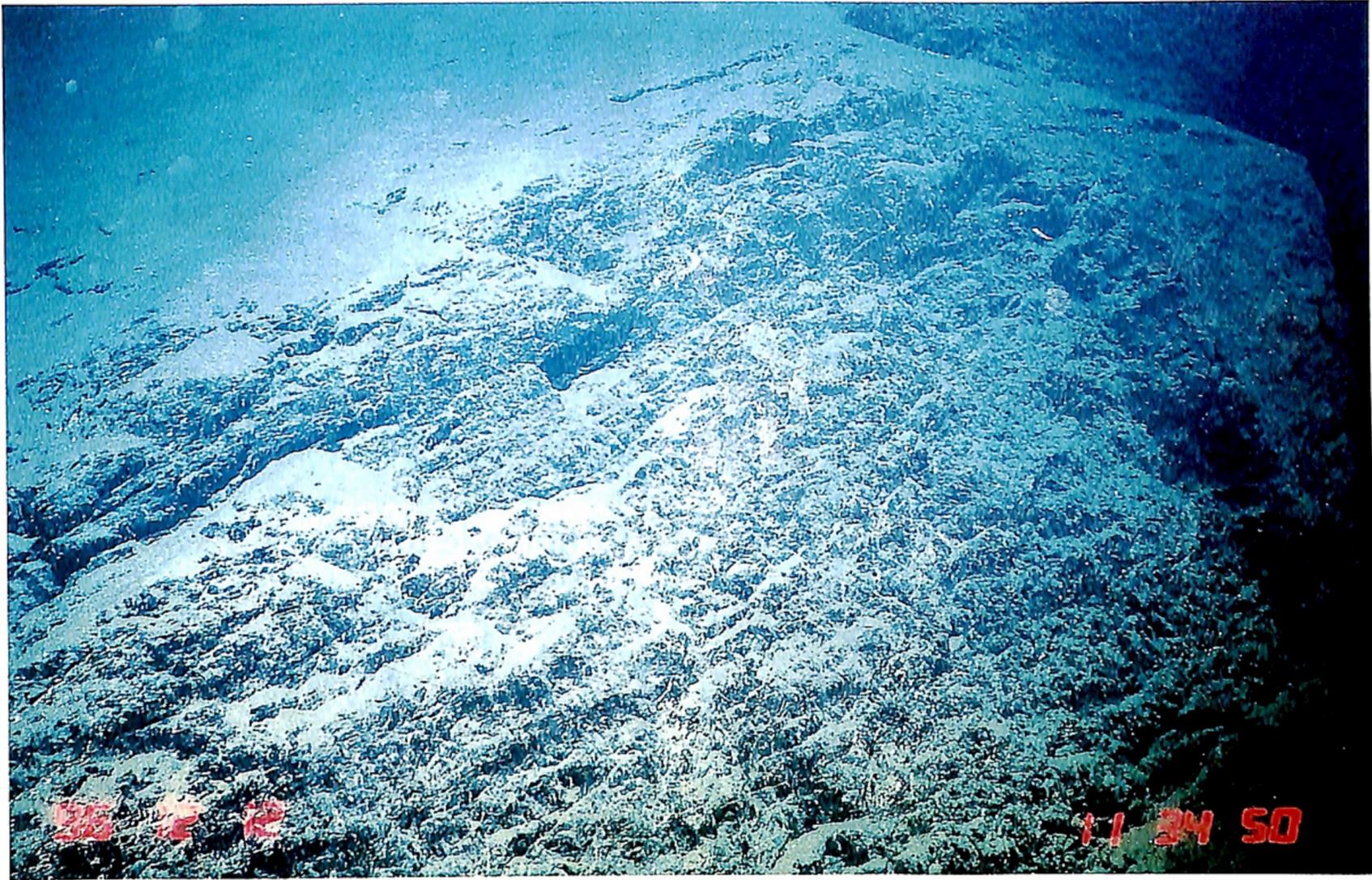
Dive 358

Modal compositions of the samples are listed in Table 2, along with a rock name for each sample. Sample 358–1–1 is one of the most interesting of the diverse suite recovered from Dive 358. It shows excellent phase layering, with centimeter-thick layers of dunite, anorthosite, and olivine-magnetite-hornblende-clinopyroxene gabbro, and provides the clearest evidence of any sample for crystal accumulation in the deep crust.

Sample 358–4–2 is another intriguing sample. It is a volcanic breccia with fragments of predominantly altered gabbro and subordinate clasts of tonalite and serpentinite, enclosed in a fine-grained groundmass. The fact that the groundmass is fresh and the clasts are commonly altered indicates clearly that volcanism was younger than alteration of the clasts.

