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2. Leg 195 Synthesis: Site 1201—A Geological and Geophysical Section in the West Philippine Basin from the 660-km Discontinuity to the Mudline[1]

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ABSTRACT

The installation of a borehole seismic observatory 500 m below the seafloor at Site 1201 in the West Philippine Basin has created a unique listening post for long- and short-term seismic studies of the Earth's asthenosphere and lithosphere, as well as the crust and upper mantle near one of the most active subduction complexes in the world.

Broadband waveforms recorded by ocean bottom seismometers across the Philippine Sea and the borehole seismometer at Site 1201 show that the 410- and 660-km discontinuities are located at depths of 377 and 669 km, respectively, below the site, whereas controlled-source experiments over the site show the crust to be abnormally thin (3.8 km). Layer 3, which is only 2.3 km thick, is strongly anisotropic, with V_P = 6.7 km/s in the east-west direction, but only 6.3 km/s in the north-south (paleospreading) direction, probably due to faults and fissures.

Coring at Site 1201 shows the upper crust to be transitional in composition between arc tholeiites and mid-ocean-ridge basalt (MORB), which is consistent with the formation of the West Philippine Basin by backarc spreading between two opposed subduction zones beginning in the Eocene. After the site drifted northwest away from the spreading axis and volcanism ceased, 0.5 km of sediments was deposited in three

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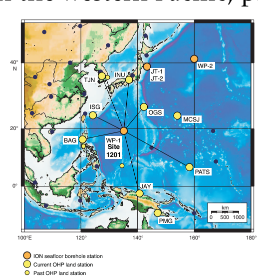
stages: (1) quiescent marine sedimentation in deep water into the late Eocene; (2) pelagic sedimentation mixed with, and finally overwhelmed by, volcaniclastic turbidites from the Palau-Kyushu Ridge from the late Eocene through the early Oligocene; and (3) waning turbidite deposition, followed by barren, deep-sea pelagic sedimentation below the carbonate compensation depth (CCD) from the early Oligocene to the early Pliocene, when sedimentation ceased altogether.

Extensive low-temperature (100°–150°C) zeolite facies hydrothermal alteration occurred in many of the basalts under oxidizing open-circulation conditions, which became more restricted as sedimentation proceeded. In the overlying sediments, the deeper levels of the turbidites have undergone profound low-temperature (<100°C) diagenesis, causing the vitric shards in the turbidites to be completely replaced by smectite, mixed-layer clays, and zeolites and the interstitial seawater to be replaced by pore water that is extremely enriched in Ca and depleted in K and Mg, consistent with alteration of basaltic glass to zeolites and clays. High geochemical gradients in the pore waters above 300 meters below seafloor (mbsf) suggest that alteration is continuing at present in the upper turbidites but that below 300 mbsf the pore water has reached equilibrium with the products of alteration.

INTRODUCTION

Despite steady improvements in global seismic coverage over the past several decades, large gaps remain in the ocean basins, where most Global Seismographic Network (GSN) stations are located on islands of opportunity (Butler et al., 2004). Since these outposts are often widely spaced or missing entirely in some tectonic settings, it is often difficult to construct tomographic images of deep mantle flow in key regions of the Earth's interior or to map discontinuities in the mantle at a sufficiently high resolution to test geodynamic models of mantle structure and evolution. For example, islands are often found in backarc settings but are rare to absent on old crust in front of subduction zones because of the cooling and subsidence of the oceanic crust with age (Parsons and Sclater, 1977). To correct this bias and to improve both the coverage and resolution of seismic studies in the western Pacific, one of the most complex and dynamic zones of plate interaction on Earth, a series of long-term, three-component, broadband borehole seismic observatories has recently been deployed in the ocean basins around Japan, two on the forearc off Honshu (Sites JT-1 and JT-2 in Fig. F1) and a third (WP-2) in old ocean crust outboard of the Kurile Trench (Suyehiro, Sacks, Acton, et al., 2000; Kanazawa, Sager, Escutia, et al., 2001). One of the principal objectives of Ocean Drilling Program (ODP) Leg 195 and the prime objective at Site 1201 was to deploy a similar observatory in the middle of the West Philippine Basin behind the Mariana arc and in front of the Ryukyu and Philippine arc-trench systems (Site WP-1 in Fig. F1). As outlined in Salisbury, Shinohara, Richter, et al. (2002) and Suyehiro et al. (2002), this deployment and subsequent visits to the site by submersible to activate the seismometer and retrieve data were completely successful. The purpose of this synthesis is not to recount the deployment but to summarize the scientific results that have already been observed from this seismometer and the results of shipboard and postcruise laboratory studies of the core recovered while drilling the borehole. The seismic, coring, and laboratory studies at Site 1201, combined with earlier ocean bottom seismometer (OBS) surveys over the

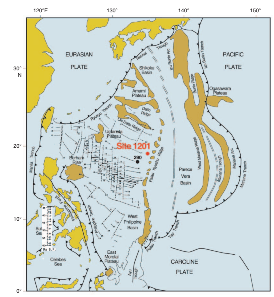
F1. Locations of seismic observatories in the western Pacific, p. 14.



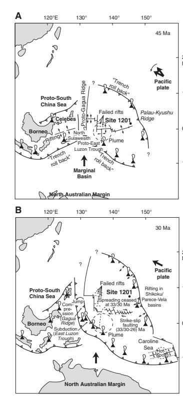
site, provide a unique, 670-km geophysical and geological section through backarc crust at scales of investigation ranging from millimeters in the core to hundreds of kilometers in the deep mantle.

In order to understand the coring and laboratory results from Site 1201 or the seismic structure of the crust and deep mantle under the site, it is necessary to examine its plate tectonic setting. Site 1201 lies on 49-Ma crust near Chron 21 in the center of the modern Philippine Sea plate, ~100 km west of the extinct Palau-Kyushu Ridge, which separates the older West Philippine Basin from the younger Parece Vela and Shikoku Basins to the east (Fig. F2) (Hilde and Lee, 1984; Salisbury, Shinohara, Richter, et al., 2002). As discussed by Okino et al. (1999) and Deschamps and Lallemand (2002), the West Philippine Basin formed between two opposed subduction zones by slow north-south to northwest-southeast backarc spreading along the Central Basin Spreading Center from 54 to ~30 Ma (Fig. F3A, F3B). Between 35 and 26 Ma, the spreading pattern reorganized: the polarity of subduction changed in the west, subduction shifted to the east from the Palau-Kyushu Ridge to the West Mariana Ridge, active spreading shut down in the West Philippine Basin, and east-west backarc spreading began in the Parece Vela Basin along the Parece Vela Ridge. The spreading direction in the Parece Vela Basin then gradually changed to northeast-southwest (Kasuga and Ohara, 1997) until ~15 Ma, when spreading shifted eastward again to the Mariana Trough, a rift that is currently propagating to the north between the West Mariana Ridge and the modern Mariana arc, the current locus of subduction. As the Philippine Sea plate grew in size, paleomagnetic evidence (Hall et al., 1995) shows that it also rotated clockwise ~60° and drifted north, so that Site 1201, which originally lay just north of the equator, is now located at 20°N (C. Richter, pers. comm., 2005). From seismologic, petrologic, and sedimentologic standpoints, it is significant that Site 1201, which formed by backarc spreading near a ridge/arc junction, now lies nearly in the center of the plate, with the nearest trench >1100 km away.

F2. Current plate tectonic setting of WP-1, p. 15.



F3. Site 1201 location at 45 and 30 Ma, p. 16.



GEOPHYSICAL AND GEOLOGICAL SECTIONS

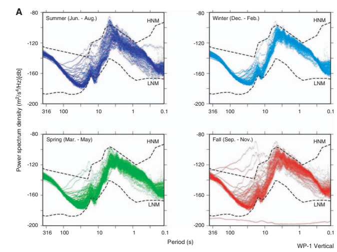
Deep Seismic Structure

Since its deployment in April 2001 and subsequent activation by the Japanese remotely operated vehicle (ROV) *Kaiko* in March 2002, the borehole observatory installed at Site 1201 has recorded >400 days of three-component broadband seismic data. Three major studies have been conducted to date using data from WP-1: (1) a detailed assessment of the acoustic noise levels at the site over time and the seismic detection threshold of the observatory (Shinohara et al., in press), (2) a long-term broadband OBS/borehole observatory study to determine the deep mantle structure under the site to the 660-km discontinuity (Suetsugu et al., 2005), and (3) an OBS/borehole observatory study of the seismic structure of the crust and upper mantle at the site (Arisaka et al., 2003).

Acoustic Noise and Event Detection Thresholds at WP-1

Seafloor observatories, particularly those deployed and clamped in basement, generally provide a quiet acoustic environment for monitoring seismic events (e.g., Kanazawa et al., 1992; Collins et al., 2001; Araki et al., 2004), but since each site and instrument is unique, it was necessary to the determine the ambient seismic noise at the site, and thus the seismic detection limits of the seismometer, before the observatory at Site 1201 could be used for research purposes. As discussed by Shinohara et al. (in press), two identical, three-component broadband seismometers with a peak response from 3 mHz to 10 Hz (330–0.1 s) were cemented 40 m into basement at Site 1201 beneath a 500-m-thick sediment cover. As can be seen in Figure F4, which shows the seasonal power spectra for the seismic noise at WP-1, the ambient noise for both the vertical and horizontal components lies between the low and high noise models of Petersen (1993) for most of the instrument bandwidth. The only significant exceptions are that both components show an increase in noise levels for short-period (T < 30 s) waves during the summer and fall typhoon seasons and the horizontal component exceeds the high noise model for long-period waves (T > 50 s). As expected for a seismometer in basement (Araki et al., 2004) the 100-s peak commonly observed in OBS data and associated with gravity waves is absent. Since the vertical component noise levels are similar to those observed at the best land stations (Shinohara et al., in press) and the horizontal component does not appear to be noise-limited at the dominant frequencies of seismic waves from most earthquakes (>0.02 Hz; T < 50 s), it is clear that WP-1 is located in a quiet environment and meets the operational and acoustic requirements for the detection of seismic events. Although numerous events have already been recorded by the observatory, a rigorous study of the detection threshold at WP-1 has not yet been completed. Comparison with Site WP-2, however, which displays similar noise spectra, suggests that WP-1 can detect M4 events out to 45° and M5.5 events worldwide.

F4. Seasonal power spectra for WP-1, p. 17.

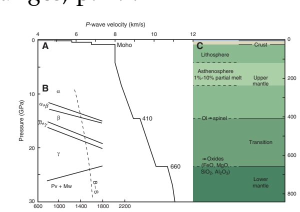


Deep Mantle Structure

One of the earliest and most critical seismic studies conducted at any new observatory after the initial noise analysis is the determination of the deep mantle structure under the site. This is not only an important scientific objective but an operational requirement, since the deep structure is the lens that refracts and delays all incoming waves detected by the station and thus controls the station receiver function.

