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1. Leg 203 Synthesis: Summary of Scientific Results[1]

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ABSTRACT

The primary objective of Ocean Drilling Program (ODP) Leg 203 was to install a cased legacy hole on behalf of the International Ocean Network (ION). ION is engaged in planning, coordinating, and implementing the installation of the Ocean Seismic Network of seafloor geophysical observatories. The site location had been designated by the Dynamics of Earth and Ocean Systems (DEOS) planning effort that was under way at that time in the United States (since subsumed into the U.S. National Science Foundation [NSF] ORION program) and in the United Kingdom, as a site intended for sustained, multidisciplinary observations at and below the seafloor and in the overlying water column. The second objective of Leg 203 was to obtain basement cores, to carry out wireline logging, and to carry out physical, petrological, and paleomagnetic studies of relatively young (11 Ma), unaltered equatorial Pacific oceanic crust. The sites drilled during Leg 203 are representative of those originating in fast-spreading environments. Approximately one-half of the surface area of contemporary oceanic plates originated in the 20% of the global ridge system associated with fast-spreading segments. Prior to Leg 203, only three holes had been drilled during ODP/deep Sea Drilling Project (DSDP) with penetrations >100 m in such "normal" Pacific crust. The Leg 203 coring and logging goals were intended to add to the limited inventory of baseline data about this understudied, yet common lithospheric setting.

All goals identified in the Leg 203 science plan were achieved. A cased legacy hole was installed and cemented in place, providing >100 m of basement penetration, and coring and logging operations were carried out in a second hole, providing 195 m of total penetration, including 85 m of basement.

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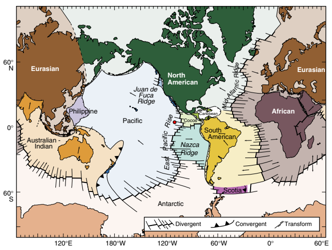
INTRODUCTION

Initial Results Recap

Hole 1243A is in 3882 m of water at 5°18.0541′N, 110°4.5798′W in the equatorial Pacific (Fig. F1). The site was chosen as the location for a future broadband seismic and complementary geophysical observatory by ION, the International Ocean Network, an Inter-association Committee of the International Union of Geodesy and Geophysics (IUGG). Hole 1243A was cased and cemented in place to accommodate future installation of the borehole seismometer.

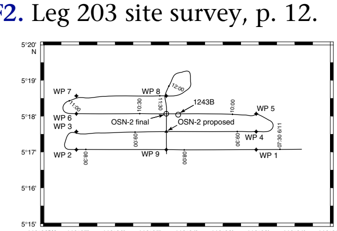
F1. Location of Site 1243, p. 11.



Basement age at Hole 1243A is ~11 Ma, as established by spreading rate (van Andel et al., 1975) and by biostratigraphic and paleoceanographic analysis of the age of the near-basement part of the sediment column obtained from nearby Hole 851, drilled during Ocean Drilling Program (ODP) Leg 138 (Psias et al., 1995; Shackleton et al., 1995). This is a site with equivalent sediment thickness located ~0.5 nmi from Hole 1243A. Total seafloor penetration of 224 m was achieved, consisting of a sedimentary section of 121 m and 103 m of basement. Technical challenges in seating a 16-in casing unit into a hole with an 18½-in bore led us to complete Hole 1243A by drilling with an 18½-in rotary bit without coring, followed by insertion of a 10¾-in casing. The hole was cased to a depth of 212 m below seafloor (mbsf) and cemented in place, with the top of the cement at 199 mbsf. A schematic view of the cased legacy hole installed at Hole 1243A is shown in figure F9 of Shipboard Scientific Party, 2003. Casing with adequate bonding to basement rock was required because Hole 1243A is intended in the future to contain an observatory-quality broadband seismometer. The casing preserves the integrity of the hole for future reentry operations, whereas the cement bonding assures good mechanical coupling between the seismic sensors and the host rock. It is anticipated that the power, data storage, and telemetry infrastructure installed at and above the seafloor to support the seismic instrument will also be used for geomagnetic, geoelectric, and other complementary geophysical and oceanographic observatory sensors.

Technical complications related to installation of the casing were an impediment to logging and coring at this site. In order to achieve the goals identified for coring and logging of this site, an environment associated with lithospheric origin at a fast-spreading ridge crest, we tripped out of Hole 1243A and located a second, uncased hole (Hole 1243B) 600 m east of Hole 1243A, at 5°18.0543′N, 110°4.2544′W (Fig. F2). Given the limited time available to ODP Leg 203, and compounded by the requirement to curtail operations so the ship could make way to an alternative port of entry (Victoria, British Columbia, rather than San Francisco), we prioritized obtaining basement rock samples as the main objective of coring at that site, with wireline logging of the entire sediment and basement section as a secondary objective.

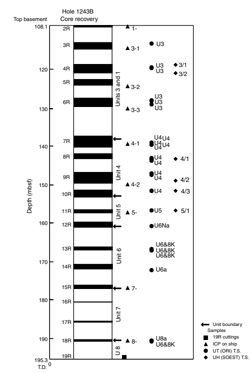
F2. Leg 203 site survey, p. 12.