Four other samples are diabases (358–1–3, 1–4, 1–5, and 4–3), with relatively fresh plagioclase and ophitic to sub-ophitic clinopyroxene. Chlorite is the dominant secondary mineral in the diabases. Another three samples (358–1–2, 3–1, and 3–2) are variolitic basalts. Two samples (358–4–4 and 5–2) are highly serpentinized ultramafic rocks. Two samples from sites 358–4 and 5 are felsic plutonic rocks (358–4–1 and 358–5–1), consisting of feldspar, muscovite, and amphibole. Tonalite 358–4–1 does not contain free quartz, but 358–5–1 contains abundant quartz. Tonalite 358–5–1 contains a thin (~1 cm thick) mafic dike that demonstrates that mafic igneous activity post-dated felsic activity. The opposite relationship- felsic veins intruding a mafic host- was documented for rocks of the area by Stern *et al.* (1996), and the combined observations demonstrate that mafic and felsic ingeous activity was broadly contemporaneous.
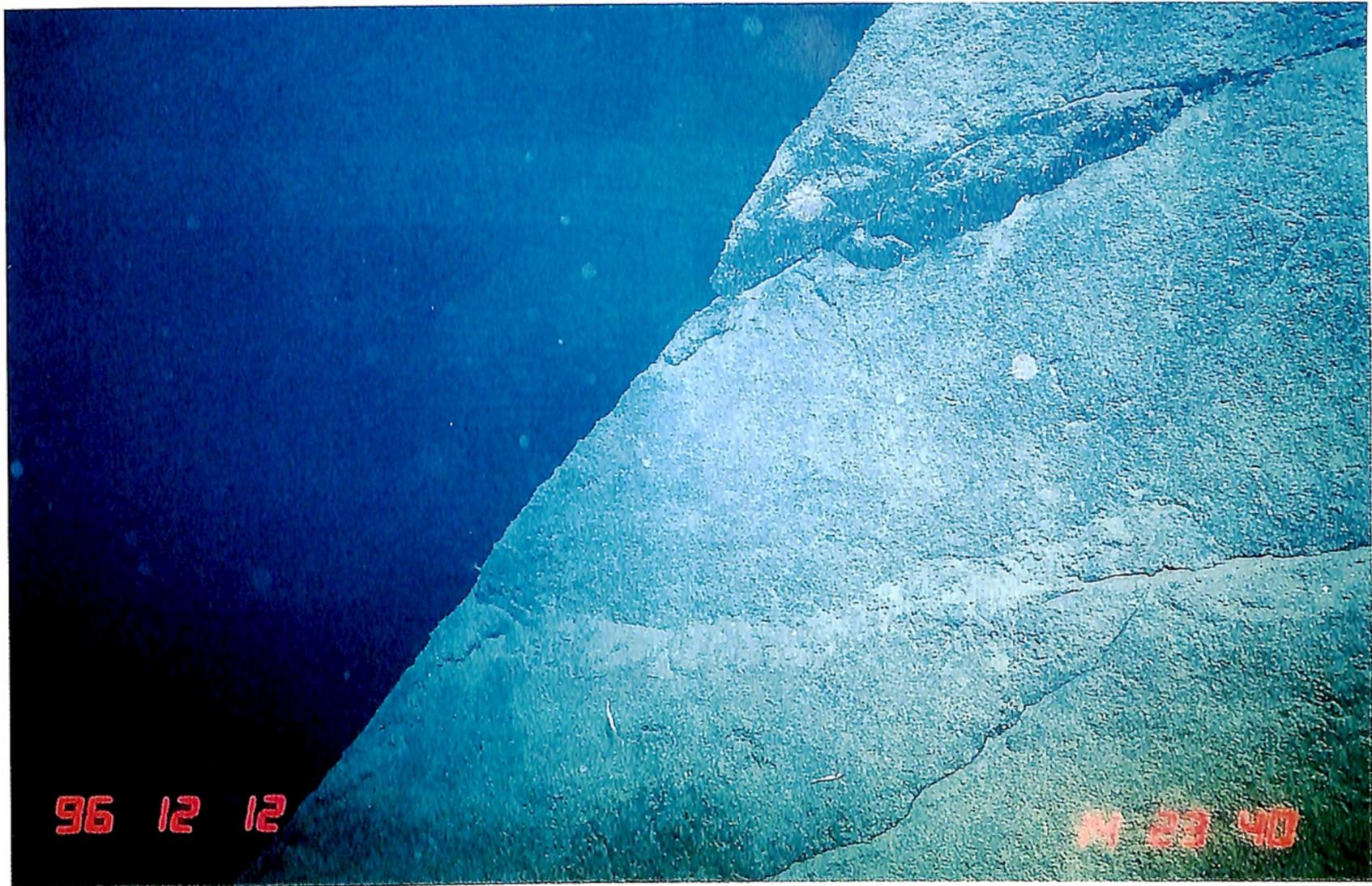
Fig. 5 Bottom photographs taken during Dive 359. A) Outcrop of layered or foliated gabbro or peridotite with a thin sediment cover, taken near the beginning of Dive #359 (1135 hours), at about 5,175m, between stations 1 & 2. B) Cliff face of massive igneous rock (possibly gabbro) with possible sill or layer of coarser material visible about 1/3 from the bottom of the photograph. Small fish visible beneath sill/layer. Photograph taken towards the end of the Dive #359 (1423 hours), at about 4,560m, between stations 5 & 6.
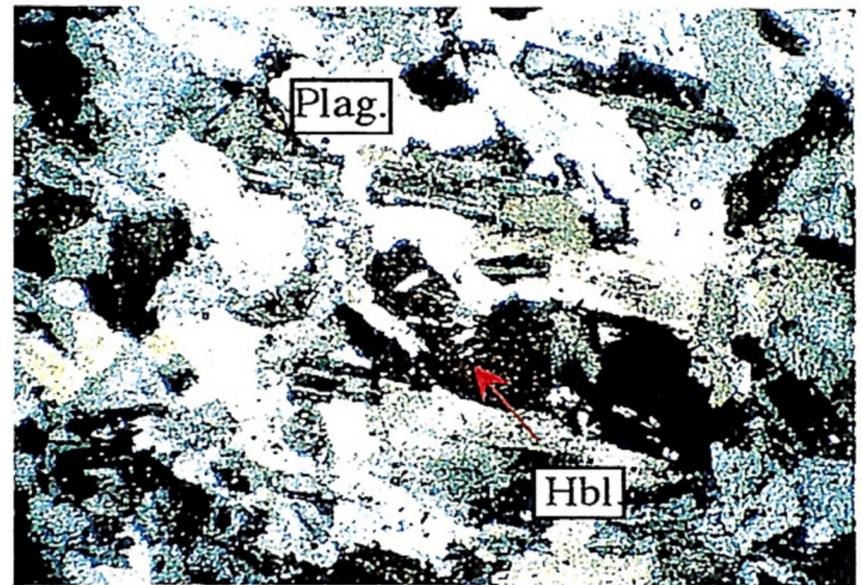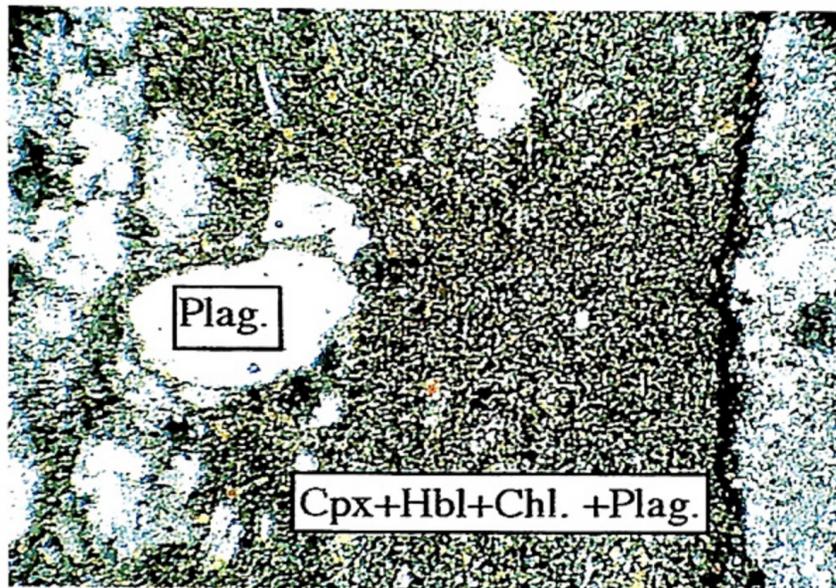
Mafic dike intruding tonalite (358-5-1)   Hornblende tonalite (358-4-1)
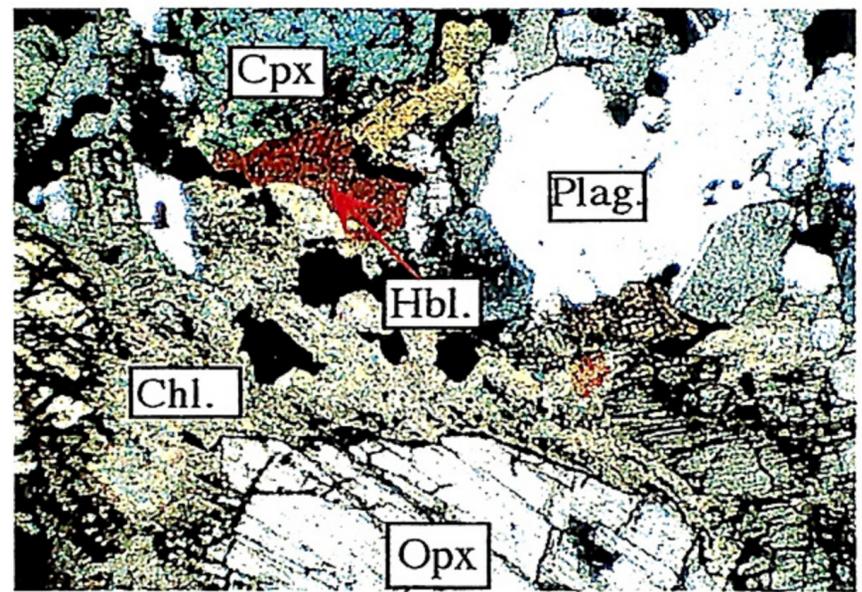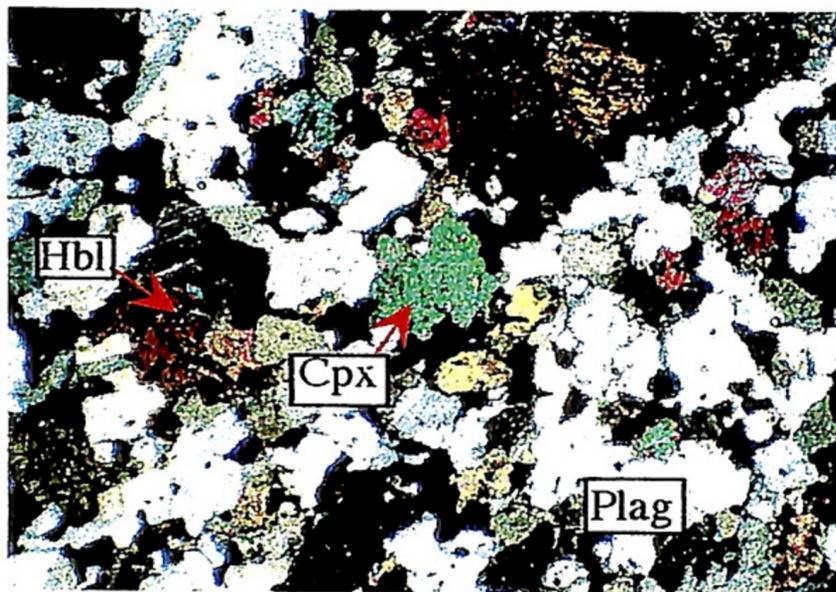
Gabbro (359-3-1)   Gabbro (359-1-1)