Radial models of the velocity structure of the Earth based on teleseismic studies consistently show velocity discontinuities at depths of ~410 and 660 km in the mantle (e.g., Dziewonski and Anderson, 1981; Kennett et al., 1995), and laboratory studies strongly suggest that these are caused by mineral phase changes induced by increasing pressure and temperature with depth. As can be seen in Figure F5, the “410” discontinuity is attributed to a transition from olivine to modified spinel at ~14 GPa and 1400°C, whereas the “660” discontinuity marks a transition from spinel to simple oxides such as perovskite and magnesio-wustite at ~24 GPa and 1480°C (e.g., Katsura and Ito, 1989; Ito and Takahashi, 1989). If the 410 and 660 discontinuities are caused by phase changes, it follows that the depths to these discontinuities can be perturbed by mantle upwelling and subduction, since these can respectively raise or lower the mantle geotherm. Earlier studies of mantle structure under the Philippine Sea using ScS reverberation (Ohtaki et al., 2002), SS underside reflection (Gu et al., 2003), and *P*-wave triplication techniques (Shito and Shibutani, 2001) suggest that the 660 discontinuity is anomalously deep, while the 410 discontinuity has no substantial topography under the Philippine Sea, but since these meth-

F5. Velocity and mineral phase changes, p. 19.

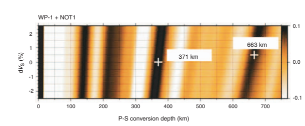


ods all have low spatial resolution, the anomalous depths cannot be attributed with certainty to the lower temperatures expected in the vicinity of the Izu-Bonin-Mariana subduction zone.

As discussed by Suetsugu et al. (in press), however, the deep structure of the mantle can be determined with high spatial resolution from broadband borehole seismometer and OBS data using receiver function and velocity spectrum stacking (VSS) analysis. While the VSS technique ultimately depends on energy from teleseismic events to determine mantle structure, it can produce a local, rather than a regional, solution because it exploits *S*-waves rising through the mantle from a point under the site on the 660 discontinuity where they were converted from teleseismic *P*-waves. The solution is local because the observed travel-time delay between the direct *P*-wave and the converted *S*-wave from each event is controlled solely by the depth of the discontinuity and the *P*- and *S*-wave velocities in the mantle overlying the conversion point.

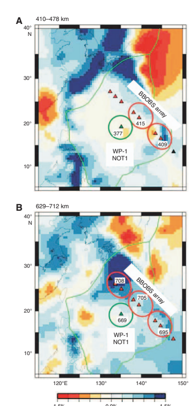
During the first 6 months of operation, WP-1 recorded 17 seismic events with magnitudes ≥5.6 from epicentral distances of 30°–90° which had signal-to-noise (S/N) ratios sufficient for receiver function analysis, and a broadband OBS located several kilometers away (NOT1) recorded 13 such seismic events over the same time period. Receiver functions were then calculated for each of the 30 WP-1 and NOT1 seismic events with the highest signal-to-noise ratios, and the functions were stacked using interactive moveout corrections in order to enhance the converted *S*-wave signals and determine the velocity-depth model family with the best S/N ratio. In the model with the highest S/N ratio, found after successive depth and V_S perturbations, the 410 layer is observed at a depth of 371 km and the 660 layer is at 663 km (Fig. F6). Correcting for the water layer, the 410 and 660 layers are at 377 ± 4 km and 669 ± 9 km, respectively (Suetsugu et al., 2005).

F6. Velocity spectrum stacking plot, p. 20.



If the 410 discontinuity is ~35 km shallower than normal under the site and the 660 is ~10 km deeper, the phase diagrams shown in Figure F5B imply that temperatures are depressed under the central Philippine Sea by ~500°C at the 410 discontinuity and 100°C at the 660 discontinuity. Since seismic velocities increase with decreasing temperature, both predictions can be independently tested by *P*-wave tomography. As can be seen in Figure F7, which shows the *P*-wave velocity anomaly patterns determined by Obayashi and Fukao (2001) for the 410 and 660 discontinuities under the Philippine Sea along with the results of earlier VSS studies (Suetsugu et al., in press), minor depression of the 660 discontinuity to 669 km under the site due to a slight decrease in temperature is consistent with the observed velocities, but elevation of the 410 discontinuity by 35 km due to a large decrease is not, since there is no corresponding positive velocity anomaly at that depth. As noted by Suetsugu et al. (2005), the elevation of the 410 discontinuity must be due to another cause, perhaps an anomaly in mantle composition. As can be seen in Figure F3 from Deschamps and Lallemand (2002), this is extremely likely; west-dipping subduction occurred on the Palau-Kyushu Ridge just to the east starting at ~50 Ma but ceased by ~25 Ma, which would leave a compositional anomaly under the site (a stalled slab) but no pronounced negative thermal anomaly, since the slab would have warmed from 25 Ma to the present. As expected, however, positive velocity anomalies are observed at 410 and 660 depths under the active Izu-Bonin Mariana subduction complex and VSS studies based on OBS array data show that the 660 discontinuity is significantly depressed in the vicinity of the IBM slab (Fig. F7).

F7. *P*-wave velocity anomalies, p. 21.

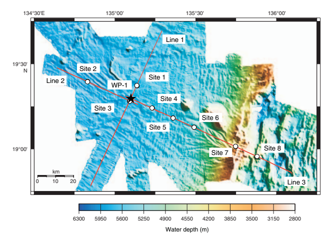


For higher levels in the mantle, it is tempting to attribute the strong signals seen at 140 and 220 km in Figure F6 to the base of the lithosphere and the base of the asthenosphere, respectively, but synthetic modeling suggests these are due to reverberations in the crust and water column. Although seismic data from WP-1 have not been used to date to determine the depth and properties of the asthenosphere under the Philippine Sea, surface wave studies indicate that the lithosphere is unusually thin and that shear wave velocities in the asthenosphere are anomalously low (Seekins and Teng, 1977; Isse et al., 2004), suggesting that temperatures are high and the mantle is partially molten in the asthenosphere under the entire plate.

Crust and Upper Mantle Structure under Site 1201

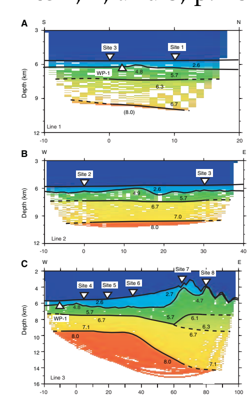
In addition to providing information on the deep mantle structure under Site 1201, seismic data from WP-1 have recently been used in conjunction with data from a colocated OBS array to determine the velocity structure of the crust and upper mantle immediately under the site (Arisaka et al., 2003). As can be seen in Figure F8, three refraction lines were shot to an array laid out in a cross with borehole seismometer WP-1 at the center. Line 1, which is 100 km long, is aligned parallel to the paleospreading direction (see Fig. F1), whereas Lines 2 and 3, with a combined length of 120 km, are normal to the spreading direction and cross the extinct Palau-Kyushu Ridge. Twelve OBSs were used in total for the three surveys and air guns were used as the sound source. The tau-p inversion method of Diebold and Stoffa (1981) was used to model the shallow structure under the site, while two-dimensional (2-D) ray tracing (Cerveny and Psencik, 1984) was used to estimate the deep structure.

F8. Seismic refraction lines used to determine seismic structure, p. 22.

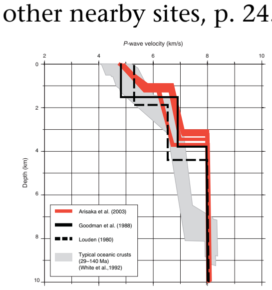


As can be seen in Figure F9, the upper mantle at Site 1201 lies 3.3–3.8 km below the top of basement and has a compressional wave velocity of 8.0 km/s in the east-west direction (Arisaka et al., 2003). Mantle anisotropy could not be determined because V_P could not be measured directly in the north-south direction under Line 1. Layer 3, which is thought to be composed of gabbros and amphibolite-facies sheeted dikes, is ~2.3 km thick and is strongly anisotropic, with V_P increasing with depth from 6.7 km/s at the top of the layer to 7.1 km/s at the base in the east-west direction and from 6.3 to 6.7 km/s in the north-south direction, which is consistent with the existence of open cracks normal to spreading, as is commonly observed in the ocean basins (e.g., Stephen, 1985; Dunn and Toomey, 2001; Tong et al., 2004). On the other hand, Layer 2, which is composed of extrusive basalts, is 1–1.2 km thick and appears to be isotropic, with V_P increasing from ~4.8 km/s at the top to 5.7 km/s at the base in both directions. Finally, the seismic results indicate that basement is covered by ~500 m of sediments with an average *P*-wave velocity of 2.6 km/s, in excellent agreement with coring, logging, and laboratory results from Hole 1201D (Shipboard Scientific Party, 2002). Whereas the velocities determined above for Layers 2 and 3 are quite typical of those observed in the ocean basins, the thicknesses are not. As can be seen in Figure F10, the total combined thickness of Layers 2 and 3 in the vicinity of Site 1201 is 3.3–3.8 km. This is about half the thickness of normal ocean crust but is consistent with other refraction results which show that the crust in the Philippine Sea is anomalously thin (Goodman et al., 1989; White et al.,

F9. Velocity structure under refraction Lines 1, 2, and 3, p. 23.



F10. Crustal velocity at Site 1201 and other nearby sites, p. 24.



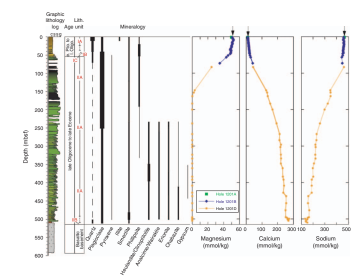
1992). For reasons which remain unclear, the crust is also anomalously deep for its age (Louden, 1980).

Not surprisingly, the refraction results show that the crust is substantially thicker under the Palau-Kyushu Ridge than it is under the West Philippine Basin, in part because Layers 2 and 3 are thicker (3.5–4.0 and >4.0 km, respectively), but also because an additional layer with a *P*-wave velocity of 6.1–6.3 km/s and a thickness of 2–3 km is present between Layers 2 and 3 under the center of the ridge. It is also clear from Figure **F9** that the sediments at Site 1201 are derived from the Palau-Kyushu Ridge since they belong to a sediment apron which thickens toward the ridge but thins on the summit. Since the sediment source now lies several kilometers below sea level and the Palau-Kyushu Ridge only displays a very small gravitational anomaly along most of its length, the root zone appears to be isostatically compensated.

Basalts at the Top of the Crust and Their Sediment Cover

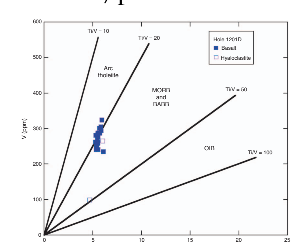
Unlike the deep mantle and crustal sections discussed above, which we have only been able to examine by indirect seismic methods, it has been possible to study the uppermost 0.6 km of the section at Site 1201 directly because the section was drilled and continuously cored to a depth of 600 m during Leg 195 in order to install the borehole seismic observatory in basement below the influence of gravity waves. As can be seen in Figure **F11,** Hole 1201D penetrated 90 m of altered basalts in the top of Layer 2 and a 510 m section of sediments (Shipboard Scientific Party, 2002).

F11. Lithology, sediment mineralogy, and pore water geochemistry, p. 25.