We jetted-in Hole 1243B to a point just above the sediment/basement interface and achieved a total penetration of 195 m, including 110 m of sediment and 85 m of basement. Sediment was recovered from the base of the sediment column in Hole 1243B in Core 203-1243B-1R (102–108 mbsf) comprising ooze of the same colors and lithologies as those recovered from Leg 138 Site 852 (Psias et al., 1995), which was located ~0.5 nmi south of Hole 1243B and which had nearly identical depth of sediment cover. The ooze is predominantly coccolithic, with small quantities of planktonic foraminifers, discoasters, radiolarians, iron oxide globules, and glass.

Basement samples were recovered from 17 cores (Cores 203-1243B-2R through 18R) obtained in the interval 108–195.3 mbsf. Recovery rates varied between 1.6% and 63.7% (average = 25%). In addition, the lowermost core, Core 203-1243B-19R, contained 5.3 m of drilling breccia/cuttings; however, postcruise analysis indicates that Core 19R comprised cuttings rather than breccias. The basalt samples from Hole 1243B largely consisted of mildly altered pillow basalts, including both aphyric and sparsely plagioclase and olivine phyric basalts. There was no evidence of thicker, massive basalt flows of the type encountered at ODP Site 1256, a basement section formed at ~15 Ma during an episode of superfast accretion on the East Pacific Rise (Wilson, Teagle, Acton, et al., 2003). Shipboard studies determined that the basement section comprised seven igneous lithologic units, one (Unit 2) of which comprised a single sample of limestone (Fig. **F3**). With the exception of lithologic Unit 4 (an alkali basalt), all igneous units were tholeiitic.

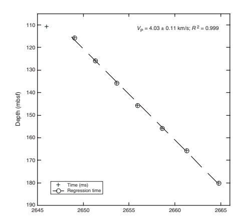
F3. Basement lithologic units, p. 13.



A reentry funnel was left in place in Hole 1243B to facilitate future installation of borehole instrumentation at a site identified by the Dynamics of Earth and Ocean Systems (DEOS) planning effort for geophysical observatory operations.

Wireline logging was carried out in Hole 1243B in the lower sediment section and throughout the basement section. Multiple trips were made with triple combination (triple combo) and Formation MicroScanner (FMS)-sonic tool strings, with a single trip of a Well Seismic Tool (WST) in a vertical seismic profile (VSP) configuration (Fig. **F4**). Cement bond and vertical inclination logs were also obtained from Hole 1243A, to confirm its suitability for installation of a broadband seismic sensor package.

F4. WST traveltime vs. depth, p. 14.



POSTCRUISE SCIENTIFIC RESULTS

Igneous Ocean Crust Studies

Hole 1243B penetrated 87.1 m basement, for a total depth of 195.3 mbsf. The lowermost part of Hole 1243B was characterized by recovery rates <10%, coincident with evidence for extensive caving below ~156 mbsf. There is an unresolved discrepancy of 6.3 m between wireline depths (which are deeper) and core depths. The depths presented here are those determined from measurements of the drill pipe (i.e., the curated core depths).

Eight basement units were identified during shipboard inspection of phenocryst content, vesicularity, and degree of alteration (Fig. **F3**). Recovery from the bottommost unit was sufficiently poor that emphasis was placed on detailed examination of fine-scale cuttings from the bottom of Hole 1243B rather than concentrating efforts exclusively on conventional core sample analysis of this unit. Although identified as a breccia in the Leg 203 *Initial Reports* volume (Orcutt, Schultz, Davies, et al., 2003), the cuttings were not breccia but rather a mechanically disrupted sample of intact host rock. The expectation prior to detailed analysis was that the cuttings would either represent the geochemical composition of the bottommost section of the hole, where conventional recovery was poor or alternatively might represent a geochemical average of the upper basement. Implicit in this approach was the assumption that all lithologic units so sampled had equivalent brittleness, that the ratio of basaltic glass to hypocrystalline basalt does not vary significantly between the units, and that the glass cuttings recovered represented a sufficiently randomized sampling.

Out of thousands of primarily hypocrystalline grains examined under a binocular microscope, 582 glassy grains of ~1 to 2.5 mm diameter were identified and analyzed. In addition to cuttings, nine thin sections of glassy pillow basalt edges were obtained from core samples and provided a lithologic context for the cuttings, helping to establish correlations between core stratigraphy and the cuttings.

Postcruise electron microprobe analysis (EMPA) on cuttings and thin sections at the University of Hawaii and the University of Tokyo (i.e., Table T1 of Moberly et al., this volume) enabled identification of five distinct compositional groups within the basement section. These groups, reported here, were not identified during shipboard analysis, and are summarized in detail in Table T4 of Moberly et al. (this volume).