Harzburgite (359-1-2)   Dunite layer (358-1-1)

O   1   2mm
Scale

Fig. 6   Photomicrographs of representative samples collected during ''Shinkai 6500'' dives 358 and 359.

Table 1 Sample localities and summaries, D358 & D359

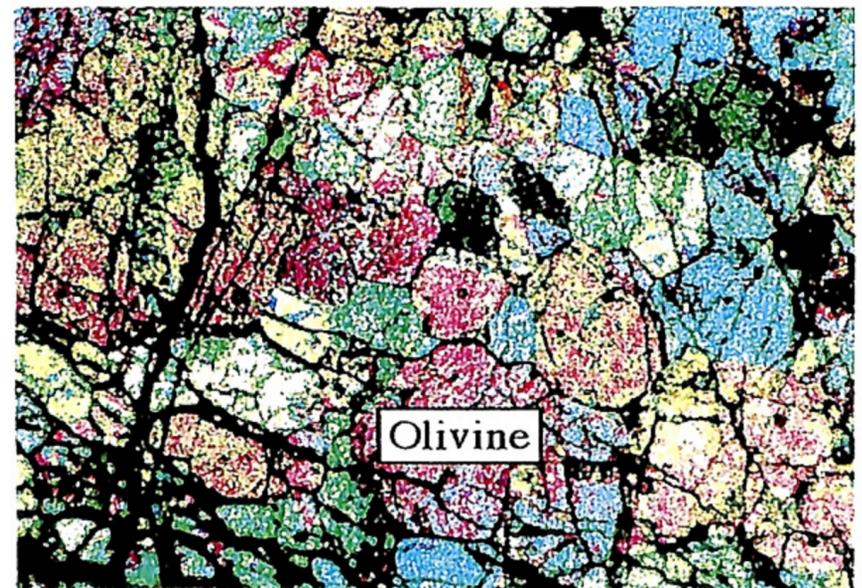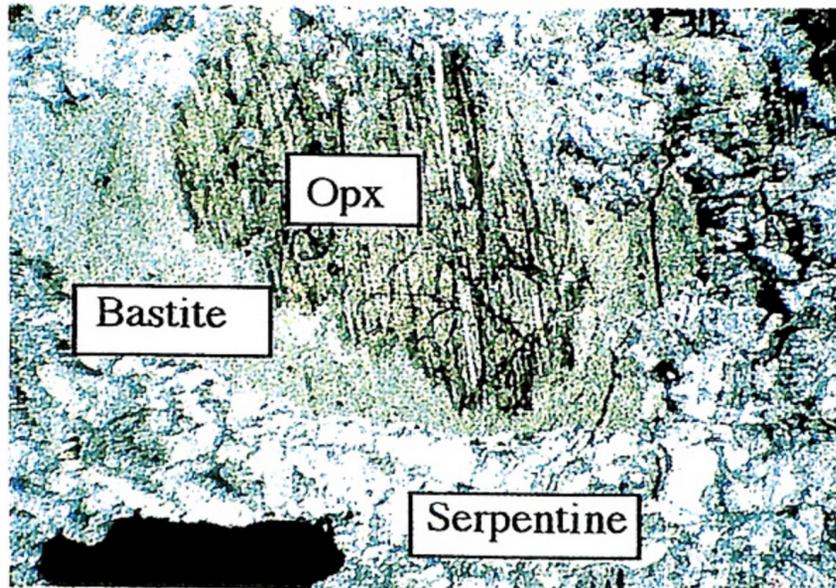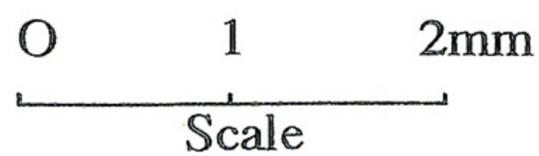| Station	Depth (m)	Number of samples	Lithologies
D358			
-1	5603	5 rocks	gabbro, diabase (3), basalt
-2	5560	sediment	
-3	5430	3 rocks, 1 sediment	basalt
-4	5162	4 rocks	breccia, diabase, tonalite, serpentinite
-5	4790	2 rocks	tonalite, serpentinite
D359			
-1	5200	4 rocks	peridotite (2), gabbro (2)
-2	5149	3 rocks	peridotite
-3	5061	4 rocks	gabbro
-4	4957	5 rocks	peridotite (3), gabbro (2)
-5	4793	5 rocks	peridotite (3), gabbro (2)
-6	4536	3 rocks	peridotite

