The Initiation of Subduction: From kinematics to dynamics

Theme: Subduction Zones

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Subduction initiation (SI), although only a transient phenomenon, is a vital phase of the plate tectonics cycle. Long-lived and well-developed subduction zones disappear and new subduction zones form. The initiation of subduction is arguably the last major component of the kinematics of plate tectonics that remains unsolved. Consequently, our understanding of SI dynamics is perhaps the least poorly developed part of geodynamics. However, since nearly half of all presently active subduction zones initiated during the Cenozoic (Fig. 1), we have an enormous opportunity for accelerated progress if we link field and geochemical studies of back-arcs, fore-arcs and ophiolites, detailed seismic images, and regional and global geodynamic modeling.

After a hiatus of a number of years, computational and synthesis models of subduction initiation are now being advanced that offer testable predictions [1,2]. Moreover, empirical studies from the MARGINS program show that the tempo of individual activities is increasing, including earlier work on the structure and morphology of the northern segment of the Macquarie Ridge Complex [3]; detailed thermochonlogy showing the detailed space-time pattern of rock uplift associated with SI in Fiordland, New Zealand [4]; the recognition that the world's largest ophiolites and their attendant ore deposits originate just after subduction initiation [5]; the discovery of widespread MORB-type basaltic volcanism just before bonititic volcanism in the IBM system [6]; and the recent discovery of compression and vertical motions associated with Tongan SI [7]. These studies indicate that a broadly based, empirical underpinning to a new understanding of SI is emerging.

That such a large proportion of subduction zones are young (Fig. 1) indicates that subduction initiation is a semi-continuous process in which the net force resisting SI is routinely overcome during the normal evolution of plates. Subduction initiation may have occurred in a variety of tectonic settings: old fracture zones, transform faults, and extinct spreading centers and through polarity reversal behind active subduction zones [1,2]. Although occurring within different tectonic settings, the four best-understood subduction initiation events (Izu-Bonin-Mariana (IBM) along a fracture zone, Tonga-Kermadec along an extinct subduction boundary, New Hebrides within a back arc, and Puysegur-Fiordland along a spreading center) were typified by major structural changes and vertical motions that reveal fudamental aspects of SI dynamics [2]. Detailed studies of the pertrology and geochemistry of the IBM fore-arc reveal the evolution of melting conditions as the Pacific Plate first descended below the Philippine Sea Plate in the Eocene [5].

Subduction initiation is intimately linked to changes in plate motion (another frontier area of geodynamics). Understanding the putative change in Pacific Plate motion during the Eocene is critical for deciphering the dynamics of plate tectonics. Refined geochronology now suggests that the bend in the seamount chain started at ~50 Ma and occurred over a period of ~8 Myr [8]. The best examples where we know subduction started and has since evolved into fully self-sustaining subduction zones, including the Eocene initiation of the IBM and Tonga-Kermadec are likely intimately linked to this change in Pacific plate motion [9]. However, if SI preceded (and hence caused) changes in plate motion, or post-dated the change (and SI was forced) remains an outstanding but clearly solvable problem [1,2]. Recently, there have been important advances clarifying how these major SI events unfolded.

The eruption of boninites has long been associated with the initiation of the IBM subduction zone [10], but recent manned submersible diving in the IBM fore-arc has discovered that

MORB-like tholeiitic basalts crop out over large areas. These “fore-arc basalts” (FAB) underlie boninites and overlie gabbroic rocks (Fig.2). FAB trace element patterns are similar to those of MORB and most IBM back-arc lavas. However, Ti/V and Yb/V ratios are lower in FAB indicating that their mantle source experienced a distinctly higher oxygen fugacity compared to the source of basalts from mid-ocean ridges and back-arc basins. The most likely origin of FAB is that they were the first lavas to erupt when the Pacific Plate began sinking beneath the Philippine Plate at about 51 Ma. FAB magmas were generated by mantle decompression during near-trench spreading with little or no mass transfer from the subducting plate. Boninites were generated later when the residual, highly depleted mantle melted at shallow levels after fluxing by a water-rich fluid derived from the sinking Pacific Plate. This magmatic stratigraphy (Fig. 2) of MORB-like tholeiites overlain by boninites is similar to that found in ophiolites, suggesting that the latter were also generated by fore-arc volcanism in association with subduction initiation.

The Tonga-Kermadec subduction may also have initiated in the Eocene and be associated with the change in Pacific Plate motion. Recently, seismic-reflection (Fig. 3) and rock-sample data have been used to propose that the first-order physiography of the New Caledonia Trough and Norfolk Ridge formed in Eocene and Oligocene time, and was associated with the onset of subduction and back-arc spreading at the Australia-Pacific plate boundary [7]. The analysis suggests permanent subsidence of the New Caledonia Trough and transient uplift of Lord Howe Rise during Eocene and Oligocene initiation of Tonga-Kermadec subduction [7].