The predominant group, termed "Group M," comprised 299 samples. "Group K," named for its high K_2O content, comprised 188 samples. "Group A" (55 samples) and "Group B" (24 samples) have similar TiO_2 content but differ in Al_2O_3 and FeO content. "Group H" (16 samples) had a distinct signature in terms of oxide composition. These results indicate that the glass recovered from the bottom of Hole 1243B can be traced to five distinct sources. Under the range of assumptions about the sampling method indicated previously, EMPA indicates that the five sources are

1. 51.4% (±2.0%) tholeiitic, normal mid-ocean-ridge basalt (N-MORB)—identified as Group M;
2. 2.7% (±0.6%) mid-ocean-ridge basalt (MORB) similar to Group M but with enhanced Mg, Al, and Ca and lower Fe, and Ti—identified as Group H;
3. 4.1% (±0.7%) MORB similar to Group M but with reduced Mg, Al, and Ca and enhanced Fe and Ti—identified as Group B;
4. 9.4% (±1.2%) MORB similar to Group B in Ca and Ti but with borderline enrichment of Fe, P, and K—identified as Group A; and
5. 32.3% (±1.8%) moderately enriched, borderline alkalic MORB—identified as Group K.

The EMPA-derived glass cutting groupings do not in general show clear correlation to the petrological groups identified aboard ship. Moberly et al. (this volume) interpret this to indicate that rather than a random sampling of the entire section drilled, the cuttings come largely, if not entirely, from the bottom of the hole.

The shipboard determination of eight petrological units (Orcutt, Schultz, Davies, et al., 2003) has been refined by Moberly et al. (this volume). A limestone that previously had been taken to be a boundary between Units 3 and 4 is reinterpreted to represent calcareous ooze that drifted into a fissure or was engulfed by a tongue of basalt flow. Thus, previous Units 1 and 3 are now interpreted to be the same unit. Consequently, six units of basement basalt were cored in Hole 1243B. Of these, tholeiitic Units 1, 3, and 5 have similar MgO and CaO content to cuttings from the predominant Group M, although Group M composition differs in terms of other indicator oxides, and Units 1, 3, and 5 bear little resemblance to any other postcruise compositional groups. None of the postcruise compositional groups resembled the composition of

Unit 4. The origin of Group M cuttings is therefore from deep within Hole 1243B, probably below 170 mbsf. Group K materials are compositionally similar to Unit 8 and nearly identical to Unit 6 and are interpreted by Moberly et al. to originate from ~160 mbsf or deeper, and possibly as deep as 190.67 mbsf. Group A's composition likely matches Unit 5 (~156 mbsf). Group B deviates from the known unit compositions and may be a differentiate of Group M, as may be Group H, although Group H's composition may be attributable to Units 6 or 8.

Moberly et al. (this volume) conclude that on the balance of evidence from petrologic and geochemical analysis and wireline logging, that approximately two-thirds of the basement penetrated in Hole 1243B is N-MORB, and one-third comprising Unit 4, Group K, and, potentially, Unit 5 Group 5, is enriched or transitional MORB. Ultimately this argues for two different parental magmas for the basement material. Moberly et al. posit that this may be a manifestation of the Galápagos plume or it may be a consequence of spreading rate and mantle thermal regime.

Paleomagnetic Studies

Zhao et al. (2006) examine and contrast basement cores obtained from seven ODP legs, including samples from the Newfoundland-Iberia rifted margin, the Mid-Atlantic Ridge, the eastern equatorial Pacific (this leg, 203), the Ontong Java Plateau, and the Kerguelen Plateau/Broken Ridge. These five regions represent disparate ages and tectonic settings. The samples comprise primarily basaltic flows, diabase sills, and serpentinized peridotites. Seafloor ages range between 140 ka and 121 Ma. The goal of the Zhao et al. study is to investigate the magnetic expression of the mineral changes that can be related to the alteration of basement rocks given different settings in which they were formed, and under different stages in their evolution. In all cases, magnetic-bearing minerals are titanomagnetite and titanomaghemite in varying degrees of oxidation.

Igneous samples obtained during Leg 203 were analyzed for Curie temperature using 0.05-mT and 1-T applied fields; hysteresis loop measurements of saturation magnetization, saturation remanence, coercivity, and remanent coercivity determined over a temperature range of 10–400 K; saturation isothermal remanent magnetization over a temperature range of 10–300 K; alternating-current (AC) susceptibility measurements at varying field amplitudes and frequencies; and Mössbauer spectroscopy.

In contrast to igneous samples obtained from some other sites (e.g., Mid-Atlantic Ridge), the Leg 203 Hole 1243B samples do not exhibit a clear Verwey transition. The Verwey transition is a spontaneous, intercorrelated change in lattice symmetry and electrical conductivity in certain ionic crystals, such as those containing magnetite. The transition represents an abrupt change in crystallographic structure at a critical temperature near ~125 K and is typically associated with material-dependent anomalies in the magnetic, thermodynamic, and other rock properties (Walz, 2002). The presence or absence of a detectable Verwey transition is therefore a useful diagnostic indicator of the composition of the material as well as its alteration history.