Table 2 Modal composition of rock samples collected in Dive 358

	1-1	1-2	1-3	1-4	1-5	3-1	3-2	4-1	4-2	4-3	4-4	5-1	5-2
Ol.	20	-	5	5	5	2	2	-	-	2	-	-	-
Opx	2	-	-	-	-	-	2	-	-	-	-	-	-
Cpx	10	-	-	-	22	-	-	-	5	20	-	-	-
Plag.	35	20	60	40	30	5	4	50	30	35		40	-
Amph.		5	-		-	-	-	-	15	-	5	10	-
Oxide	10	10	6	5	10	-	-	-	-	12	7	3	1
Serp.	18	-	-	-	-	-	-	-	5	-	-	-	40
Carb.	-	-	-	-	-	-	-	-	-	-	-	-	9
Epid.	-	-	5	-	-	-	-	-	-	-	3	3	-
Chl.	-	10	8	5	18	-	-	-	5	13	-	-	10
Talc	-	-	-	3	-	-	-	-	-	-	40	-	40
Muscovite	-	-	-	-	5	-	-	-	-	-	-	-	-
Sericite/clay	-	-	1	-	-	-	-	3	-	-	45	-	-
Alkali Feld.	-	-	-	-	-	-	-	5	-	-	-	4	-
Quartz	-	-	-	-	-	-	-	22	-	-	-	40	-
Biotite	-	-	-	-	-	-	-	5	-	-	-	-	-
Matrix/ Groundmass	-	60	15	25	-	93	92	-	55	-	-	-	-
Palagonite	-	-	-	17	10	-	-	-	-	18	-	-	-
Grain Size (mm)	0.5-4	0.25	1-2	1-2	1-2.5	0.25	0.5	2.5	0.5-4	1-2	2	0.2-1	1
Rock Name	G	BV	D	D	D	BV	BV	T	VB	D	S	T	S

G=Layered Gabbro-Dunite-Anorthosite BV=Basalt, Variolitic texture VB=Volcanic Breccia
D=Diabase T=Tonalite S=Serpentinite

Table 3 Modal composition of rock samples collected in Dive 359

	1-1	1-2	1-3	1-4	2-1	2-2	2-3	3-1	3-2	3-4	4-1	4-2	4-3
Ol.	2	10	-	-	15	5	15	-	-	2	-	5	4
Opx	3	20	-	-	25	2	20	4	-	1	2	20	8
Cpx	42	6	22	42	-	1	-	8	-	37	5	-	1
Plag.	30	-	42	5	-	-	-	45	35	40	40	-	-
Amph.	6	-	7	5	-	-	-	-	15	10	15	2	-
Oxide	5	12	25	8	12	15	15	5	10	5	15	2	15
Serp.	-	50	-	-	40	70	50	-	-	-	3	63	70
Carb.	-	2	-	-	5	2	-	-	-	-	-	Tr	-
Epid.	-	-	-	-	-	-	-	10	-	3	-	-	-
Chl.	10	-	4	40	-	-	-	25	40	2	10	Tr	2
Talc	-	Tr	-	-	3	5	-	-	-	-	Tr	8	-
Sericite/clay	4	-	-	-	-	-	-	3	-	-	-	-	-
Grain Size (mm)	1-7	0.5-3	0.5-5	3-5	1-4	0.5-3	0.3-3	2-8	3-10	2-6	1-3	0.5-2	2-6
Rock Name	G	L	G	P	H	H	H	G	G	G	G	H	H

	4-4	4-5	5-1	5-2	5-3	5-4	5-5	6-1	6-2	6-3
Ol.	50	-	4	-	-	-	-	11	7	15
Opx	4	-	11	-	5	-	20	15	12	13
Cpx	-	15	2	2	-	40	-	5	1	2
Plag.	-	35	-	20	-	40	-	-	-	-
Amph.	-	25	5	20	10	4	-	3	-	-
Oxide	4	7	5	8	5	4	10	8	12	15
Serp.	20	-	37	10	54	-	70	45	42	60
Carb.	-	-	15	-	10	-	-	8	-	3
Epid.	-	8	-	-	-	2	-	-	-	-
Chl.	-	10	1	40	8	10	-	1	-	-
Talc	22	-	20	-	3	-	-	4	25	-
Sericite/Clay	-	-	-	-	5	-	-	-	1	-
Grain Size (mm)	2-4	1-5	1-4	1-4	1-3	2-15	1-2	0.25-3	0.25-2	0.25-3
Rock	D	G	H	G	H	G	H	H	H	H

D=Dunite

H=Harzburgite

L=Lherzolite

G=Gabbro

P=Pyroxenite

Dive 359

The 24 samples recovered from 6 sites along the dive track represent a diverse suite of 10 gabbroic and 14 ultramafic plutonic rocks. Modal compositions of the samples are listed in Table 3, along with a rock name for each. Samples from the first station consist of two peridotites and two gabbroes. The peridotites include the only lherzolite (359-1-2) and pyroxenite (359-1-4) recovered during either dive. The gabbro contains minor amounts of hornblende.

