Resolving Fundamental Questions of Subduction Initiation in New Zealand

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Resolving fundamental questions on the nature, history and dynamics of subduction initiation (SI) is a central theme of the *GeoPrisms* and *IODP* science plans. New Zealand has two of only a handful of well-preserved examples of SI – a nascent subduction to the south (Puysegur-Fiordland), and a fully developed system intimately related to a global change in plate motion to the North (Tonga-Kermadec). Targeted observations in each region will constrain geodynamic parameters and provide insights that will underpin new types of models.

Subduction Initiation. Initiation of subduction and changes in plate motion are linked, as the largest driving and resisting forces associated with plate tectonics occur within subduction zones. By far the largest change in Pacific plate (PAC) kinematics since 80 Ma is manifest as a bend in the Emperor-Hawaii seamount chain. A westward swerve in Pacific plate motion occurred at about the time subduction zones initiated throughout the western Pacific. It follows that clarifying what happened in the western Pacific during Eocene time is likely to lead to fundamental insights into SI and the general physics of plate tectonics. There are two widely held views: either subduction initiates spontaneously or it has to be induced (Stern, 2004; Gurnis et al, 2004). In the spontaneous model, oceanic lithosphere ages, thickens, increases in density, and eventually sinks into the mantle under its own weight. In the induced model, externally applied compressive stresses are necessary to overcome the strength of the lithosphere and pre-existing faults before subduction can be induced.

Geochronology shows that the bend in the Emperor-Hawaii seamount chain started at ~50 Ma and may have occurred over a period of ~8 Myr (Sharp and Clague, 2006). The onset of plate motion change corresponds with the timing of Pacific-Farallon plate boundary rearrangement and termination of spreading in the Tasman Sea. This reorganization was followed by a change in direction and rapid increase in rate of Australia (AUS)-Antarctic spreading with consequent northward acceleration of Australia and initiation of Australia-Pacific spreading southwest of New Zealand. Reconfiguration of plate boundaries in Antarctica, the Indian Ocean, and Asia reveal the truly global nature of this phase of tectonic change.

Most work on SI has focused on initiation of Izu-Bonin-Mariana (IBM) subduction, which was synchronous with the change in Pacific Plate motion at ca. 50 Ma. The early arc was dominated by boninitic volcanism, which requires a high degree of partial melting of a source depleted in major elements but enriched in volatiles (Stern and Bloomer, 1992). Samples recovered from the Mariana forearc and ~1,500 km farther north near the Bonin islands reveals a volcanic stratigraphy containing basalts, similar to mid-ocean ridge basalt (MORB), that were the first to erupt in the nascent arc (52-49 Ma), which were then quickly followed by boninites (49-45 Ma), and then by normal arc lavas within several million years (Reagan *et al*., 2010; Ishizuka *et al*., 2011). IBM is a natural laboratory to constrain models of SI and distinguishing between spontaneous and induced models is a central goal of upcoming IODP Expedition 351. However, there are limitations of the IBM example. First, the relative motion between the Philippine Sea Plate and PAC during the Eocene is unknown. Second, because the subduction zone has long transitioned from nascent to self-sustaining SI, we do not know the mechanics and structural evolution of the Pacific plate as it first started to subduct. Third, the intra-oceanic deep-water setting of IBM results in a highly-condensed sedimentary record of events. These issues are minimized around New Zealand, and indeed the Tonga-Kermadec example is part of the same 50 Ma SI event as IBM.

Puysegur-Fiordland. The Puysegur-Fiordland subduction zone forms the northern extremity of the transpressional AUS-PAC plate margin south of New Zealand. Although juvenile, and potentially not yet a self-sustaining subduction zone, the margin is characterized by convergence, a trench (gravitationally and bathymetrically), a Benioff zone (down to 170 km depth, Fig. 1 inset), and sparse, young calc-alkaline volcanism on the overriding Pacific plate. Previous geophysical surveys demonstrate that the morphology of Puysegur Ridge, a bathymetric high on the overriding Pacific plate, immediately east of the trench, shows a characteristic change from uplift to subsidence with increasing AUS-PAC convergence. This proximal change in vertical motion precedes the change in overall dynamic state of the incipient subduction zone. The segment associated with greatest convergence (≈ 200 km) is associated with a highly-anomalous gravity signal. An approximately -100 mGal free air anomaly is associated with a relative bathymetric high and suggests that there is a strong vertical force pulling downward on the Puysegur Ridge, consistent with the history inferred from geomorphology. Comparison of these features with geodynamic models, strongly suggests that the margin is making a transition from forced to a self-sustaining subduction. No other subduction zone is in this critical state; this area thus presents us with a unique observational target to measure parameters that are fundamental to the geodynamics. These key parameters could be obtained with a well-designed geophysics cruise involving seismic reflection & refraction, bathymetry, gravity and magnetics. Understanding the force balance along Puysegur Ridge and how the slab-pull force is coupled into the over-riding plate requires a refined gravity and mechanical model, and hence measurement of the crustal thickness and the geometry of the slab. We hypothesize that a strengthening of the slab-pull force causes subsidence along the ridge. Existing, but low-resolution seismic-reflection data suggest that the region is relatively transparent for a subduction zone and indicates that modern MCS and refraction data would easily detect subducting oceanic crust. Forward modeling of well-designed seismic source-receiver configurations shows that one would be able be able to measure the dip and other features of the slab (Fig. 2). We know of no other comparable region where such a set of measurements could be made at this critical phase of SI.