With one exception only, magnetic remanence of basement core samples from Hole 1243B decays linearly over low temperatures during cooling and during heating, without exhibiting the abrupt changes indicative of a Verwey transition. Zhao et al. (2006) suggest that the magnetite in these samples is either oxidized or enriched in titanium. Thermomagnetic experiments suggest that low-temperature oxidation (maghemitization) is a possible explanation for the lack of a Verwey transition in these samples. In addition, igneous Sample 203-1243B-17R-1, 7–9 cm, exhibited an apparent self-reversal, with remanence changing sign both during cooling and heating. Zhao et al. (2006) suggest that this behavior may be consistent with that observed in other oceanic basalts, in some continental basalts, and in some synthetic titanomagnetites. The apparent partial self-reversing behavior in fine-grained basalt from Site 1243 (and 1277) is observed only in samples during progressive thermal demagnetization and in a narrow temperature window that corresponds to the titanomaghemite phase determined from thermomagnetic experiments. Zhao et al. suggests that one of the following processes may be responsible for this effect: (1) natural partial self-reversal during low-temperature oxidation, (2) natural partial remagnetization during oxidation, or (3) partial self-reversal during laboratory heating through N-type ferromagnetism. The low-temperature cycling data suggest that the magnetization below the 300 K self-reversal in Sample 203-1243B-17R-1, 7–9 cm, must be in a different phase than the one causing partial self-reversal during thermal demagnetization at higher temperatures (>300 K), or this single phase would show two self-reversals at both low and high temperatures.

Analysis of AC susceptibility measurements indicates that Samples 203-1243B-11R-1, 83–85 cm, and 17R-1, 7–9 cm, contain a broad distribution of grain sizes, with a large proportion of single-domain grains and significant quantities of pseudosingle domain and multidomain particles. The preponderance of single-domain grain sizes from Miocene-aged basement samples from Hole 1243B contrasted with the more common pseudosingle and multidomain grain sizes as found in Cretaceous-aged basalt recovered from the Newfoundland-Iberia Margin, the central Newfoundland Basin, the Ontong Java Plateau, and the Kurgeulen Plateau and Broken Ridge (Zhao et al., 2006) implies that the single-domain fraction of those basalts may have diminished as those basalts aged.

Zhao et al.'s analysis of rock magnetic data from seven ODP sites demonstrates that spatial-temporal variations in rock magnetic properties of basaltic samples depend primarily on mineralogy and alteration. Significantly, there is no clear indication of a relationship between the age of the seafloor and the degree of low-temperature alteration.

Vertical Seismic Profiling Studies

The lack of in situ seismic velocity measurements for young (0–11 Ma) ocean crust has impeded efforts to ground-truth the inference, from a variety of seismic observations, that seismic velocities within Layer 2A increase rapidly and then level off as the ocean crust ages from 0 to ~10 Ma. Layer 2A is the uppermost igneous section in which hydrothermal circulation, heat removal, and alteration occurs, following emplacement within the ridge-crest neovolcanic zone. Seismic velocities increase with age as a consequence of alteration and infilling of fissures, cracks, and grain boundaries through persistent low-temperature water-rock reactions driven by the residual heat of formation and by the geotherm. Whereas evidence for such aging and alteration has been found in the marine seismic literature since the 1970s, prior to ODP Leg 203 the only in situ measurement of seismic velocity within such a young ocean basement section was obtained by an oblique seismic experiment in Deep Sea Drilling Project (DSDP)/ODP Hole 504B (Stephen, 1985). Carlson (2004) reports on the first VSP obtained from young normal ocean basement material within Layer 2A. The VSP was obtained in Hole 1243B, which is dated at 10–12 Ma (Orcutt, Schultz, Davies, et al., 2003).

In addition to VSP, Carlson reports on physical property measurements from 20 basaltic core samples. Measured bulk densities vary between 2.52 and 2.82 kg/m^3 (mean = 2.69 ± 0.02 kg/m^3), porosities between 4% and 17% (mean = 7.7% ± 0.7%), and *P*-wave velocities between 4.3 and 5.7 km/s at atmospheric pressure. Orcutt, Schultz, Davies, et al. (2003) report a mean sonic velocity of 4.73 km/s, obtained by sonic log within the upper basement section at 110–149 mbsf.

A VSP was obtained using the Schlumberger WST from 110.7 to 180.0 mbsf. The dominant frequency of the VSP records is near 100 Hz (Carlson, 2004), which is somewhat higher than the frequencies recorded in typical seismic refraction experiments. The VSP data are summarized in Table T1.

T1. WST data, p. 16.