All three samples from the second station are variably serpentinized harzburgites, which nevertheless contain significant (5 to 15%) relict olivine. All three samples from station three are clinopyroxene gabbroes, showing cumulus texture. Clinopyroxene makes up the cumulus phase, with plagioclase occurring as intercumulus material. Olivine is rare and hornblende occurs as rims on clinopyroxene and as a separate phase. Both clinopyroxene and plagioclase show alteration.

Samples from station 4 consist of 3 peridotites and 2 gabbros. Peridotites are heterogeneous, with amphibole-bearing harzburgite (359-4-2), harzburgite (359-4-3), and dunite (359-4-4). These peridotites are largely serpentinized but still contain significant relict olivine. The two gabbro samples (359-4-1 & 5) consist mostly of clinopyroxene, plagioclase, and hornblende, with trace amounts of olivine. These are characterized by a poikilitic texture, with plagioclase oikocrysts and clinopyroxene and amphibole as chadecrysts. Amphibole is secondary after clinopyroxene.

Samples from station 5 consist of gabbro and peridotite. Sample 359-5-1 is a serpentinized amphi-

bole-bearing lherzolite that contains a small amount of relict olivine, whereas the olivine in harzburgite 359–5–5 is completely replaced by serpentine. Sample 359–5–3 is also heavily serpentinized, with subequal amounts of clinopyroxene and amphibole. Gabbro samples 359–5–2 and 5–4 are composed of clinopyroxene, hornblende, and plagioclase.

All three samples from station 6 are heavily serpentinized harzburgites that nevertheless contain relict olivine. Sample 359–6–1 contains a small amount of amphibole, which is developed from secondary alteration of clinopyroxene.

4. Discussion

The observations from "Shinkai 6500" and our petrographic studies allow us to comment on several aspects of Mariana Trough crust and upper mantle structure and composition. First, it appears that the eastern wall of the Southern Basin exposes a cross-section of back-arc basin crust and upper mantle, with mantle exposed at depths of greater than 4,530m along the track of dive 359. We know from Dive 358 that crustal rocks lie above 4,790m, the shallowest depth that the debris flow was sampled. No additional constraints on crustal structure can be inferred from the suite recovered from Tunes 7 D45, but the KH–84–1–23 dredge haul (Shibata and Segawa, 1985) in the northern part of Fig. 3 recovered only tholeiitic basalts, which suggests that lower crustal and upper mantle exposures lie deeper than 4km. These relationships are consistent with the position of the crust-mantle transition, also known as the 'petrologic Moho', as we have shown it on Fig. 7, although we emphasize that more "Shinkai 6500" diving is needed to prove this. If the petrologic Moho can be found and documented it would be the only known *in situ* exposure of oceanic lower crust and petrologic Moho and would rank as one of the great geologic discoveries of the decade.

The samples that we collected from Dive 359 provide valuable insights into the nature of back-arc basin mantle. It is somewhat surprising that nearly half of the samples recovered during Dive 359 are gabbroes. While we cannot prove that these gabbroes did not fall from higher up the wall, we tried only to sample at the base of cliffs in an effort to ensure that samples did not come from much higher on the scarp; the absence of unequivocal crustal samples such as basalt, diabase, or tonalite makes us think we succeeded in this effort. We therefore think that the abundance of gabbro in the mantle section is due to the intrusion of mafic sills or dikes into the mantle, a suggestion that is supported by the identification of sill-like features in outcrop (Fig. 5B). A similar situation is noted for mantle drilled in the Hess Deep near the East Pacific Rise, where coring during ODP Leg 147 revealed a substantial amount of troctolite intruding a harzburgitic mantle section (Arai and Matsukage, 1996), and in the MARK of the northern Mid-Atlantic Ridge, where gabbro and diabase sills comprise substantial parts of the mantle harzburgite section cored during ODP Leg 153 (Cannat *et al.*, 1997). These results suggest that the oceanic Moho may not mark a sharp boundary between ultramafic rocks below and mafic rocks above, as inferred from seismic refraction studies, but that the underlying mantle contains abundant mafic intrusions. Following the density arguments of Kelemen *et al.* (1997), we speculate that these intrusions become more common as the Moho is approached, so that the Moho marks the shallowest occurrence of mantle rocks.

There are several apparent differences between the gabbroes recovered during Dive 359 and those recovered from the best-documented occurrences in the Hess Deep, the MARK area, and Broken Spur in the Indian Ocean. First, Central Graben gabbroes appear to be more evolved, with abundant clinopyroxene and little olivine. This contrasts with the aforementioned sites from mid-ocean ridge settings, where olivine is dominant. The reason for the differences in anhydrous mineralogy is unknown. Second, there is abundant redbrown amphibole in Central Graben gabbroes, both as rims on clinopyroxene and as primary phases. This is consistent with the much greater water content of back-arc basin basaltic magmas in general and Mariana Trough basaltic magmas in particular. For example, Mariana Trough basaltic glasses contain up to 2.8% H_2O (Gribble *et al.*, 1996), much greater than the $<0.2\%$ H_2O typical of MORB (Michael, 1988), and the greater water fugacity should result in a larger stability field for amphibole.