Tonga-Kermadec (TK). Records of SI are rarely well preserved, because of subsequent tectonic and volcanic disruption, but TK SI occurred near the margin of thinned continental crust (Norfolk Ridge, Lord Howe Rise) that was tectonically isolated by subsequent backarc spreading. Persistent Cenozoic submarine conditions led to continuous sedimentation in many places. Cessation of spreading in the Tasman Sea at 52-50 Ma and deformation of New Caledonia with a peak of high-pressure metamorphism at 44 Ma provides a direct temporal link between southwest Pacific events, IBM, and the Emperor-Hawaii bend. Australia-Pacific plate motions are precisely known since 44 Ma (Fig. 3) from ocean crust created at the southern end of the boundary, and via plate closure calculation (Cande and Stock, 2004; Sutherland, 1995). Eocene convergence rates varied from <1 cm/yr in New Zealand to 10 cm/yr near New Caledonia.

Seismic-reflection data (Fig. 4) reveal stratal records of Eocene change, including evidence for distal (>300 km) km) minor compression and >1 km of uplift-subsidence, and proximal uplift-subsidence of Norfolk Ridge and deep-water sedimentary basin formation in the New Caledonia Trough. The stratigraphic records of compression and vertical motions provide a unique opportunity to understand with high precision the temporal and spatial context of large-scale SI through geophysical surveys tied to IODP drilling. New seismic-reflection lines are needed to supplement a large recently-released dataset and hence define drilling targets, and transects of boreholes are needed to understand along-strike and proximal-distal relationships. These would be achieved through cruise TECTA (Tectonic Event of the Cenozoic in the Tasman Area) and the dredging cruise VESPA (Volcanic Evolution of the South Pacific), both currently ranked priority 1 by the French National Oceanographic Fleet Committee for 2014 / 2015. The primary goals of the seismic, dredging and drilling would be: to establish the regional timing and magnitude of deformation, uplift, and subsidence, to constrain the SI process; and to relate TK and IBM events to global plate motion changes and the evolution of global plate-driving forces.

References:

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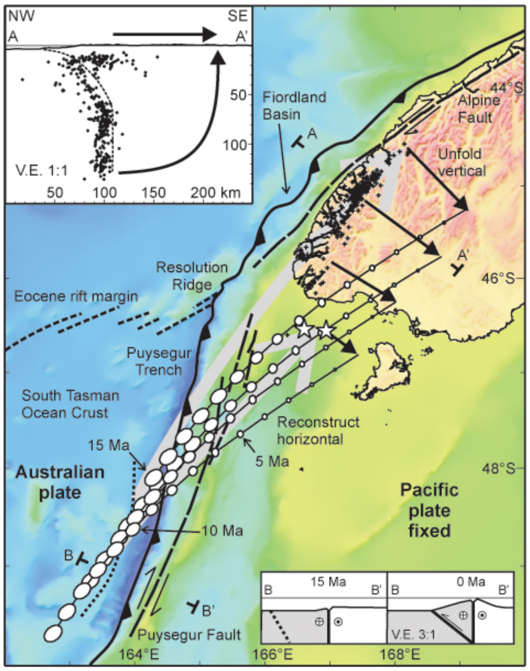