Although the basalts were fairly fresh and massive near the bottom of the hole, the top of the basement consisted of strongly altered pillows with palagonitized rims and interstitial fillings composed of altered hyaloclastic shards in a fine sediment matrix. Since the sediments contain siliceous marine microfossils but no calcareous microfossils, and the uppermost basalts show significant Na enrichment and Ca depletion (Shipboard Scientific Party, 2002; D'Antonio and Kristensen, 2004), it is clear that the basalts erupted and altered in a marine environment in deep water below the carbonate compensation depth (CCD). Furthermore, since geochemical studies show that the basalts are slightly enriched backarc basin basalts (Fig. **F12**) (Shipboard Scientific Party, 2002; Savov et al., 2005), it seems clear that the seafloor in the vicinity of Site 1201 formed by eruption in a backarc setting rather than by capture of an old Pacific spreading ridge behind the Palau-Kyushu Ridge as suggested by Hilde and Lee (1984). Since the paleomagnetic inclinations in these basalts are low (~7°), it is apparent that these eruptions occurred within the Philippine plate and near the equator (Deschamps and Lallemand [2002]; C. Richter, pers. comm., 2005). As observed at some other sites in the western Pacific, Pb isotope systematics for the basalts from Site 1201 display an Indian Ocean isotope affinity (Savov et al., 2001).

F12. V vs. Ti, p. 26.



Whereas the sediments at most Deep Sea Drilling Project (DSDP) and ODP sites bear little relation to the underlying igneous basement, the sediment veneer at Site 1201 is unusual in that it is largely derived from igneous sources. As discussed by Salisbury, Shinohara, Richter, et al. (2002) and summarized in Figure **F11,** the sediment section consists of three units: a 5-m-thick layer of upper Eocene pelagic clays immediately overlying basement; a 452-m-thick layer of upper Eocene–upper Oligocene turbidites; and finally, a 53-m section of upper Oligocene–lower

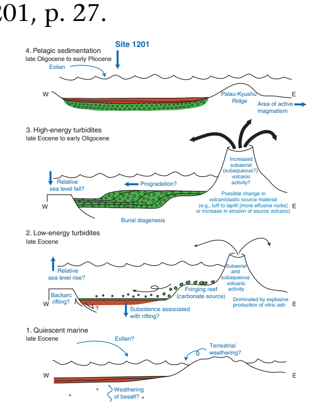
Pliocene pelagic sediments. The Pliocene–Pleistocene section was either never deposited or has been removed by erosion. While the almost barren pelagic sediments at the top and bottom of the section are to be expected in a deepwater setting far from land, the turbidites recovered at Site 1201 are remarkable.

First, they are composed almost entirely of volcaniclastics. As described in detail by Salisbury, Shinohara, Richter, et al. (2002), the turbidites consist of vitric shards and fragments of basalt with traces of scoria and reef detritus and range in grain size from clays and silty clays to coarse sandstones and breccias. The abundance of vitric material demonstrates that the basalts were largely submarine in origin, but the presence of scoria and coral fragments shows that at least some of the volcanic sources extended near or above sea level and were surrounded by fringing reefs. While the individual turbidite layers display classic graded bedding, the sequence as a whole tends to coarsen upward and the layers themselves increase in thickness from a few millimeters just above basement to tens of meters near the top of the section, indicating a gradual change from a low- to a high-energy depositional environment.

Second, the turbidites are profoundly altered. Whereas those at the top of the unit are dark gray and fairly fresh, they become dark greenish gray, then vivid green, and finally, gray-green with depth. Thin section and X-ray diffraction (XRD) analyses (Fig. **F11**) show that these changes are due to the devitrification of glass, infilling of voids and vesicles by clays and zeolites, and alteration of plagioclase to clay in the upper 240 m of the unit and the complete replacement of volcaniclastics by smectite, chlorite, and zeolites in the lower part of the unit during diagenesis. These changes are reflected in the pore water chemistry, which shows a large increase in pH, Ca, and chlorinity with depth and a corresponding decrease in Mg, Na, and K as Ca is leached from the volcaniclastics and Mg, Na, K, and water are removed during the formation of clay, smectite, and zeolites. As can be seen in Figure **F11,** the pore water composition appears to have reached stable values in the lower levels of the turbidites, where it is now a Ca chloride, rather than a Na chloride solution, but shows strong gradients higher in the section. Since such gradients can only be maintained by active chemical reactions, the alteration appears to have gone to completion in the base of section but is continuing to this day in the upper levels. As at ODP Sites 792 and 793 on the Izu-Bonin Ridge, the only other ocean drilling sites known to display such profound alteration in volcaniclastics (Taylor, Fujioka, et al., 1990), the alteration at Site 1201 is due to the abundance of fine-grained vitric particles and moderately elevated temperatures (<100°C).

Third, the volume of the turbidite deposits is enormous. As can be seen in Figure **F9C,** Site 1201 (borehole seismometer site WP-1) was drilled in a vast sediment apron derived from the now extinct Palau-Kyushu Ridge and extends >100 km to the west along its entire length. At Site 1201, which lies 80 km west of the ridge, the turbidites are 452 m thick, or 90% of the section, and even at Site 290, which lies on the edge of the apron ~150 km from the ridge, the volcaniclastics are still 80 m thick (Karig, Ingle, et al., 1975). Even if the proportion of volcaniclastics decreases eastward toward the source of the sediments, the total thickness will increase, implying that the volume of volcaniclastics shed from the Palau-Kyushu Ridge exceeds the present-day volume of the ridge itself, which is consistent with eruption on the ridge over an extended period of time (Fig. **F13**). The turbidites were also deposited rapidly, allowing the most robust calcareous nannofossils entrained in

F13. History of deposition at Site 1201, p. 27.



the deposits, such as *Sphenolithus distentus* and *Discoaster barbadiensis*, to be preserved, even though they were deposited below the CCD. From the best-preserved of these specimens, it has been possible to show that the ridge shed volcaniclastics into the Oligocene (~30 Ma) and that the rate of deposition, even at Site 1201, which was far from the source, exceeded 100 m/m.y. (Salisbury, Shinohara, Richter, et al., 2002).

Finally, the last sediments deposited at the top of the column consist of a 53-m veneer of soft pelagic clay with interbedded cherts and sandstones and significant amounts of barren red clay. Deposition, which was slow after the cessation of turbidite deposition, was interrupted by an unconformity from the early Oligocene to the mid-Miocene and ceased altogether from the early Pliocene to the present.

CONCLUSIONS

From a combination of seismic studies using the borehole observatory installed at Site 1201 and an array of ocean bottom seismometers deployed around the site and drilling conducted at the site itself, it has been possible to determine the composition of a thick section from the seafloor to the 660-km discontinuity in the West Philippine Basin and to determine the geological history of the site from the late Eocene to the present. Six major conclusions can be reached from these studies:

1. The 660-km discontinuity, marking the transition from spinel to perovskite and magnesio-wustite in the mantle, is depressed to 669 km under the site, suggesting that the temperature is depressed by ~100°C (Suetsugu et al., in press), which is consistent with the results of *P*-wave tomography (Obayashi and Fukao, 2001).
2. The 410-km discontinuity, marking the olivine to modified spinel transition, is elevated to 377 km. Since this is much too large a shift to be caused by thermal effects, it is likely due to anomalous mantle composition (Suetsugu et al., in press). This could be due to the presence of a stalled slab associated with the extinct Kyushu-Palau Ridge, which was active just to the east of the site from 55 to 25 Ma.
3. Surface wave studies (Isse et al., 2004) show that the lithosphere is thin and that shear wave velocities in the asthenosphere are low under the Philippine plate, implying that temperatures are high and that the asthenosphere is partially molten.
4. The oceanic crust beneath Site 1201 displays typical Layer 2 and 3 velocities but is only half the thickness of normal ocean crust (Arisaka et al., 2003).
5. The basalts recovered at Site 1201 were extruded during the Eocene in a quiet backarc setting below the CCD. Following an initial period of pelagic sedimentation, the site was overwhelmed by volcaniclastic turbidites during the early Oligocene when the Palau-Kyushu Ridge, which began to rise when subduction was initiated to the east during the Eocene, finally breached the surface. Pelagic sedimentation resumed in the late Oligocene when active subduction shifted to the Marianas and the Palau-Kyushu Ridge subsided below sea level. Eventually, even pelagic sedimentation ceased at the site at the beginning of the Pliocene.

6. Finally, the state-of-the-art borehole seismic observatory installed at Site 1201 during Leg 195 is now fully operational (Shinohara et al., in press). Analysis of data recovered from the observatory by submersible is providing invaluable new information on the subduction zones and deep mantle structure of the western Pacific.

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REFERENCES

Araki, E., Shinohara, M., Sacks, S., Linde, A, Kanazawa, T., Shiobara, H., Mikada, H., and Suyehiro, K., 2004. Improvement of seismic observation in the ocean by use of seafloor boreholes. *Bull. Seismol. Soc. Am.,* 94(2):678–690.

Arisaka, M., Shinohara, M., Yamada, T., Mochizuki, K., Kaiho, Y., Araki, E., Nakahigashi, K., Ito, M., Shiobara, H., Suyehiro, K., and Kanazawa, T., 2003. Seismic structure of uppermost mantle and crust beneath West Philippine Basin and Kyushu-Palau Ridge by seafloor borehole seismometer and airgun experiment. *Eos, Trans. Am. Geophys. Union,* 84(S31):F-0824.

Brown, J.M., and Shankland, T.J., 1981. Thermodynamic properties in the Earth as determined from seismic profiles. *Geophys. J. R. Astron. Soc.,* 66:579–596.

Butler, R., Lay, T., Creager, K., Earl, P., Fischer, K., Gaherty, J., Laske, G., Leith, B., Park, J., Ritzwoller, M., Tromp, J., and Wen, L., 2004. The global seismograph network surpasses its design goal. *Eos, Trans. Am. Geophys. Union,* 85:225–232.

Collins, J.A., Vernon, F.L., Orcutt, J.A., Stephen, R.A., Peal, K.R., Wooding, F.B., Spiess, F.N., and Hildebrand, J.A., 2001. Broadband seismology in the oceans: lessons from the Ocean Seismic Network pilot experiment. *Geophys. Res. Lett.,* 28:49–52.

Cerveny, V., and Psencik, I., 1984. SEIS83—numerical modeling of seismic wave fields in 2-D laterally varying layered structures by the ray method. *In* Engdahl, E.R. (Ed.), *Documentation of Earthquake Algorithims:* Boulder (NOAA).

D'Antonio, M.D., and Kristensen, M.B., 2004. Hydrothermal alteration of oceanic crust in the West Philippine Sea Basin (Ocean Drilling Program Leg 195, Site 1201): inferences from a mineral chemistry investigation. *Mineral. Petrol.,* 83(1–2). **doi:10.1007/s00710-004-0060-6**

Deschamps, A., and Lallemand, S., 2002. The West Philippine Basin: an Eocene to early Oligocene back-arc basin opened between two opposed subduction zones. *J. Geophys. Res.,* 107(B12):2322. **doi:10.1029/2001JB001706**

Diebold, J.B., and Stoffa, J.L., 1981. The traveltime equation, tau-p mapping, and inversion of common midpoint data. *Geophysics,* 46:238–254.

Dunn, R.A., and Toomey, D.R., 2001. Crack-induced seismic anisotropy in the oceanic crust across the East Pacific Rise (9°30′N). *Earth Planet. Sci. Lett.,* 189:9–17.