We have little structural or stratigraphic control on the crustal section that provided the material for the debris flow sampled by D358. If the samples we have recovered are representative, the crust is dominated by basalt, diabase, and tonalite. We presume the basalt is from lava flows, the diabase is from dikes or sills, and the tonalite was generated and emplaced within the crust. Our results along with those from Tunes 7 D45 and KH–84–1–23 indicate that this crust is predominantly mafic, but with a significant amount-perhaps 10%– of its volume composed of felsic intrusions. There is only one sample of gabbro from the D358 suite (358–1–1) and we do not know if this scarcity indicates that gabbro is an unimportant part of the crustal section or if the debris flow did not sample the crustal gabbro 'layer'. If our interpretation of the source of the debris flow is correct, the crustal gabbro 'layer' cannot be very thick, a few hundred meters at most. This is very similar to the situation that exists for crustal and upper mantle exposures in the MARK area of the Mid-Atlantic Ridge. Serpentinized peridotites there are directly overlain by basalts, with no intervening outcrops of gabbroic rocks that could represent the lower part (Layer 3) of the oceanic crust (Mével *et al.*, 1991), but gabbroic rocks are common intrusions in the ultramafic rocks (Cannat *et al.*, 1997). In this case, the standard model for oceanic crust, that 'Layer 3' (Raitt, 1963) comprises an about 4 km thick gabbro body, may be a poor model for Mariana Trough crustal structure.

Submersible and drilling studies of crust-mantle transition zones may force reconsideration of what we mean by the term 'Moho'. Strictly speaking, this is a geophysical term, indicating the depth in the earth where P-wave velocities increase from about 6.5 or 7 km/sec to about 8 km/sec. For more than twenty years most earth scientists have associated this velocity step with a petrologic change from mafic to ultramafic lithologies (e.g., Moores and Jackson, 1974; Christiansen and Salisbury, 1974), but this model may be flawed, for two reasons: First, detailed OBS studies of mid-ocean ridges have failed to identify the large magma chambers originally envisioned to be the magmatic 'factories' for thick gabbro section envisioned on the basis of ophiolite studies (e.g., Pallister and Hopson, 1981) for the lower oceanic

crust. Instead, mid-ocean ridges often do not have any magma chambers, and when these are present they are very thin 'magma cushions' (<100 m thick; Solomon and Toomey, 1992) that are not likely to be capable of forming thick sections of gabbro. Second, it is becoming increasingly clear that ophiolites are not appropriate models for the oceanic crust. Twenty years ago, ophiolites were thought to form at mid-ocean ridges, but geochemical studies demonstrated a strong arc component in the best preserved ophiolites such as those of Cyprus and Oman. The chemical problem was overcome by hypothesizing that these ophiolites formed in a backarc basin but this created a new problem: how can back-arc basin crust, which forms hundreds of kilometers from the plate boundary, be obducted, and why is there no evidence of the associated arc? More recently it has been argued that well-preserved ophiolites such as those Oman and Cyprus formed during a short episode of fore-arc spreading that happens when a subduction zone forms (Bloomer and Stern, 1992; Stern and Bloomer, 1992). We do not know the details of the subduction initiation process but ophiolitic crust produced in this way should be very different than normal oceanic crust formed by seafloor spreading at a midocean ridge or in a backarc basin. The presence or absence of thick gabbroes and the nature of the Moho are two features that might be produced differently.

If we accept the implications of our observations in the Central Graben, that thick sections of gabbro may not make up much of the lower crust beneath the Mariana Trough, what might we expect to mark the Moho? Hess (1962) suggested that the oceanic Moho marked the isothermal boundary between serpentinized mantle above and unserpentinized peridotite below, This idea languished because of the dominance of the ophiolite model, but was revived by Clague and Straley (1977) and has become increasingly attractive as studies have demonstrated the importance of serpentinites at slow-spreading, amagmatic mid-ocean ridges (Cannat, 1993) and questioned the existence of a thick gabbro layer in oceanic crust formed at slow-spreading ridges. Even beneath ODP site 735B, where a 500m thick section of mostly olivine gabbro was recovered, the lower 3km of the oceanic crust is interpreted by

Muller *et al.* (1997) to be composed of partially serpentinized peridotite. Increasingly, the seismic Moho is being recognized as a serpentinization front, so that oceanic crust -that is, mafic crust -is much thinner. Thus, the seismic Moho may not be exposed on the east of the Mariana Trough Central Graben, while the petrologic Moho is exposed as shown on Fig. 7.