The mean *P*-wave velocity over the interval 115.7–180 mbsf is 4.03 ± 0.11 km/s (Carlson, 2004). Within the more restricted interval also sampled by the sonic log (Orcutt, Schultz, Davies, et al., 2003), *P*-wave velocity is 4.21 ± 0.08 km/s. Figure F5 displays the results of the VSP experiments along with the mean sonic log data, the oblique seismic experiment in ODP Hole 504B (Stephen, 1985), and a compilation of marine seismic survey data by Grevemeyer et al. (1999). The VSP data are consistent with the overall pattern of increasing *P*-wave velocity with the age of the seafloor. These values are lower than those measured in the laboratory from Hole 1243B core samples. Carlson notes this is consistent with the presence of incompletely filled cracks in situ that would reduce the bulk density and velocity, whereas core samples measured in the laboratory would be relatively free of embedded cracks. The difference between the WST and the sonic log velocities is attributed by Carlson to the wavelength of the sonic signal source (~40 cm), which is near the characteristic scale of pillow basalts, whereas the wavelength of the WST source is 400 m—indicating that the WST measurements are of a broader, depth-averaged nature. The VSP experiment returned seismic velocities within the upper igneous section that are consistent with those for Layer 2A and too low compared to those attributed to Layer 2B. Carlson concludes that this argues against thinning of Layer 2A with age but rather indicates it persists through ages of 8–11 Ma. Neither the VSP experiment nor the sonic logs showed evidence for a significant vertical gradient in seismic velocity within Layer 2A. This supports Grevemeyer et al.'s (1999) and Peterson et al.'s (1986) view that aging of the oceanic basement is marked by a progressive infilling/sealing of Layer 2A, from the bottom up (Carlson, 2004). Figure F5 also shows the fit to the seismic velocity vs. age data from an asperity deformation model (Gangi, 1978). The relevant parameters for this model are the confining pressure, pore pressure, initial pressure, and the fractional area of contact of the asperities across the cracks. By assuming that fractional area of contact is simply proportional to the age of the seafloor, Carlson (2004) fits the observed velocity-age distribution with R^2 = 0.93. This is consistent with an increase in fractional area of contact across cracks of a factor of ~100 as the crust ages over its first 10 m.y. This has profound implications for hydrothermal circulation and the related processes of mineral deposition, dissolution, and diagenesis.

F5. *P*-wave vs. seafloor age, p. 15.

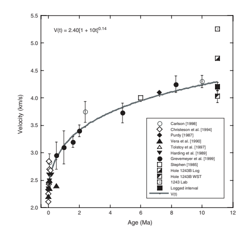


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Figure F1. Location of Site 1243.