Dziewonski, A., and Anderson, D.L., 1981. Preliminary reference Earth model. *Phys. Earth Planet. Inter.,* 25:297–356.

Goodman, D., Bibee, L.D., and Dorman, L.M., 1989. Crustal seismic structure beneath the West Philippine Sea, 17°–18°N. *Mar. Geophys. Res.,* 11:155–168.

Gu, Y.J., Dziewonski, A.M., and Ekstrom, G., 2003. Simultaneous inversion for mantle shear velocity and topography of transition zone discontinuities. *Geophys. J. Int.,* 154:559–583.

Hall, R., Fuller, M., Ali, J., and Anderson, C., 1995. The Philippine Sea plate: magnetism and reconstructions. *In* Taylor, R.B., and Natland, J. (Eds.), *Active Margins and Marginal Basins of the Western Pacific*. Geophys. Monogr., 88:371–404.

Hilde, T.W.C., and Lee, C.S., 1984. Origin and evolution of the West Philippine Basin: a new interpretation. *Tectonophysics,* 102:85–104.

Isse, T., Yoshizawa, K., Shiobara, H., Shinohara, M., Nakahigashi, K., Mochizuki, K., Sugioka, H., Suetsugu, D., Kanazawa, T., and Fukao, Y., 2004. 3-D shear wave speed structure beneath the Philippine Sea plate. *Eos, Trans. Am. Geophys. Union,* 85(47):S52B-08. (Abstract)

Ito, E., and Takahashi, E., 1989. Postspinel transformations in the system Mg_2SiO_4-Fe_2SiO_4 and some geophysical implications. *J. Geophys. Res.,* 94:10637–10646.

Kanazawa, T., Sager, W.W., Escutia, C., et al., 2001. *Proc. ODP, Init. Repts.,* 191 [CD-ROM]. Available from: Ocean Drilling Program, Texas A&M University, College Station TX 77845-9547, USA. [**HTML**]

Kanazawa, T., Suyehiro, K., Hirata, N., and Shinohara, M., 1992. Performance of the ocean broadband downhole seismometer at Site 794. *In* Tamaki, K., Suyehiro, K., Allan, J., McWilliams, M., et al., *Proc. ODP, Sci. Results,* 127/128 (Pt. 2): College Station, TX (Ocean Drilling Program), 1157–1171.

Karig, D.E., Ingle, J.C., Jr., et al., 1975. *Init. Repts. DSDP,* 31: Washington (U.S. Govt. Printing Office).

Kasuga, S., and Ohara, Y., 1997. A new model of back-arc spreading in the Parece Vela Basin, northwest Pacific margin. *Isl. Arc,* 6:316–326.

Katsura, T., and Ito, E., 1989. The system Mg_2SiO_4-Fe_2SiO_4 at high pressures and temperatures: precise determination of stabilities of olivine, modified spinel and spinel. *J. Geophys. Res.,* 94(B11):15663–15670.

Kennett, B.L.N., Engdahl, E.R., and Buland, R., 1995. Constraints on seismic velocities in the Earth from traveltimes. *Geophys. J. Int.,* 122:108–124.

Louden, K.E., 1980. The crustal and lithospheric thickness of the Philippine Sea as compared to the Pacific. *Earth Planet. Sci. Lett.,* 50:275–288.

Obayashi, M., and Fukao, Y., 2001. Whole mantle tomography with an automatic block parameterization. *Abstr. Japan Seismol. Soc. Annu. Mtg.,* B08.

Okino, K., Ohara, Y., Kasuga, S., and Kato, Y., 1999. The Philippine Sea: new survey results reveal the structure and the history of marginal basins. *Geophys. Res. Lett.,* 26:2287–2290.

Ohtaki, T., Suetsugu, D., Kanjo, K., and Purwana, I., 2002. Evidence for a thick mantle transition zone beneath the Philippine Sea from multiple ScS waves recorded by JISNET. *Geophys. Res. Lett.,* 29. **doi:10.1029/2002GL014764**

Parsons, B., and Sclater, J.G., 1977. An analysis of the variation of ocean floor bathymetry and heat flow with age. *J. Geophys. Res.,* 82:803–827.

Petersen, J., 1993. Observations and modeling of seismic background noise. *Open-File Rep.—U.S. Geol. Surv.,* 93-322.

Salisbury, M.H., Shinohara, M., Richter, C., et al., 2002. *Proc. ODP, Init. Repts.,* 195 [CD-ROM]. Available from: Ocean Drilling Program, Texas A&M University, College Station TX 77845-9547, USA. [**HTML**]

Savov, I.P., Hickey-Vargas, R., Ryan, J.G., and D'Antonio, M., 2001. Pb isotopic ratios in volcanic rocks from ODP Leg 195, Site 1201, West Philippine Basin. *Eos, Trans. Am. Geophys. Union,* 82:T41C-894. (Abstract)

Savov, I.P., Hickey-Vargas, R., D'Antonio, M., Ryan, J., and Spadea, P., 2005. Petrology and geochemistry of West Philippine Basin basalts and early Palau-Kyushu arc volcaniclastics from ODP Leg 195, Site 1201: implications for the early history of the Izu-Bonin-Mariana subduction factory. *J. Petrol.,* 47(2):277–299. **doi:10.1093/petrology/egi075**

Seekins, L.C., and Teng, T.L., 1977. Lateral variations in the structure of the Philippine Sea plate. *J. Geophys. Res.,* 82:317–324.

Shinohara, M., Araki, E., Kanazawa, T., Suyehiro, K., Mochizuki, M., Yamada, T., Nakahigashi, K., Kaiho, Y., and Fukao, Y., in press. Deep-sea borehole seismological observatories in the western Pacific: temporal variation of seismic noise level and event detection. *Ann. Geophys.*

Shito, A., and Shibutani, T., 2001. Upper mantle transition zone structure beneath the Philippine Sea region. *Geophys. Res. Lett.,* 28:871–874.

Shipboard Scientific Party, 2002. Leg 195 summary. *In* Salisbury, M.H., Shinohara, M., Richter, C., et al., *Proc. ODP, Init. Repts.,* 195: College Station TX (Ocean Drilling Program), 1–63. [**HTML**]

Stephen, R.A., 1985. Seismic anisotropy in the upper oceanic crust. *J. Geophys. Res.,* 90:11383–11396.

Suetsugu, D., Shinohara, M., Araki, E., Kanazawa, T., Suyehiro, K., Yamada, T., Nakahigashi, K., Kawai, K., and Fukao, Y., 2005. Mantle discontinuity depths beneath the West Philippine Basin from receiver function analysis of deep-sea borehole and seafloor broadband waveforms. *Bull. Seismol. Soc. Am.,* 95:1947–1956.

Suetsugu, D., Shiobara, H., Sugioka, H., Kodaira, S., Fukao, Y., Mochizuki, K., Kanazawa, T., Hino, R., and Saita, T., in press. Thick mantle transition zone beneath the Philippine Sea inferred using data from a long-term broadband ocean bottom seismograph array. *Geophys. J. Int.*

Suyehiro, K., Araki, E., Shinohara, M., and Kanazawa, T., 2002. Deep sea borehole observatories ready and capturing seismic waves in the western Pacific. *Eos, Trans. Am. Geophys. Union,* 83:624–625.

Suyehiro, K., Sacks, S., Acton, G.D., et al., 2000. *Proc. ODP, Init. Repts,* 186 [CD-ROM]. Available from: Ocean Drilling Program, Texas A&M University, College Station TX 77845-9547, USA. [**HTML**]

Taylor, B., Fujioka, K., et al., 1990. *Proc. ODP, Init. Repts.,* 126: College Station, TX (Ocean Drilling Program).

Tong, C.H., White, R.S., Warner, M.R., and ARAD Working Group, 2004. Effects of tectonism and magmatism on crack structure in oceanic crust: a seismic anisotropy study. *Geology,* 32(1):25–28. **doi:10.1130/G19962.1**

White, R.S., McKenzie, D., and O'Nions, R.K., 1992. Oceanic crustal thickness from seismic measurements and rare earth element inversions. *J. Geophys. Res.,* 97:19683–19715.

Figure F1. Locations of seismic observatories in the western Pacific (after Salisbury, Shinohara, Richter, et al., 2002). Orange circles = borehole seismometers installed in the seafloor. Yellow circles = current (large) and past (small) stations established by the Japanese Ocean Hemisphere Project. Black circles = IRIS stations. Station WP-1 was installed at Site 1201 during Leg 195. TJN = Taejon, S. Korea; INU = Inuyama, Japan; ISG = Ishigakijima, Japan; OGS = Chichijima, Japan; MCSJ = Minami Torishima, Japan; BAG = Baguio, Philippines; PATS = Pohnpei, Micronesia; JAY = Jayapura, Indonesia; PMG = Port Moresby, Papua New Guinea.

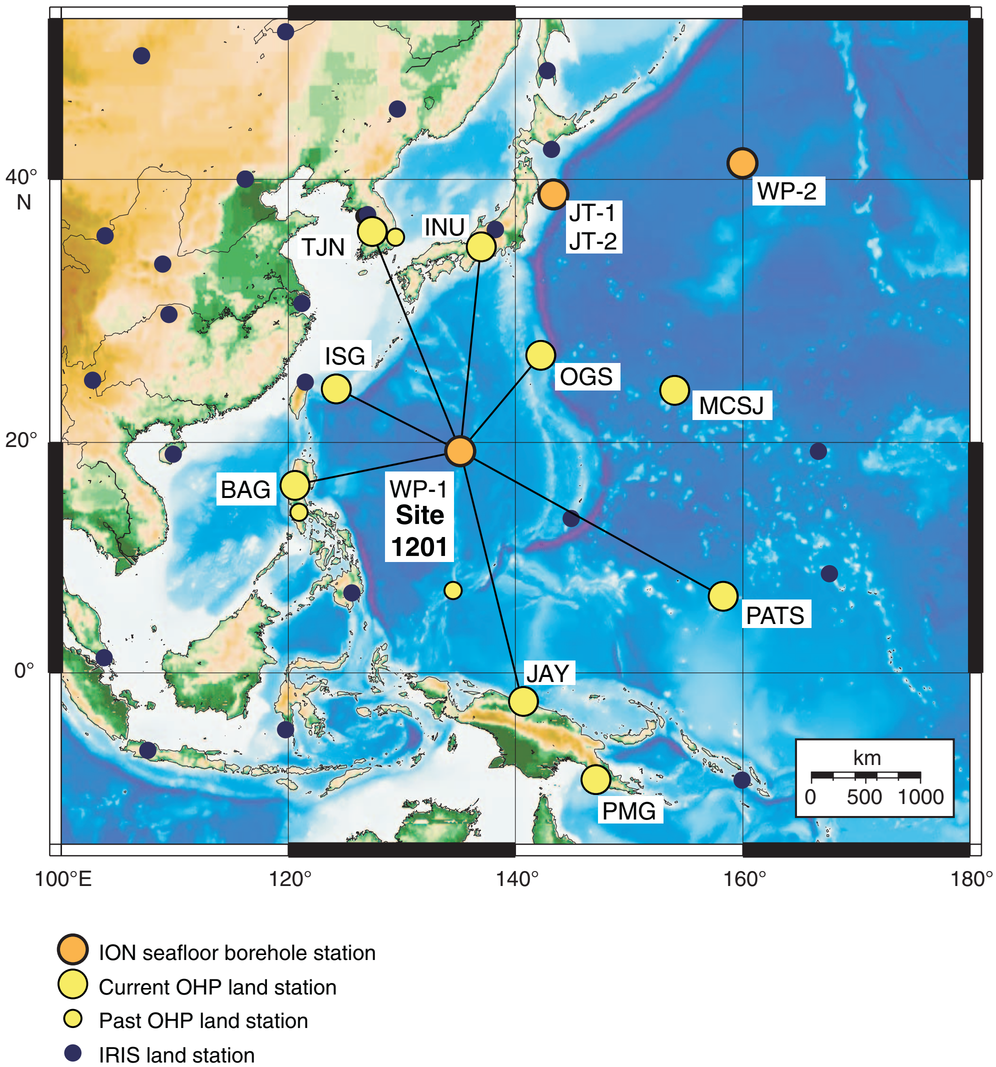

Figure F2. Current plate tectonic setting of borehole seismic observatory WP-1 at Site 1201 (after Hilde and Lee, 1984). The site is surrounded by active trenches but the nearest is 1100 km distant and the nearest active backarc spreading rift is 900 km away.