5. Conclusions

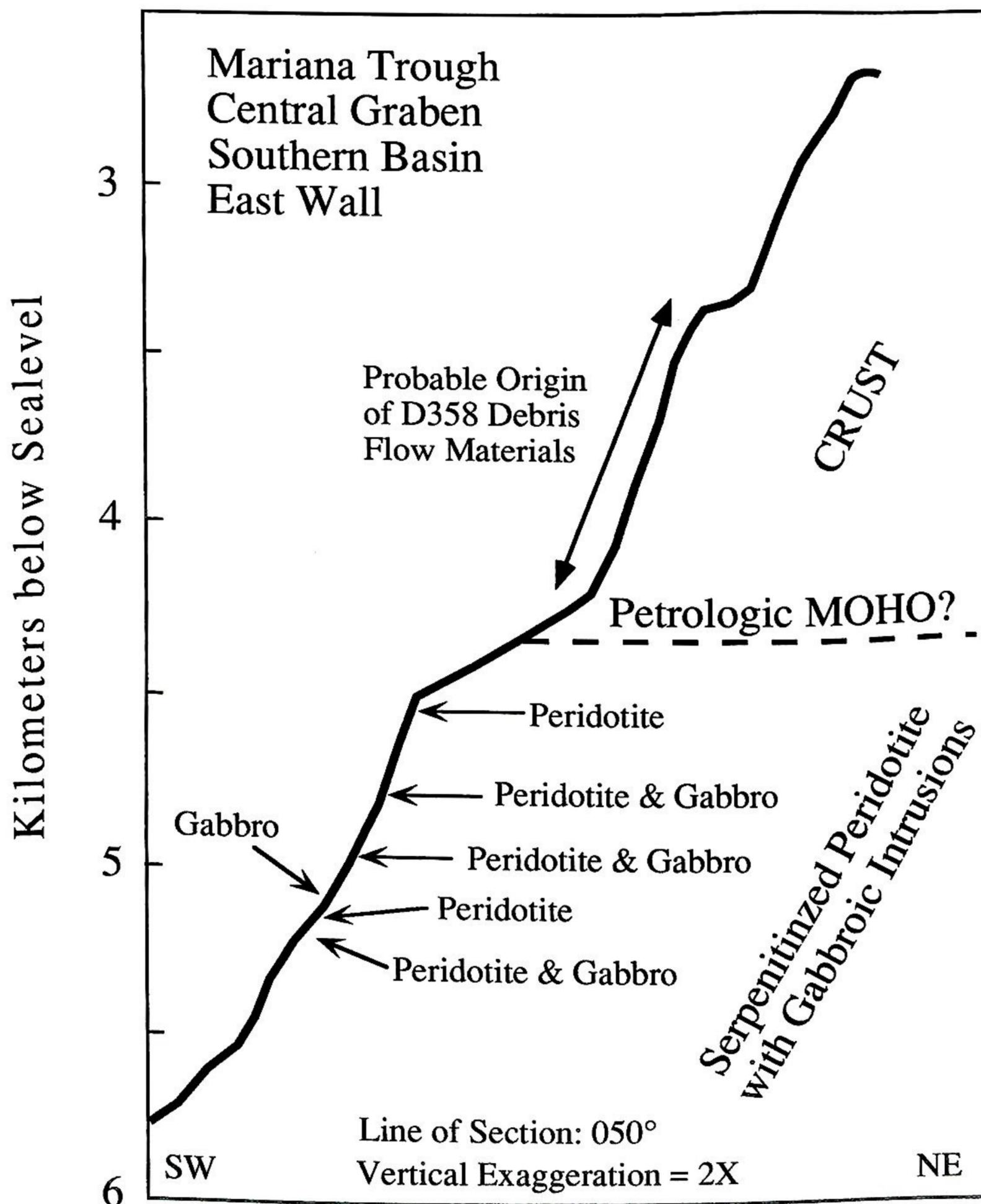The east wall of the Southern Basin of the Central

Fig. 7 Bathymetric profile in the vicinity of dives 358 and 359, with inferred crustal structure. Line of section is about 050° through the area shown in Fig. 3. Approximate positions of peridotite and gabbro samples recovered during Dive 359 are shown. Position of petrologic Moho is approximate and needs to be confirmed by future "Shinkai 6500" dives. The seismic Moho may lie deeper and not be exposed, as discussed in text.

Graben in the Mariana Trough appears to expose a complete and possibly unique section through back-arc basin crust and upper mantle. The mantle section has an apparent exposed thickness of about 1.5km and is composed of partially serpentinized harzburgite intruded by gabbroes with abundant clinopyroxene and plagioclase, subordinate hornblende and opaque minerals, and rare olivine. The crust has an apparent thickness of about 2 km, much thinner than previous estimates for Mariana Trough crustal thickness (about 6km; Bibee *et al.*, 1980); however structural complications -such as thinning of the crust due to stretching- remain to be evaluated. The crust has not yet been seen or sampled in place by "Shinkai 6500" but is expected to be composed of diabase dikes and pillowed basalts intruded by tonalite bodies, perhaps similar to that seen in the northernmost basin of the Central Graben during "Shinkai 6500" Dive #142 (Yamazaki and Yuasa, 1993). Relatively little gabbro is predicted to be found in the lower crust. The unusual opportunity to study backarc basin mantle and crustal structure preserved in the Central Graben warrants additional future studies by "Shinkai 6500", with special emphasis on determining the abundance and nature of mafic intrusions in the mantle, the structure of the crust and occurence of felsic intrusions, and above all the location and nature of the Moho.

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