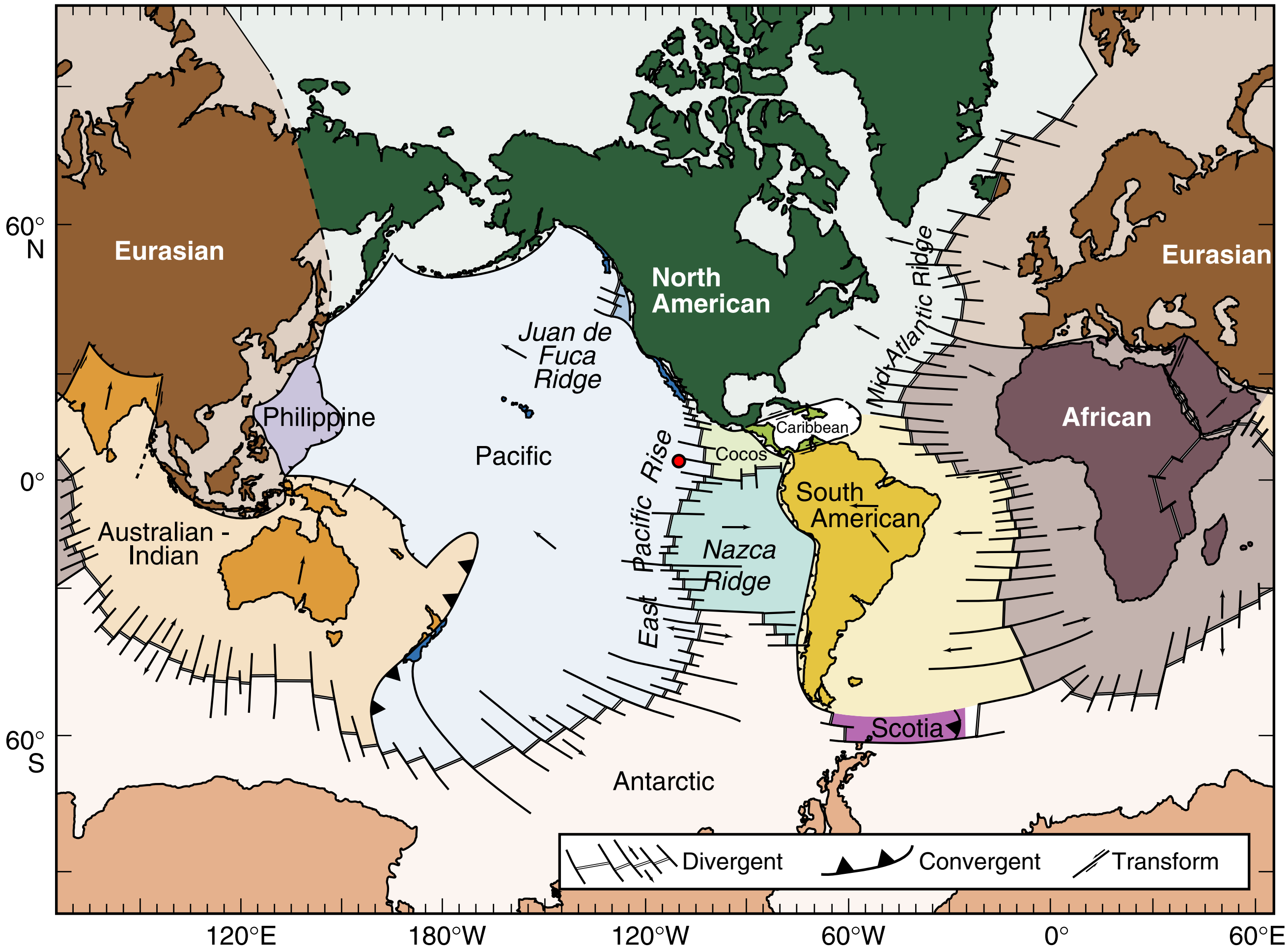

Figure F2. Track lines for the Leg 203 site survey. The east-west tracks are ~5 nmi long and are separated north-south by 0.5 nmi. The proposed location for the OSN-2 hole (triangle) was at the location of Site 852, drilled during Leg 138. The location chosen for OSN-2 (Hole 1243A) is 0.5 nmi to the north. Hole 1243B was offset 600 m east of the final OSN-2 site. The various navigational waypoints (WP) are shown as diamonds with labels.

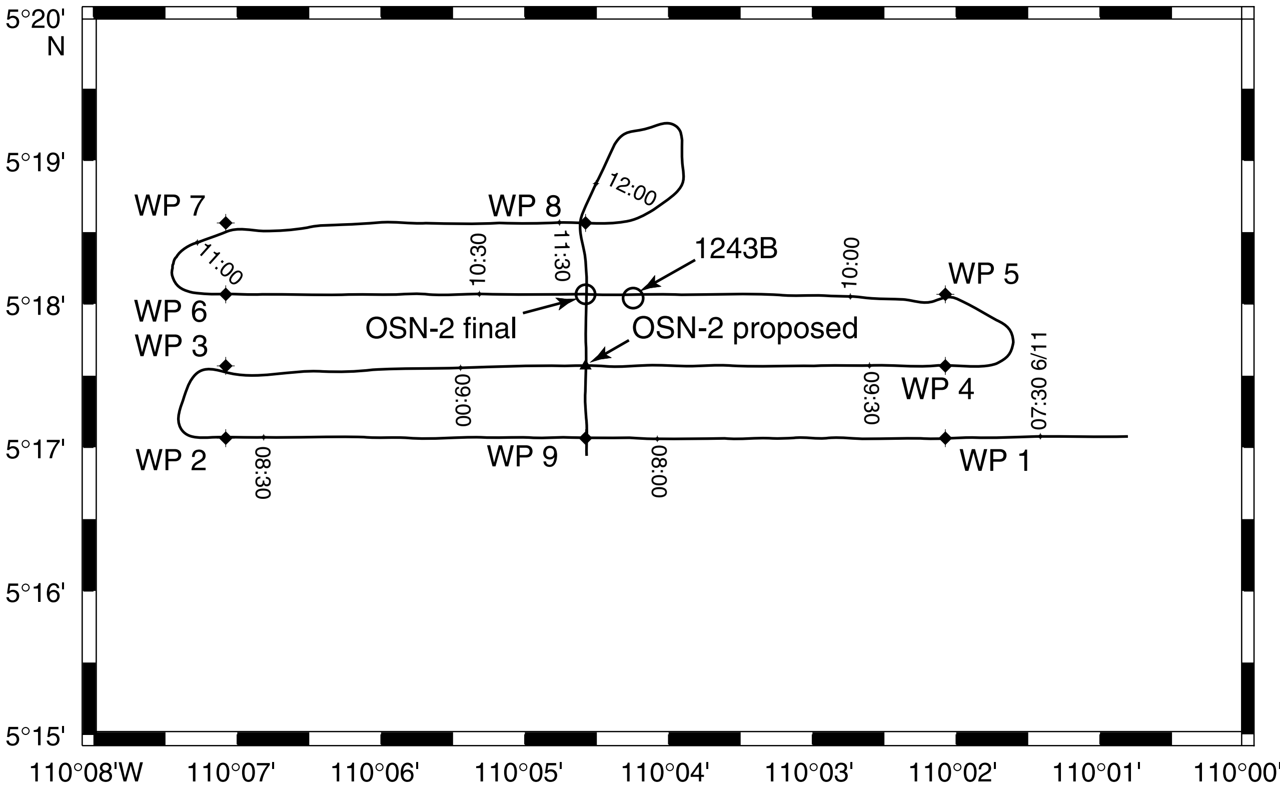

Figure F3. Basement lithologic units identified by Moberly et al. (this volume). Inductively coupled plasma–atomic emission spectroscopy (ICP) analyses made onboard ship are given by unit number with a hyphenated number (e.g., 3-1 is the first analysis of Unit 3). Thin section analyses performed at the University of Tokyo (UT[ORI]), are prefaced by the letter "U" for unit and a number, as discussed in Moberly et al. (this volume). Thin section analyses performed at the University of Hawaii (UH[SOEST]) are given a unit number and a virgule (e.g., 3/1: the first analysis of Unit 3). Figure from Moberly et al. (this volume).