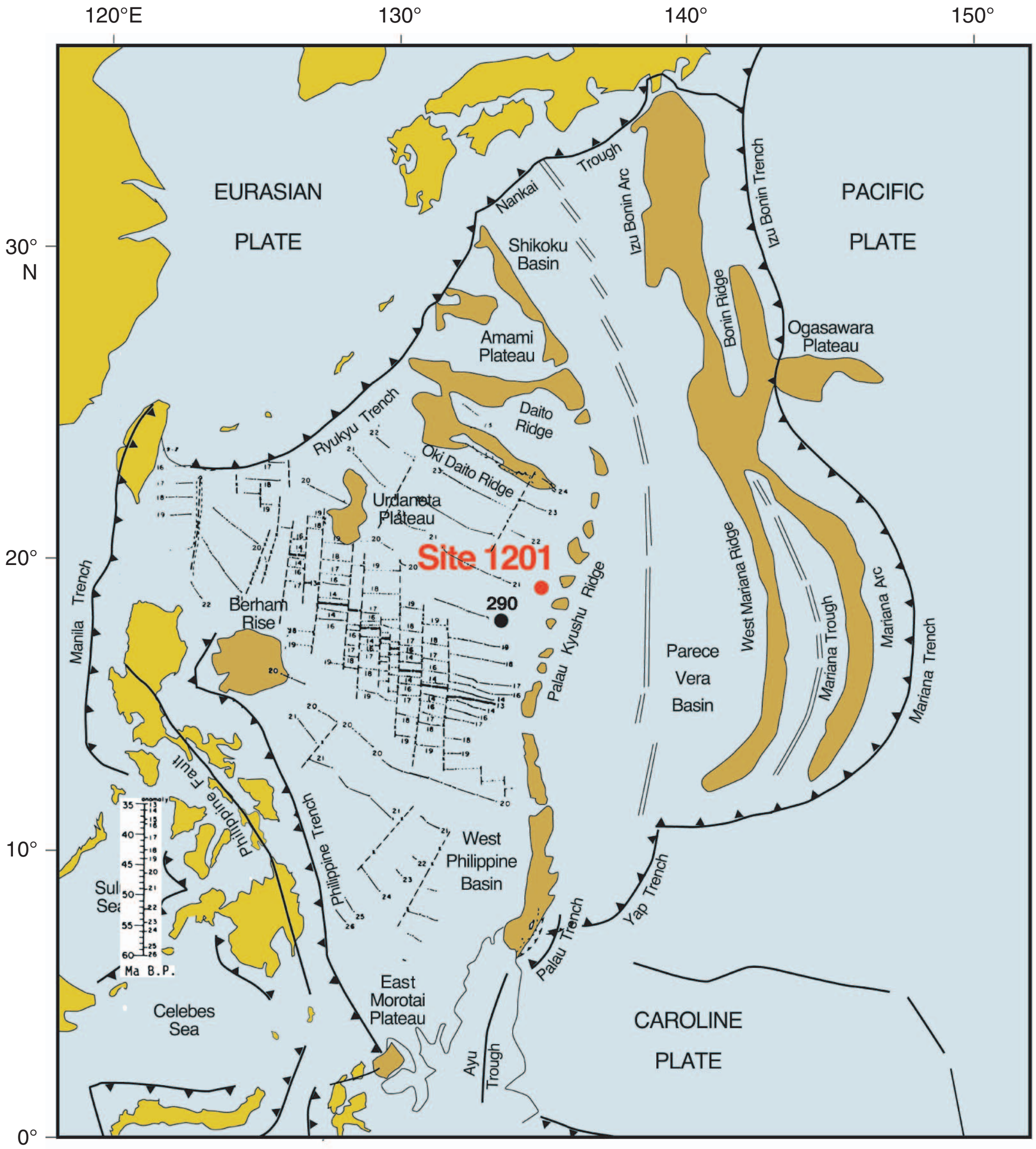

Figure F3. West Philippine Basin and Site 1201 location at (**A**) 45 Ma and (**B**) 30 Ma (after Deschamps and Lallemand, 2002).

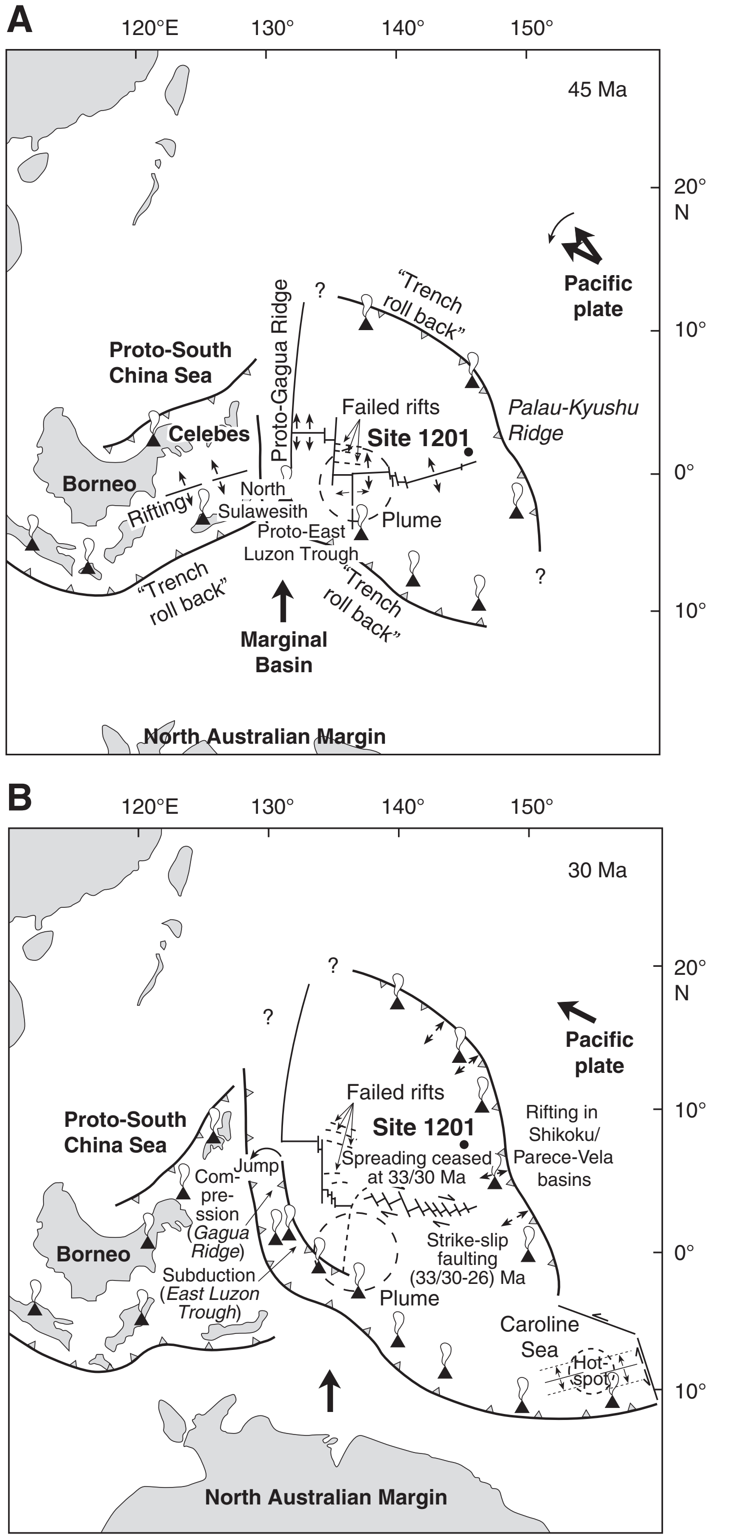

Figure F4. Seasonal power spectra for (**A**) vertical component. (**B**) horizontal component of borehole seismometer WP-1 at Site 1201. HNM = high noise model and LNM = low noise model for seismic stations (after Petersen, 1993). (Continued on next page.)