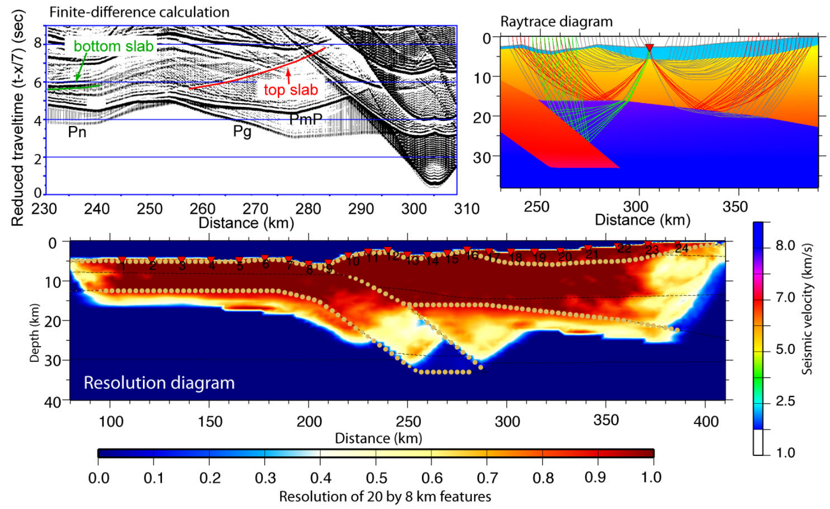
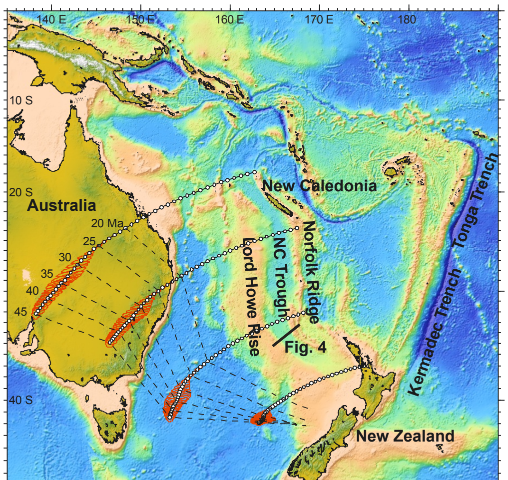


Figure 1. (above left) Unfolding and reconstructing Fiordland subduction. Crosses on the map are epicentres of earthquakes with hypocentral depth >50 km. Crosses on section A-A' are earthquake hypocentres within 40 km of section A-A'. Stars show young volcanic features, inferred to be sourced from near the top of the subducted slab at c.70 km depth. Bold arrows represent the effect of unfolding the subducted plate, restoring it to the Earth's surface with down-dip line length preserved. Sequential ellipses are the reconstructed point interpolated every 1 Ma using AUS-PAC motion. From Sutherland et al. (2009)

Figure 2. (above right) Proposed OBS array across Puysegur Trench and Puysegur Ridge. Finite-difference simulation shows turning waves (Pg and Pn), reflections from Moho, and top and bottom of oceanic crust in the subducting slab should be visible in data east of the trench. Resolution test for refracted and reflected phases between airgun and 24 OBS locations confirms that a subducting slab could be detected using OBS travel time inversion.



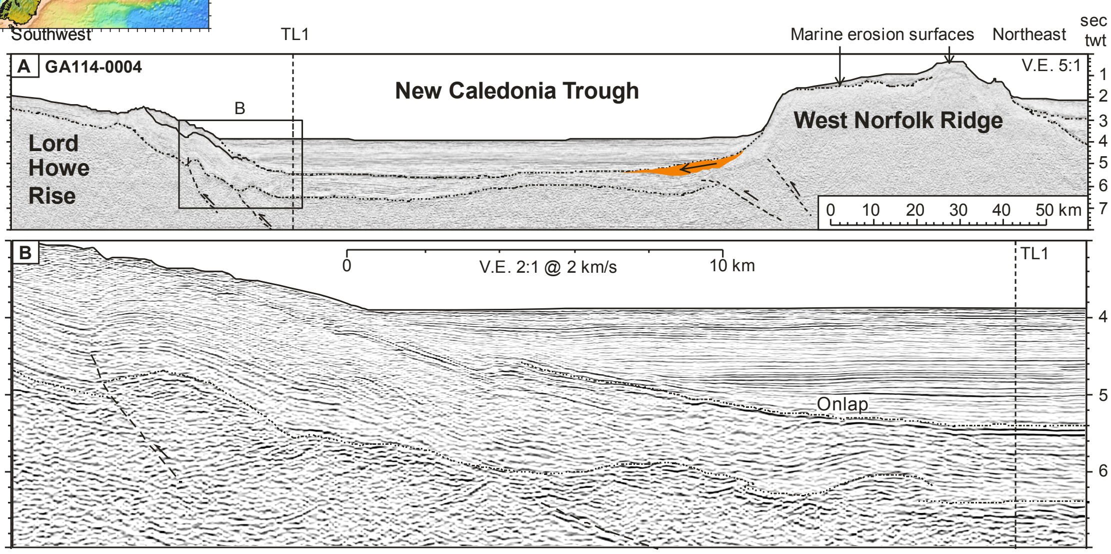


Figure 3. (above) Reconstruction of selected Australian plate points relative to a fixed Pacific plate. Note much higher convergence rates near New Caledonia (NC) shortly after subduction initiation (45-25 Ma). **Figure 4.** (right) Seismic section showing deformation, uplift of Norfolk Ridge (marine planation), with subsequent subsidence, and infilling of the New Caledonia Trough.