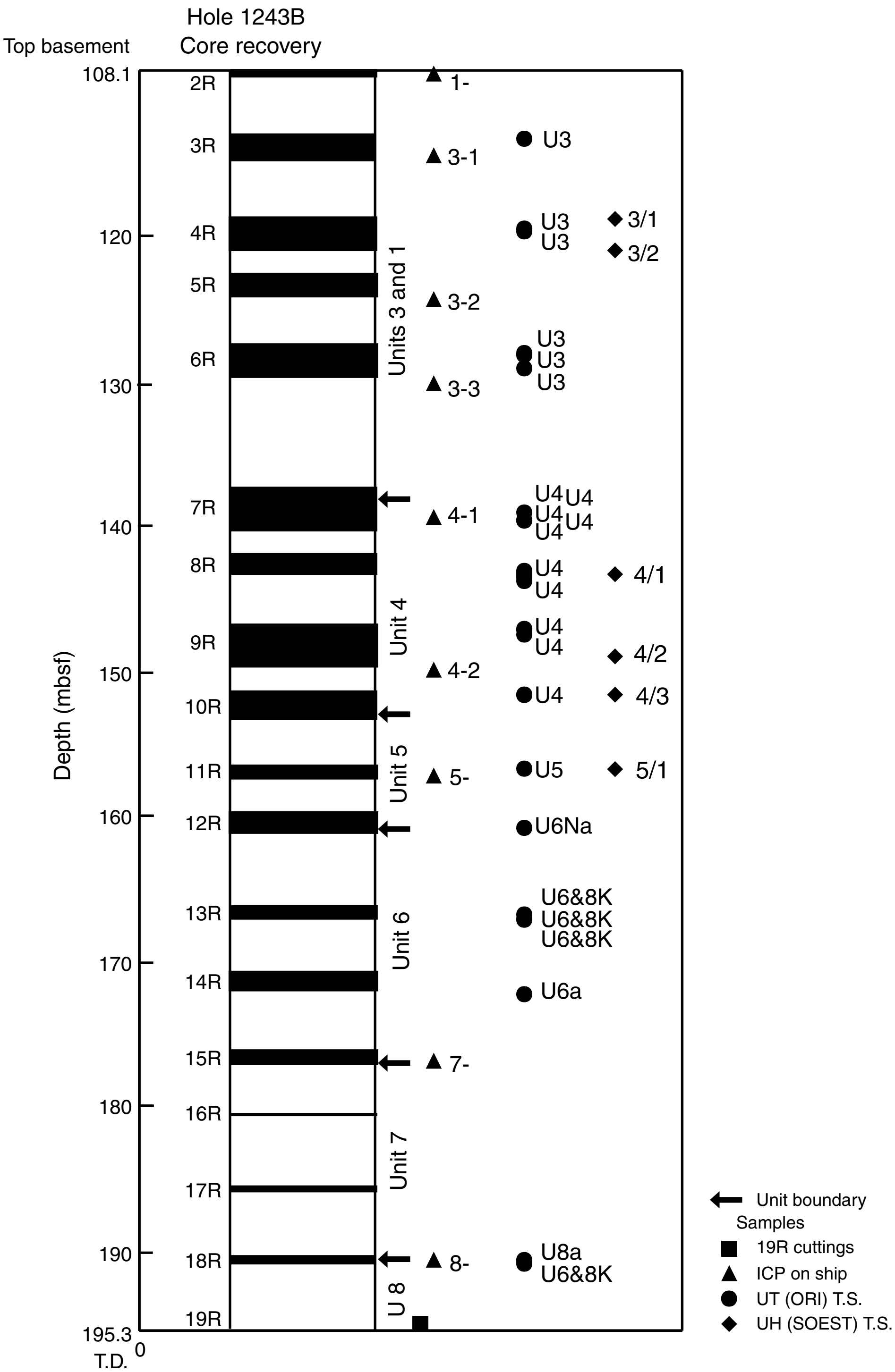

Figure F4. WST traveltime vs. depth in Hole 1243B (top of basement = 108 mbsf). Figure from Carlson (2004).