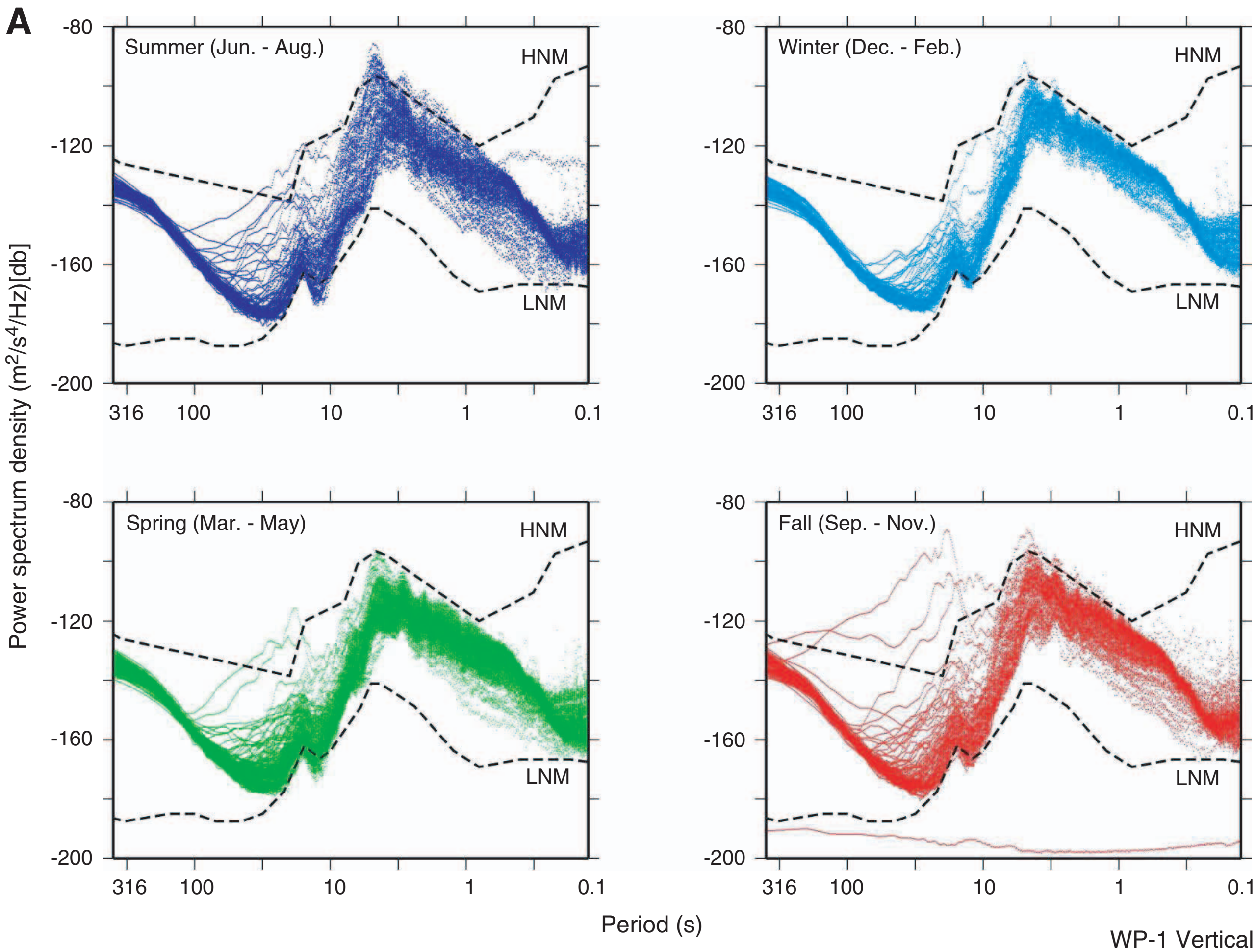

Figure F4 (continued). Seasonal power spectra for (**B**) horizontal component of borehole seismometer WP-1 at Site 1201.

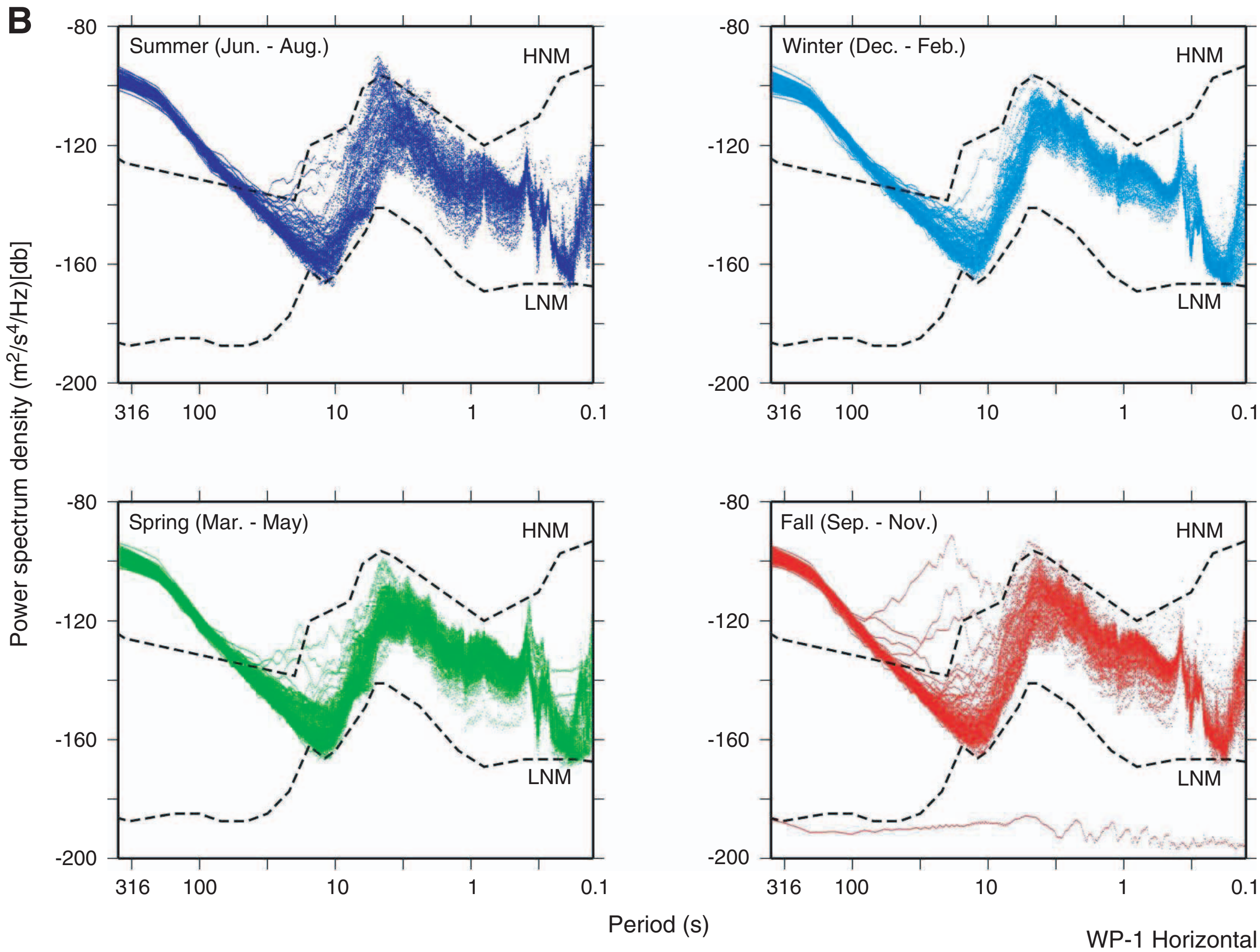

Figure F5. **A.** Average *P*-wave velocity vs. depth structure for the crust and upper mantle after Dziewonski and Anderson (1981) and Kennett et al. (1995). **B.** Mineral phase changes with increasing pressure and temperature. α = olivine, β = modified spinel, γ = spinel, Pv = perovskite, Mw = magnesio-wustite, B-S = mantle geotherm from Brown and Shankland (1981). **C.** Mineral and state changes corresponding to boundaries in the mantle.

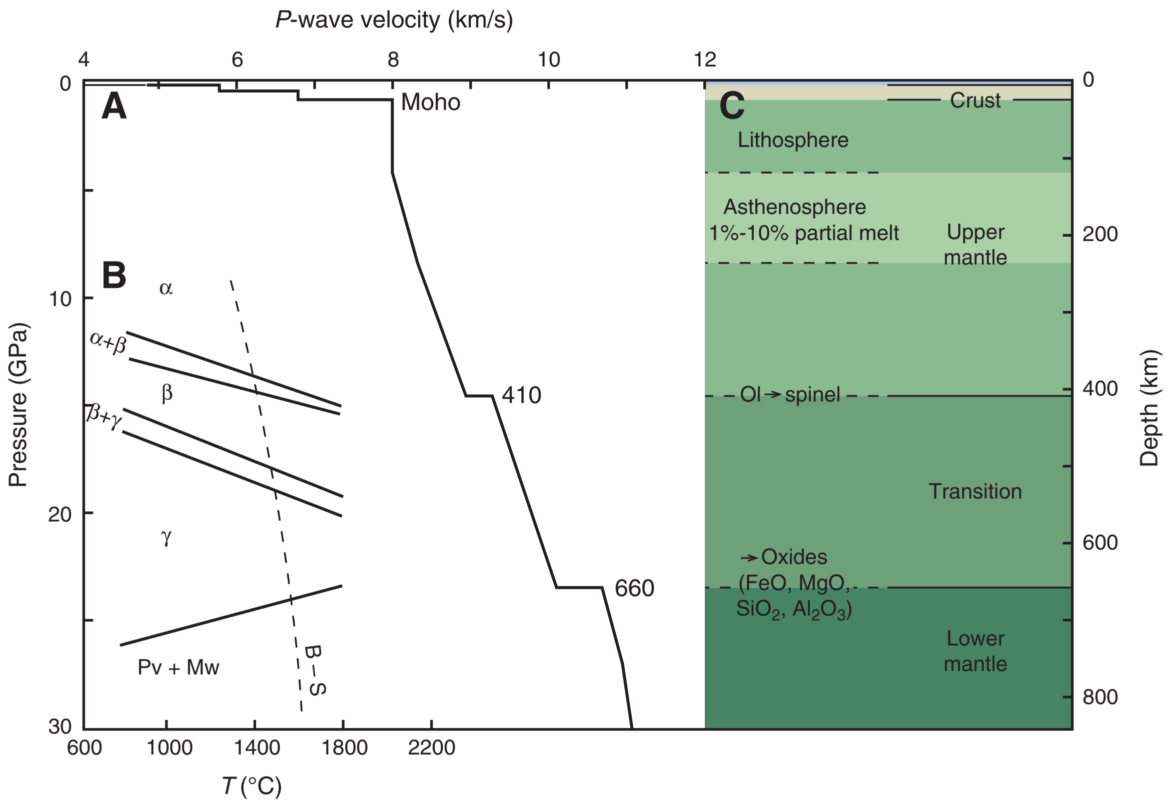

Figure F6. Velocity spectrum stacking plot showing amplitudes of stacked receiver functions for high signal-to-noise ratio teleseismic events recorded by stations WP-1 and OBS NOT1 vs. *S*-wave velocity perturbations (dV_S) and *P*- to *S*-wave conversion depths. "410" and "660" discontinuities are, respectively, located at depths of 371 and 663 km (377 and 669 km after water correction) beneath Site 1201 (after Suetsugu et al., 2005).

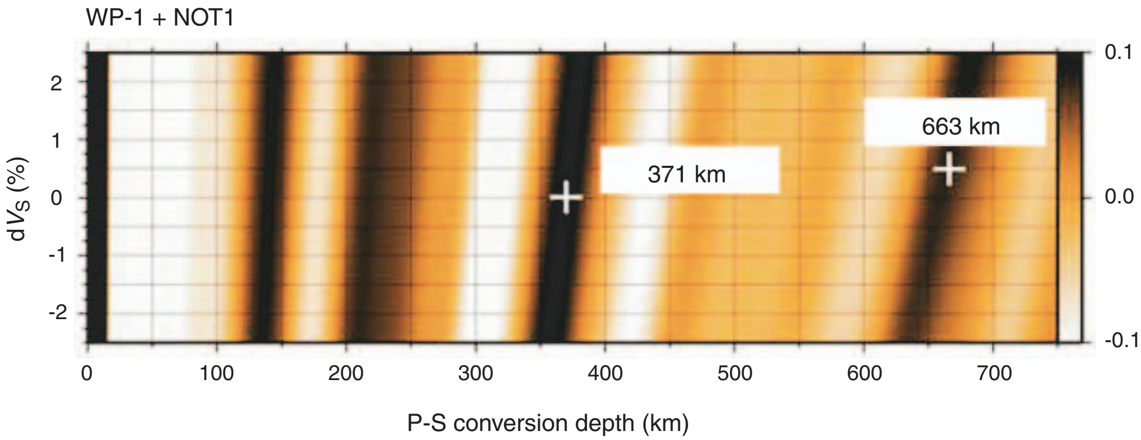

Figure F7. *P*-wave velocity anomalies at depths corresponding to (**A**) the 410 discontinuity and (**B**) the 660 discontinuity (after Suetsugu et al., in press). Red triangles = location of OBS array discussed in Suetsugu et al. (2005), green triangle = position of borehole observatory WP-1 and OBS NOT1 at Site 1201, ellipses = locations of *P*- to *S*- conversion points on the 660 discontinuity; enclosed numbers = discontinuity depths.

