Multi-scale Seismic Imaging of the Mariana Subduction Factory: Leg 1 (EW0202 MCS)

Overview: The MARGINS programs in the US and Japan (of NSF and MEXT) have funded an integrated seismic study (marine multi-channel seismic reflection, controlled-source wide-angle reflection/refraction, and passive recording of local and teleseismic earthquakes) to provide a comprehensive velocity, attenuation, structural and stratigraphic image of the Mariana island-arc system, from the subducting Pacific Plate to the backarc, at 14°-20°N, 141°-149°E. Participating institutions include SOEST, Stanford, Washinton St. Louis, Scripps, JAMSTEC, ERI, ORI and Kobe.

This study of the active Mariana arc-trench-backarc system will be implemented on several cruises, starting with EW0202 (Leg 1: MCS) and EW0203 (Leg 2: active source OBS and MCS). Another active source OBS transect will be shot on R/V Kaiyo in January/February, 2003. Finally, an array of ~75 passive OBSs will be set out in April/May 2003, to be recovered one year later, with overlapping deployments of PASSCAL seismometers on the islands of the CNMI.

Our study will provide the baseline seismic information required for the MARGINS Subduction Factory experiment in the Mariana system. We therefore plan to collect the data necessary to create images detailed enough to guide future geochemical measurements and proposed IODP drilling to understand the material fluxes input at the trench and output at the forerc, volcanic arc, and backarc. The MCS component of this intergrated program is described below.

EW0202 MCS reflection profiling of the forearc/arc/backarc:
Stratigraphy and structure of the sediments and basement

Our seismic reflection profiles of the Mariana system will provide the highest resolution images of its tectonic, volcanic and sedimentary history. They will provide the cross-sections that (1) reveal the variation of the system along- and across-strike, (ii) place outcrop and drill sites in context and (iii) allow the geologic evolution to be better interpreted. Understanding this evolution is essential if the MARGINS Subduction Factory initiative is to quantify the modern and average material fluxes through the Mariana system.

Arc Growth Versus Rupture

MCS profiles along and across the inner forearc, arc and remnant arc will image the structures and stratigraphy resultant from three stages of arc growth and two episodes of arc rupture known from seafloor drilling studies of the Mariana system. An integrating hypothesis to be tested (in concert with the wide-angle studies) is that the different crustal structures and compositions of intra-oceanic island arcs reflect their different histories of arc rifting and backarc spreading (and are not simply a function of varying slab input and mantle melting).

<u>Background</u>. Tephra studies [e.g., Bryant et al., 1999] and measures of explosivity index versus age reveal three Mariana volcanic maxima at 35-24, 18-11 and 6-0 Ma [Lee et al., 1995]. These three periods are likely related to significant magmatic differentiation and crustal growth. With a grid of MCS profiles in the Izu-Bonin system, we showed that equivalent variations in volcanic activity there correlate with recognizable seismic stratigraphic packages that can be regionally mapped [Taylor et al., 1990; Taylor, 1992]. The expectation is that we can likewise regionalize the history of arc production known from a few drill sites and islands in the Mariana system.

These periods of arc growth are to be contrasted with the two periods of arc rupture that ultimately formed the Parece Vela Basin and Mariana Trough. Studies of lithospheric rheology [e.g., Kusznir and Park, 1987] suggest that the thick crust and high heat flow of the volcanic line constitute a rheologic weak zone that will tend to focus rifting in its vicinity [Molnar and Atwater, 1978]. However, the exact location of arc rupture can vary with respect to this line [Hawkins et al., 1984]. Detailed swath bathymetry surveys show that most of the Palau-Kyushu Ridge south of 25°N is a flexed West Philippine Basin rift-flank bounded by faults on the east and with a few cross-chain volcanoes to the west [Okino et al., 1998, 1999]. This is significant because it proves that the split of the Oligocene arc occurred on its backarc side, leaving the Eo-Oligocene arc (Guam-Saipan ridge etc) and forearc to the east of the Parece Vela Basin. In contrast, the split of the Miocene Mariana arc occurred on its forearc side. Opening of the Mariana Trough isolated a majority of the Miocene arc in the remnant West Mariana Ridge and the currently active Mariana arc had to build anew on the eastern edge of the Mariana Trough [Bloomer et al., 1989a].

These observations have important implications for our study of the Mariana system:

(a) In the current Mariana forearc, arc and remnant arc (West Mariana Ridge) we have virtually the complete record of 50 m.y [Cosca et al., 1998; Bloomer et al., 1995; Stern and Bloomer, 1992] of Mariana arc output (excepting only the minor cross-chains of the Palau-Kyushu Ridge).

(b) Because of the relative rheological strength of ophiolitic forearcs and oceanic backarcs, the rifting region of intra-oceanic arcs is confined (compared to continents) so that the limits of extension and the rates of strain can be well defined [Taylor et al., 1999].