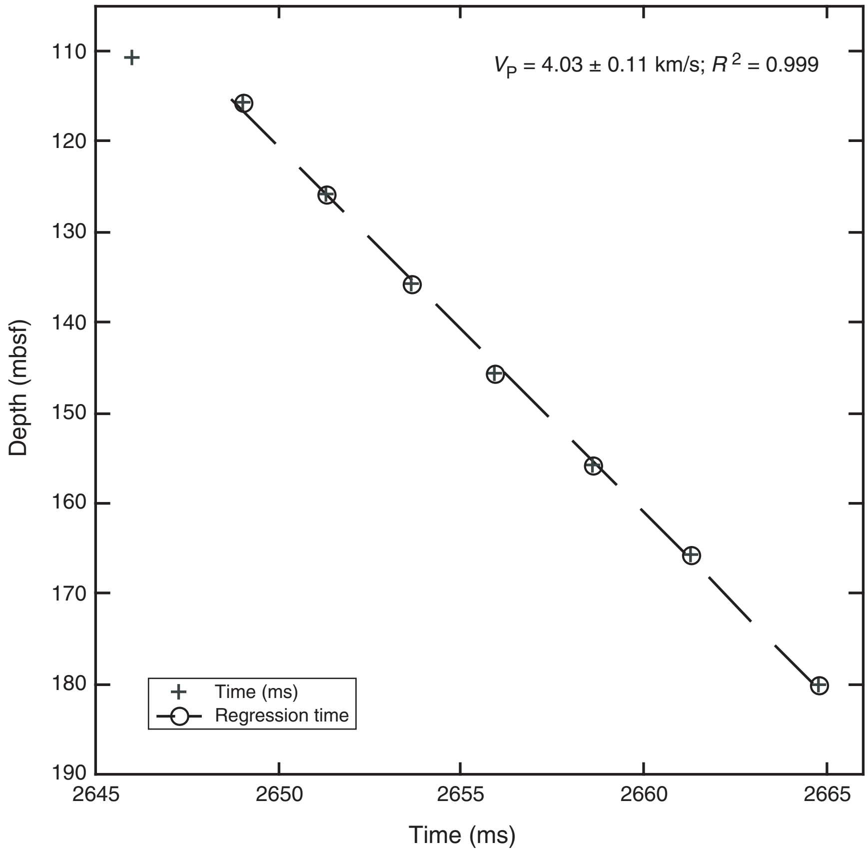

Figure F5. Seismic *P*-wave velocity at the top of the basement vs. seafloor age from a compilation by Grevemeyer et al. (1999), with laboratory velocities and mean sonic log velocities from Hole 1243B (Orcutt, Schultz, Davies, et al., 2003) and VSP velocities from Carlson (2004). WST = water sampling temperature probe. Figure from Carlson (2004).

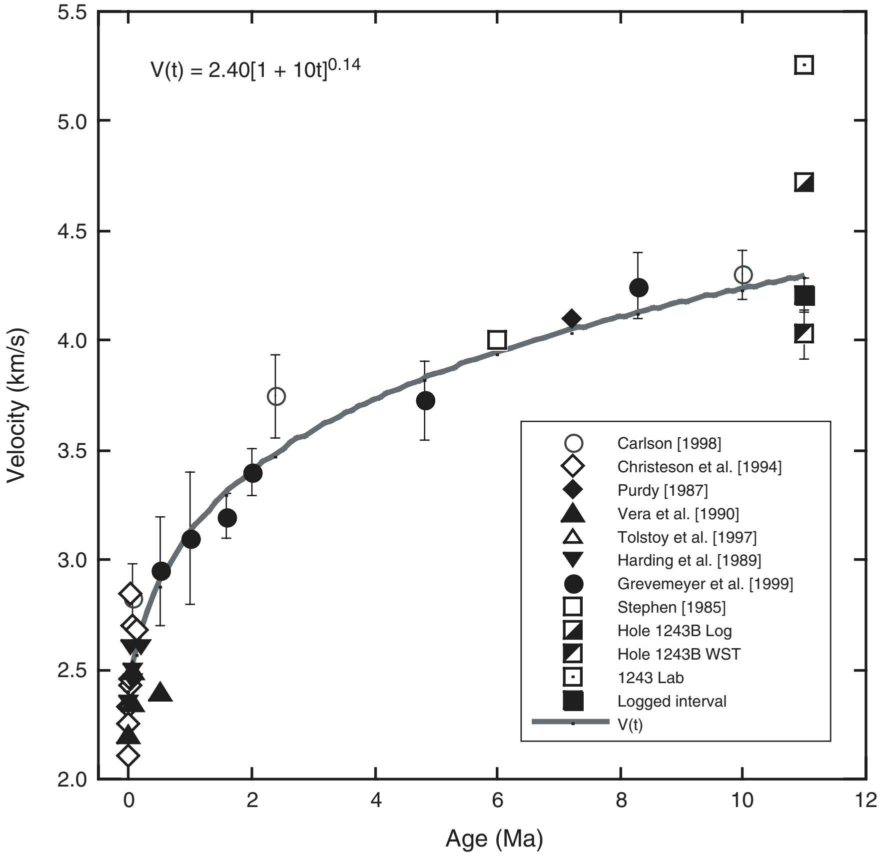

Table T1. WST data from Hole 1243B (after Carlson, 2004).

Depth (mbsf)	Traveltime (ms)	Repetitions
110.7	2646.02 ± 0.09	5
115.7	2649.02 ± 0.13	12
125.7	2651.28 ± 0.07	11
135.7	2653.57 ± 0.16	11
145.7	2655.92 ± 0.08	12
155.7	2658.57 ± 0.16	11
165.7	2661.28 ± 0.07	11
180.0	2664.85 ± 0.07	16