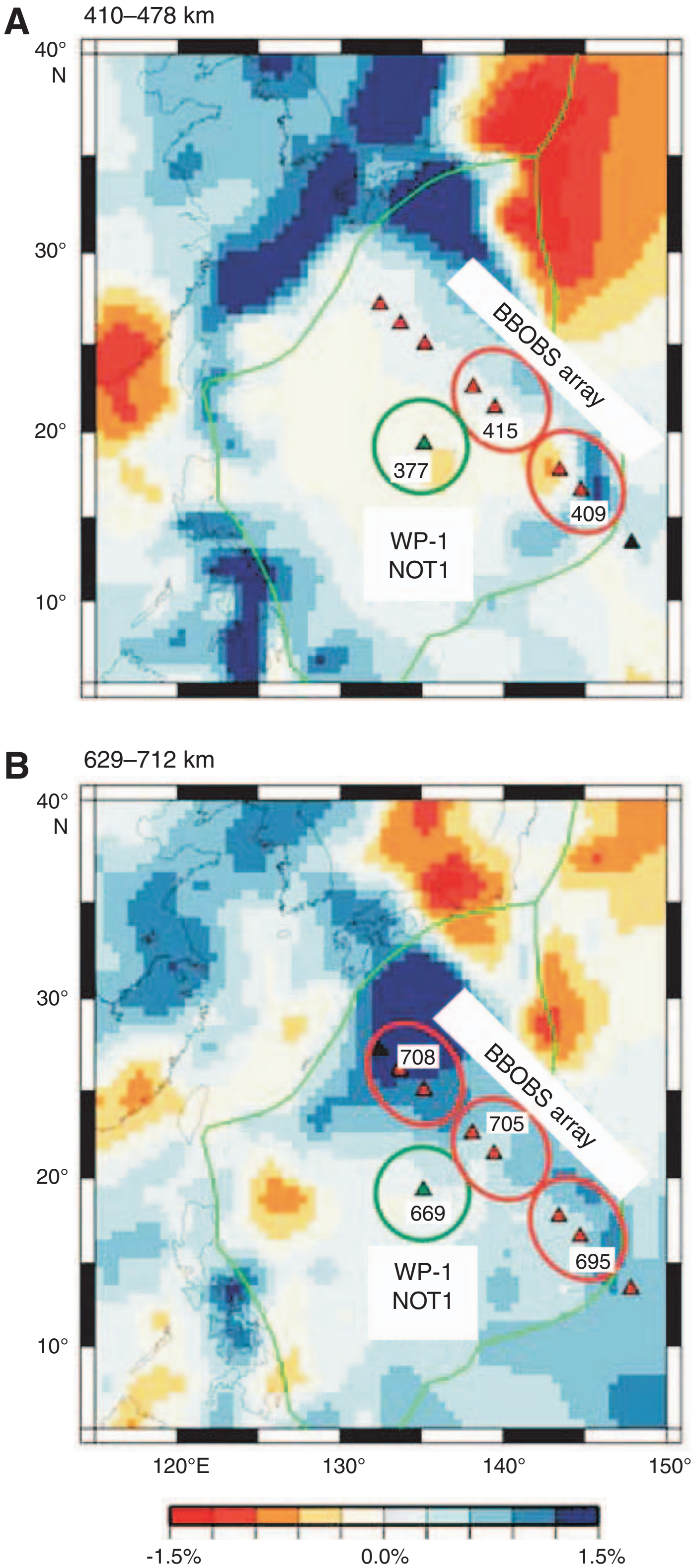

Figure F8. Locations of seismic refraction lines used to determine seismic structure of the crust and upper mantle under ODP Site 1201. Black star = location of borehole observatory WP-1, circles = OBS locations. Sites 7 and 8 lie on the summit of the Kyushu-Palau Ridge (figure from Arisaka et al., 2003).

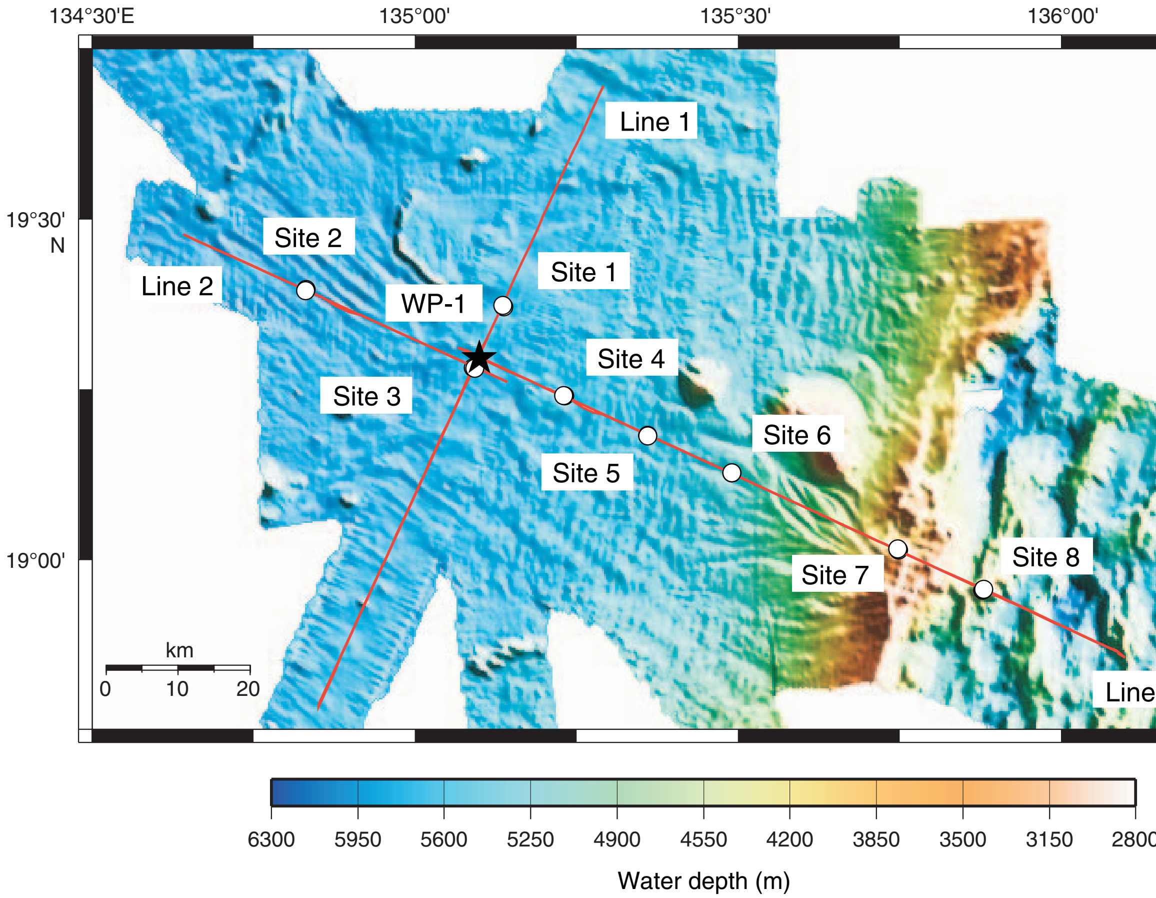

Figure F9. Compressional wave velocity structure under refraction Lines (**A**) 1, (**B**) 2, and (**C**) 3 (after Arisaka et al., 2003).

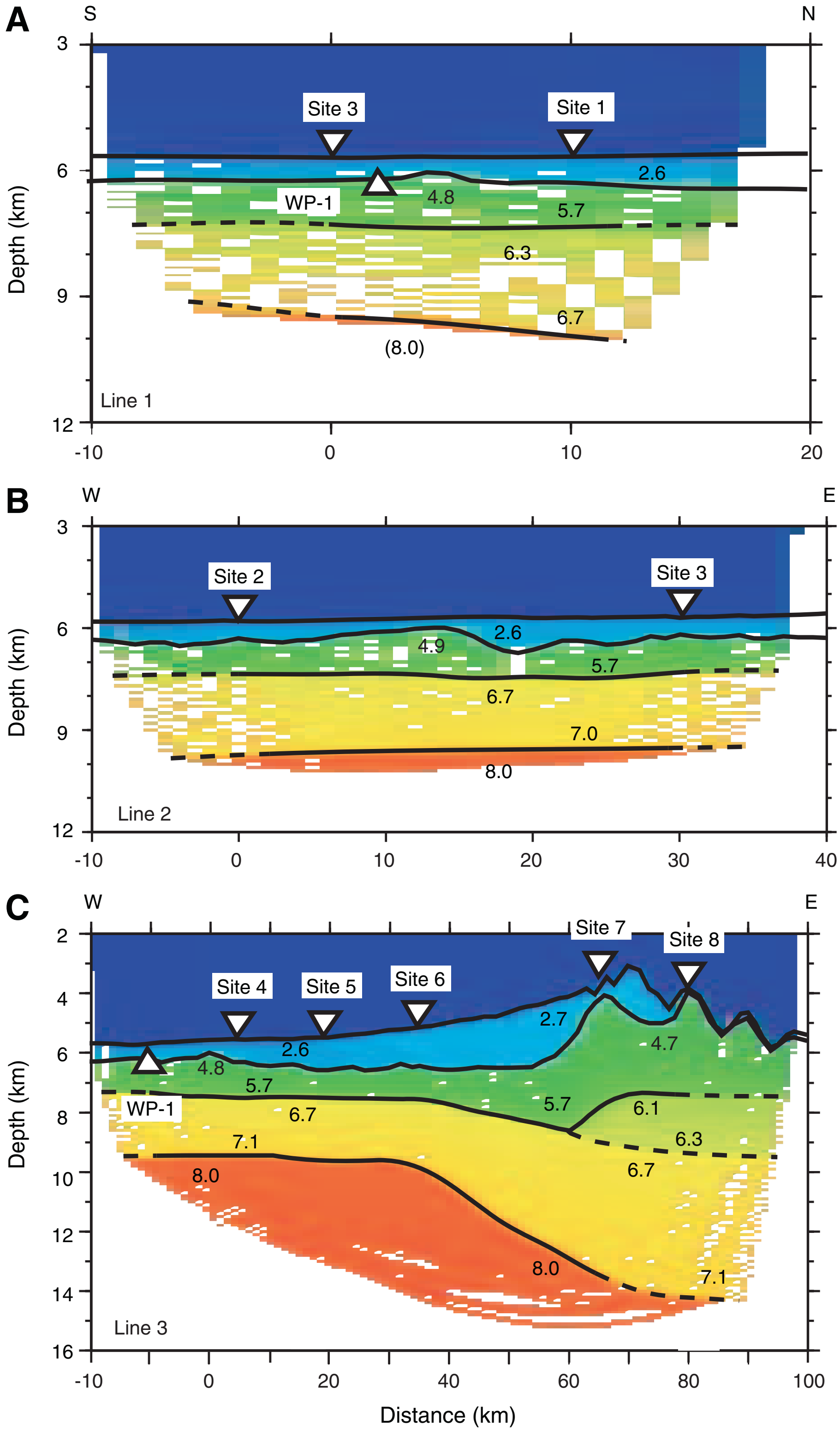

Figure F10. Comparison of crustal velocity structure at Site 1201 (this study) with that at other nearby sites in the West Philippine Basin (Goodman et al., 1989; Louden, 1980) and normal oceanic crust (White et al., 1992).