The capabilities of regional and global geodynamics is now accelerating and will afford not only the ability to link the details of fault structures and vertical motion to incipient slab dynamics, but also the history of magmatism and petrology associated with the initial descent of the slab. Indeed, despite the numerous links that have been made between mantle melting and flow within the mantle wedge, there are, as of yet, no dynamic models linking melting to SI. Finally, dynamic models of global mantle flow are capable of resolving details of subduction zones at scales as small as 500 meters [11] (Fig. 4). This suggests the possibility of linking structural details to the dynamics of changes in plate motion.

The MARGINS Successor Program can advance this effort by marshalling and coordinating on-land studies of ophiolites, marine studies of back-arcs and fore-arcs, and geodynamic and petrogenetic modeling to explain how these nucleating and fossil SI features form. Accelerated progress toward distinguishing between SI hypotheses can be achieved though a focus site approach. For example, sites could be selected that span different phases of SI from nascent (Macquarie ridge), early stage (Puysegur), to fully developed (IBM) or that elucidate SI events that occurred synchronously but in widely-separated and different tectonic settings (IBM versus Tonga). An integrated MARGINS program with well-defined focus sites provides us with an outstanding opportunity to test the competing self-nucleation and forced subduction initiation hypotheses.

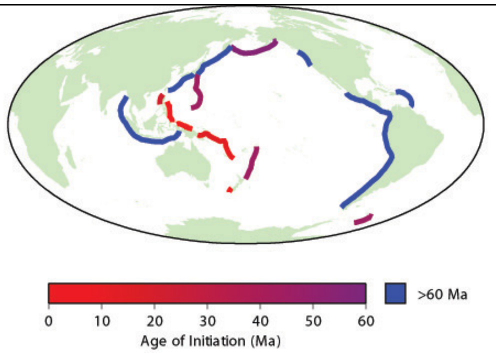


Fig. 1.Age of initiation of subduction zones showing the Western Pacific as a natural laboratory for studying subduction initiation, especially in the critical period 0-50 Ma where there is a geochemical and structural record partially deciphered that can be linked to changed in Pacific Plate motion. From [2].

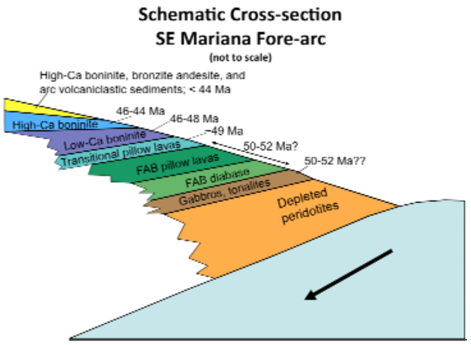
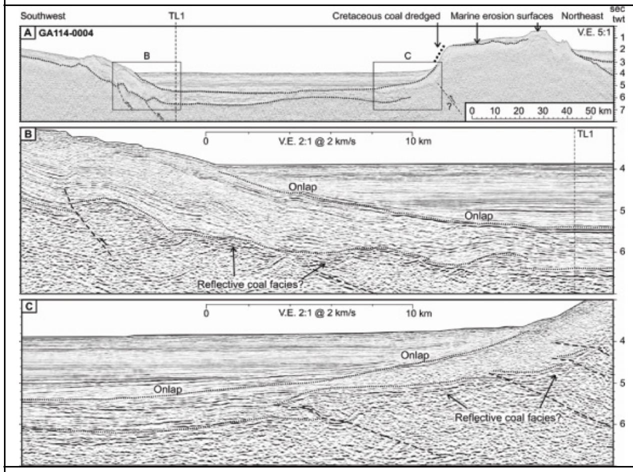


Fig. 2. Inferred cross section from petrograhic and geochemical analysis of samples recovered from recent deep sea dives in the Mariana fore-arc near Guam. There is a time span of only a few Myr between initial basaltic and boninitic outpourings. Based on the analysis in [6].



Fig, 3, Detailed seismic stratigraphy showing compressions (thrusts in c) and vertical motions (drowned terraces in a) in the New Caledonia Basin that have been linked to the initiation of the Tonga subduction zone. From [7]

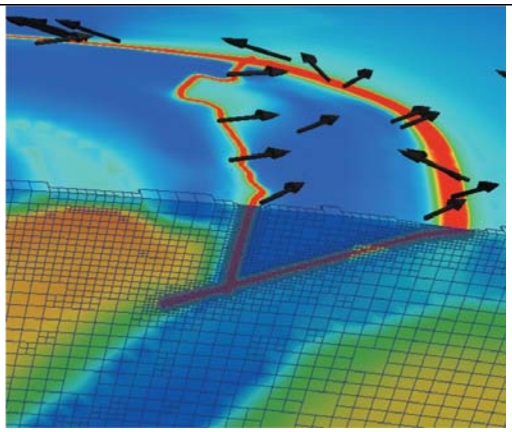


Fig. 4. Zoom in to the Lau Basin & Tonga Slab from a global model of mantle convection and plate tectonics. The fine-scale details at < 1 km can now be linked to the full dynamics of global plate motion. From [11]

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