(c) In the Mariana system we can study the structures and stratigraphy associated with the complete break-up of an arc and the initiation of backarc spreading. The syn-rift stage of arc rupture has been studied with MCS techniques in the Okinawa Trough [e.g., Sibuet et al., 1998], Bransfield Strait [Barker and Austin, 1994, 1998] and Izu-Bonin system [Taylor et al., 1991; Klaus et al., 1992]. The syn-rift structures associated with these systems, including both high- and low-angle rift-bounding normal faults, have been well imaged. What is missing are good images of the structures, and understanding of the processes, associated with the transition from backarc rifting to spreading.

Important Questions. Our MCS studies of the Mariana inner forearc to remant arc are designed to answer the following questions:

• What is the extent of rifted arc crust versus backarc basin crust in the Mariana Trough? Major differences in interpretations exist on this issue [e.g., Martinez et al., 1995; Stern et al., 1996; Yamazaki et al., 1993; Yamazaki and Murakami, 1998], in part because the low geomagnetic latitude and northerly orientation of spreading segments make magnetic anomaly lineations hard to define. No good MCS images exist in the Mariana Trough to determine the extent of oceanic versus rifted arc crust. Calc-alkaline gabbro breccias recovered from DSDP Site 453 confirm the exposure by faulting of consolidated magma chambers from deep within the West Mariana Ridge [Natland, 1981]. The structural context of these exposures (e.g., whether by normal detachments) remains unknown.

• Are the active arc volcanoes built on/through rifted arc crust [Bloomer et al., 1998] or backarc crust? The latter scenario presents the possibility of sandwiching oceanic crust directly within arc crust. Because of the thick (1-2 km) volcaniclastic wedge mantling the eastern side of the basin, existing geophysical data have been unable to image the rift or oceanic structures beneath the arc line. The MCS system on R/V EWING should readily image into the basement along lines shot between the volcanoes.

• Does the Mariana forearc contain early Oligocene rift basins equivalent to those we imaged and drilled in the Izu-Bonins [Taylor, 1992]? And, can the volcaniclastic products from the three maxima of explosive activity of the arc be recognized as seismic-stratigraphic packages and therefore regionally correlated and volumetrically quantified? Existing MCS data in the Mariana inner forearc [C2006, Mrozowski et al., 1981] do not penetrate through the sedimentary cover to image basement, and the area has not been drilled. In the Izu-Bonins, these rift basins contain 2/3rds of the forearc sedimentary section and represent a substantial record and product of volcaniclastic output. Proving their existence in the Mariana forearc would also substantiate the proposal that by the early Oligocene the IBM arc had not developed a sufficiently thick crustal root to localize rifting, and that the rifting was more distributed as a result [Taylor, 1992].

• Do the different crustal structures and compositions of intra-oceanic island arcs reflect their different histories of arc rifting and backarc spreading? The Aleutian arc crust is 30-33 km thick and has not experienced backarc spreading [Holbrook et al., 1999]. The Izu-Bonin arc crust is

20-22 km thick, has experienced one cycle of arc rupture and backarc spreading, and is actively rifting again [Suyehiro et al., 1996]. The Mariana arc crust has not been well imaged, but existing OBS-refraction data [Lange, 1992] suggest an even thinner crust (16 km). If this is correct, then it is likely that a primary control on arc crustal thickness (or rather, thinness) is the prior history of arc rupture (where, how often and when). This correlation may also explain the velocity/composition and reflectivity of the lower crust, as the arc may be underplated with high-Mg magmas during the rifting-spreading transition. Our deep near-vertical MCS reflection images, together with the wide-angle reflection profiles, will directly test this hypothesis. In particular, our proposed reflection profiles across the rifted eastern margin of the West Mariana Ridge (remnant arc) should be able to provide full crustal reflection images to Moho.

Outer Forearc Tectonics

Understanding the magmatic, tectonic and metamorphic evolution of the Mariana forearc is essential if the MARGINS Subduction Factory initiative is to quantify the modern and average material fluxes through the Mariana system. Several known processes compete in this environment [e.g., von Huene & Scholl, 1991]. Tectonic accretion or underplating will strip materials from the subducting Pacific plate and cause seaward growth and/or uplift of the forearc, whereas frontal or basal tectonic erosion will cause the opposite. Collision or passage of subducting seamounts may locally uplift then collapse the forearc. Hydration of mantle peridotites produced by slab dewatering may cause volume increases and/or serpentinite intrusion/protrusion that will uplift the forearc [Fryer, 1992b, 1996]. Arc magmas often intrude into the forearc [R. Taylor et al., 1995]. The net product of these processes (i.e., the net flux of material from its first input at the trench to passage beneath the arc), is recorded in the stratigraphy and structure of the forearc sediments and basement.