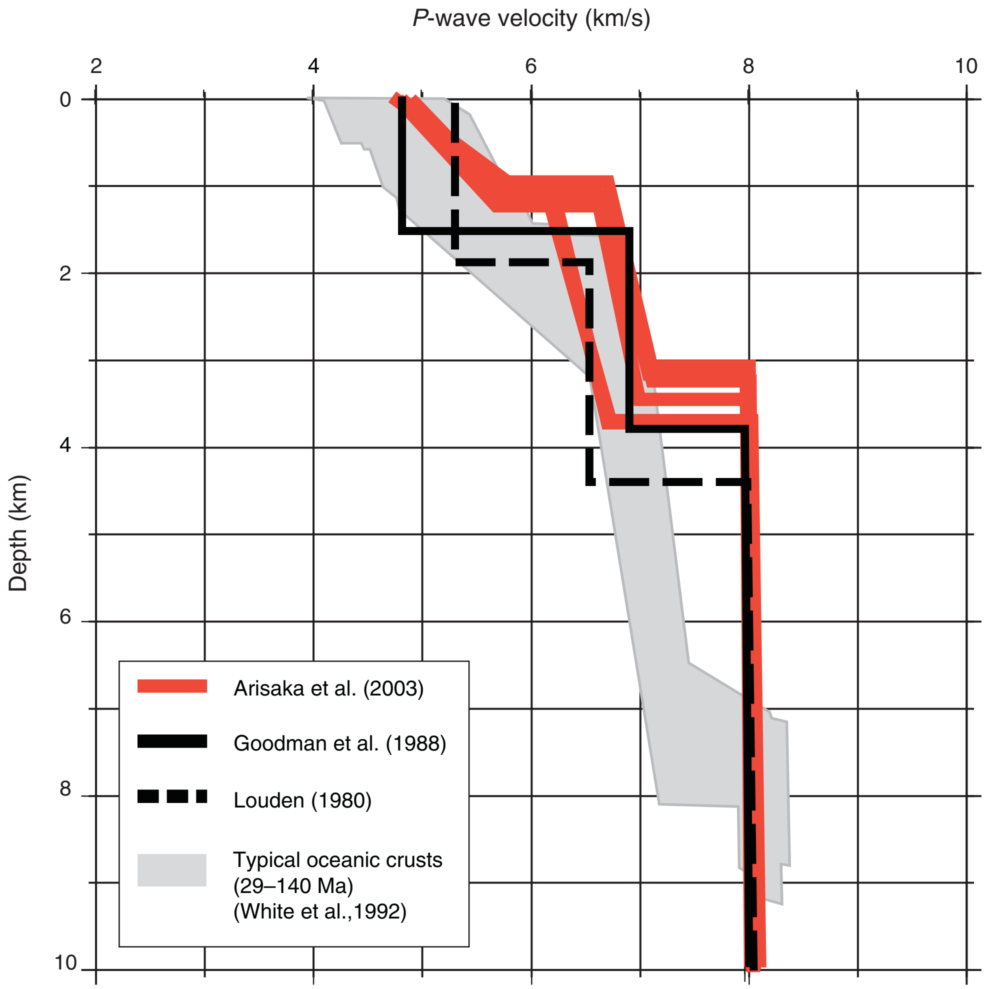

Figure F11. Lithology, sediment mineralogy, and pore water geochemistry vs. depth at Site 1201. Arrows indicate seawater values.

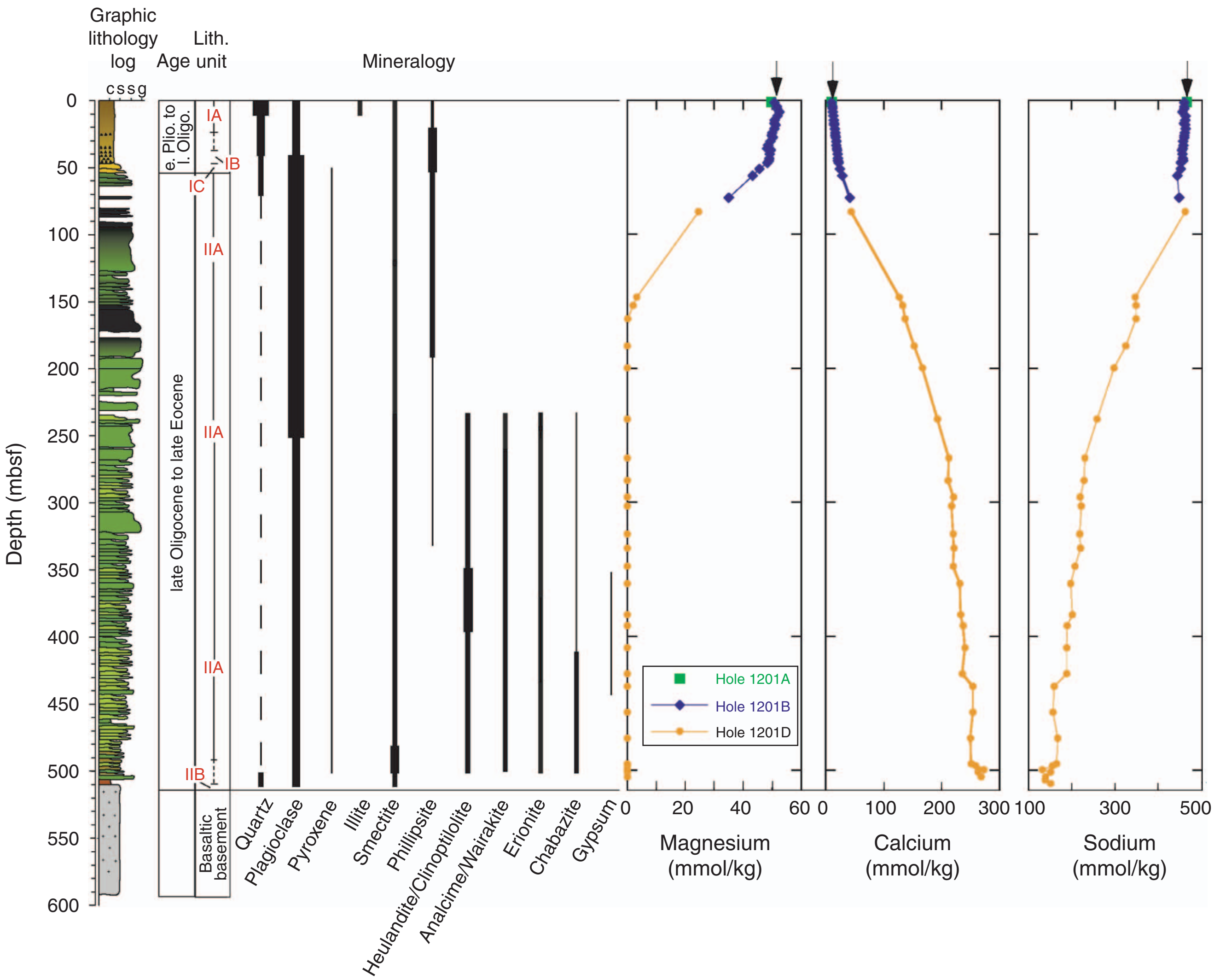

Figure F12. V vs. Ti content in basalts from Hole 1201D. The basalts are transitional between arc tholeiites on the one hand and mid-ocean-ridge basalt (MORB) and backarc island basalt (BABB) on the other.

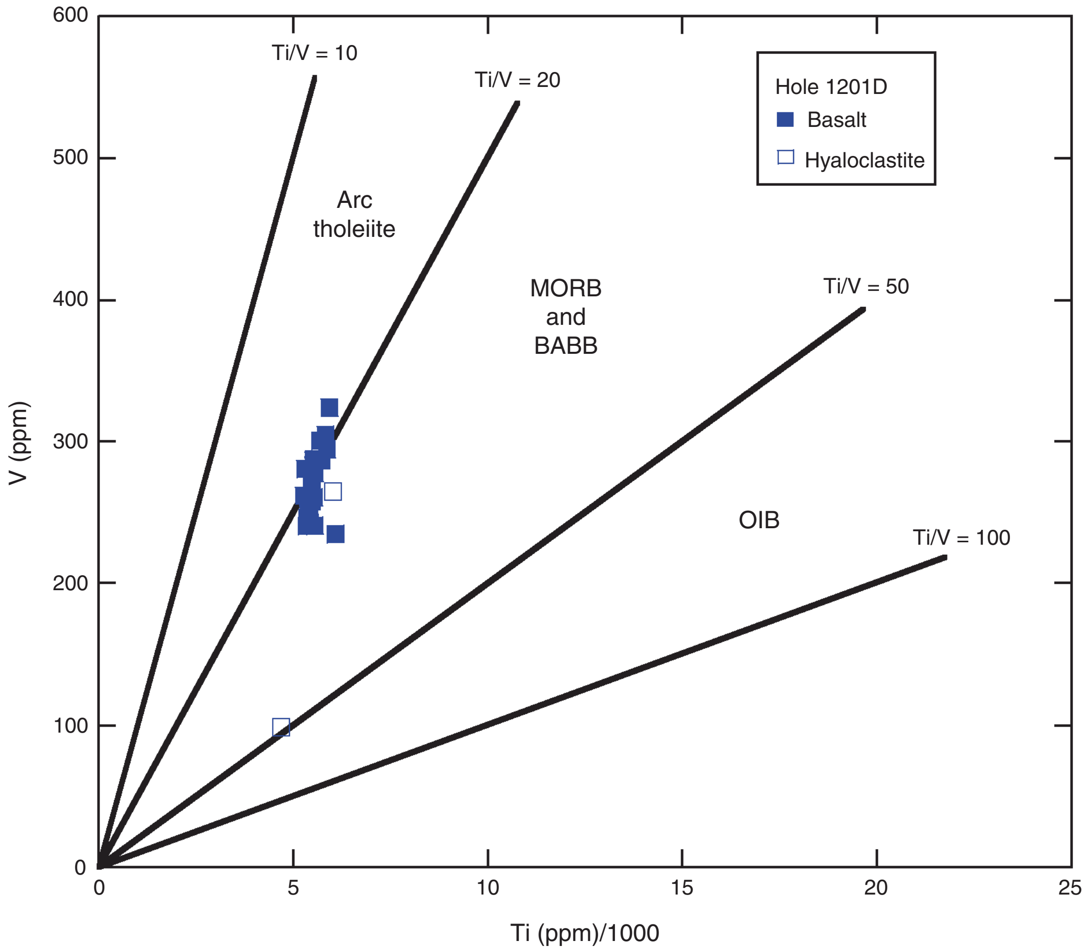

Figure F13. History of deposition at Site 1201 based on sediments and microfossils recovered during ODP Leg 195 (Salisbury, Shinohara, Richter, et al., 2002).