Our proposed MCS transects are placed to image the outer forearc in three areas with varying tectonic forcing. We propose to image the forearc in perhaps the least complex and disrupted area (ESE of Saipan), where there is an active serpentine mud volcano and subducting ridge (east of Sarigan), and along the DSDP Leg 60 drilling transect near maximum forearc disruption at 18°-19°N (see “Map of Survey Area”). Our MCS studies of the Mariana outer forearc are designed to answer the following questions:

• Although there is little evidence for modern tectonic accretion [e.g., Taylor, 1992], has there been significant tectonic erosion, and/or did accretion occur previously? The Mariana forearc has been cited as the type example of a forearc being subjected to tectonic erosion [e.g., Hussong and Uyeda, 1981], but this suggestion remains controversial [Karig and Rankin, 1983]. The key to resolving the past history of forearc uplift or subsidence, and hence the record of net basement gain or loss, are the seismic stratigraphic relations (onlap, downlap, etc) of the basal sedimentary sequences. We propose to collect MCS data to image these sequences and definitively resolve this 20-year-old controversy.

• How extensive is pre-Eocene oceanic crust within the Mariana forearc? Incorporated in the Eocene within the IBM foundation terrane to unknown extent are remnants of pre-existing Philippine Sea Plate oceanic crust [e.g., N-MORB at 32°N, DeBari et al., 1999] and trapped or accreted Mesozoic Pacific oceanic crust [e.g., at 20°N, Johnson et al., 1991; Pearce et al., 1999]. MCS profiles over the outer forearc will characterize the basement structures and may provide a means of recognizing if there is an arcward limit to these remnants that, to date, have only been sampled in the outer forearc.

• How widespread are arc magmas intruded into the Mariana forearc? Leg 125 ODP drilling at Conical Seamount (~19.2°N) unexpectedly encountered young (Plio/Pleistocene) basaltic sills over 100 km trenchward of the arc [Marlow et al., 1992]. In fact, ODP drill holes encountered Neogene forearc sills in all three (also Izu-Bonin and Tonga) forearcs drilled [R.Taylor et al., 1995]. Previously unreported, these intrusives appear to be a common feature of the western Pacific intra-oceanic forearcs. The geochemistry of the sills most closely resembles the subjacent volcanoes along the Quaternary arc. R.Taylor et al., [1995] infer that they were most likely fed by dikes that propagated from the arc in the basement. MCS profiles of the Izu-Bonin forearc reveal significant sill reflectors (one 21 km long) [Taylor, 1992; R.Taylor, 1995]. How much "arc" magmatism has penetrated the Mariana forearc, and how it gets >100 km from the arc, is unknown for want of quality reflection images.

• What is the internal structure of an active serpentine mud volcano? Fryer et al [1995, 2000] postulate that the forearc seamounts have long-lived conduits, often at intersections of basement faults, that channel rising serpentine muds and fluids to the seafloor. The fluids are slab-derived [Mottl, 1992]. Furthermore the evidence of high-pressure/low-temperature metamorphic rocks and crystal fragments in the muds indicates that the conduits tap depths as great as the top of the subducting slab [Maekawa et al., 1995]. Understanding the structure of the forearc basement is critical to understanding the evolution of these serpentine mud volcanoes and their relationships to faulting and seismicity in the region. Our proposed experiment includes MCS profiles across and surrounding some of the Seamounts proposed for drilling by Fryer et al: Celestial and Big Blue. Our MCS profiles will provide the necessary site survey for such drilling and the regional context in which to interpret the data.

• Can we map, and stratigraphically date, structures associated with the stretching of the forearc [Stern and Smoot, 1998] such as resulted from the successive episodes of backarc spreading in the Parece Vela Basin and Mariana Trough that increased its radius of curvature? This stretching [Wessel et al., 1994], apparently caused major extension of the basement. It is one reason for the massive intrusion by serpentine at 18°-19°N, where the forearc also lacks the Eo-Oligocene frontal arc ridge. Mrozowski and Hayes [1980] recognized substantial normal faulting of the 17°45'-18°N region on the two R/V Conrad 2006 MCS lines, but were unable to correlate the structures between the lines. Prior to our survey, we reprocessed and migrated these data and we will position our new lines, and include tie lines, so as to better interpolate between all four.

MCS Data Processing and Analysis

An extensive amount of initial data processing will be done on computers during the cruise. We will conduct a "first pass" of routine processing using a commercial package (ProMAX from Landmark). Field tapes (in SEGD format) will be read, converted to SEG-Y and written both to DLT tape (for archive and land-based processing) and to disk (for shipboard processing). The disk files will be used for semblance velocity analysis, bandpass filtering, NMO and stack, and post-stack migration. The stacked and migrated lines will be available for preliminary interpretation. Post-cruise, advanced processing will consist of dip moveout (DMO), refined velocity analysis after DMO, deconvolution, pre-stack migration plus depth migration.

Analysis of the MCS data will consist of four parts related to (1) the shallow velocity structure of the forearc, arc, backarc and remnant arc; (2) the deformation structures; (3) the seismic stratigraphy and (4) deep crustal reflection imaging. The 6-km streamer is long enough to permit resolution of velocities within the sedimentary section, which are necessary for good structural and stratigraphic imaging as well as to feed into the OBS component of the program. We will obtain a rough velocity estimate through NMO-semblance analyses and a refined estimate using pre-stack depth migration where there are sufficient sedimentary reflections. Structural and stratigraphic analysis will follow standard procedures. Line ties through the DSDP sites will provide essential age and lithology information for geologic interpretation.