Subduction initiation

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The initiation of new subduction zones is a key component of the plate tectonic cycle and evolution of continental crust (Stern and Scholl, 2010). Subducted slabs are the primary force driving plate motions and formation of new subduction zones and demise of existing ones is associated with the largest changes in the force balance on tectonic plates (Gurnis et al., 2004). Since subduction zones are also a primary location for volatile cycling, major temporal changes in subduction are expected to lead to changes in outgassing and reinjection of volatiles into the mantle (van Keken et al., 2011). Despite the importance of subduction initiation, our understanding of the associated geological record, geophysical and geochemical character, and geodynamical causes and consequences remain poorly understood. Addressing the initiation of subduction was a major focus of the MARGINS and GeoPRISMS programs through collection of key observations at primary sites and in exhumed terranes from ancient subduction zones.

Although slab pull is the primary driving force for plate motions, key features of this force balance remain a research focus. How much of the negative buoyancy from cold slabs is transmitted to the converging oceanic plate depends on several factors, notably on plate bending at oceanic trenches, interplate resistance, and drag around the edges of slabs and base of plates (Conrad and Lithgow-Bertelloni, 2002; Stadler et al., 2010). Given the concentration of driving and resisting forces within the slab, the initiation and termination of subduction likely determine changes in the rates and direction of plate motions.

The growth and stability of island arcs is a factor in the global mass balance of continental crust. When a young slab descends into the mantle, magmatism may be enhanced, especially if subduction was initiated by a phase of extension and mantle decompression (Stern and Bloomer, 1992). More mature subduction systems may continue to add igneous material, but an equal amount of lower arc crust may be lost by gravitational instability (Behn and Kelemen, 2006). The continental crust mass balance may therefore depend on the difference between magmatic additions at arcs versus forearc loss due to tectonic erosion. Subduction initiation may be a mechanism to maintain a positive or net balance over time.

Major episodes of subduction could play an important role in cycling CO_2 and other volatiles between the atmosphere and ocean and mantle. Paleogeographic reconstructions have most volcanism occurring along continental-arcs, where subduction zone magmatism can react with carbonate-rich crust and generate high concentrations of atmospheric CO_2. Initiation of ocean-ocean subduction zones around the Pacific during the early Eocene likely impacted CO_2 fluxes to the atmosphere (Lee et al., 2013; Reagan et al., 2013), although the direction of this shift and degree it impacted global climate remains uncertain (Kirtland-Turner et al., 2014).

Wilson (1966) recognized that the Atlantic Ocean opened near continental sutures in Paleozoic orogenic belts, with older ocean basins opening and closing there in the past. This Wilson cycle requires failure of passive margins, but theoretical studies suggest the forces required to fail thick lithosphere of a passive margin are too great, even with a sediment load (Mueller and Phillips, 1991).

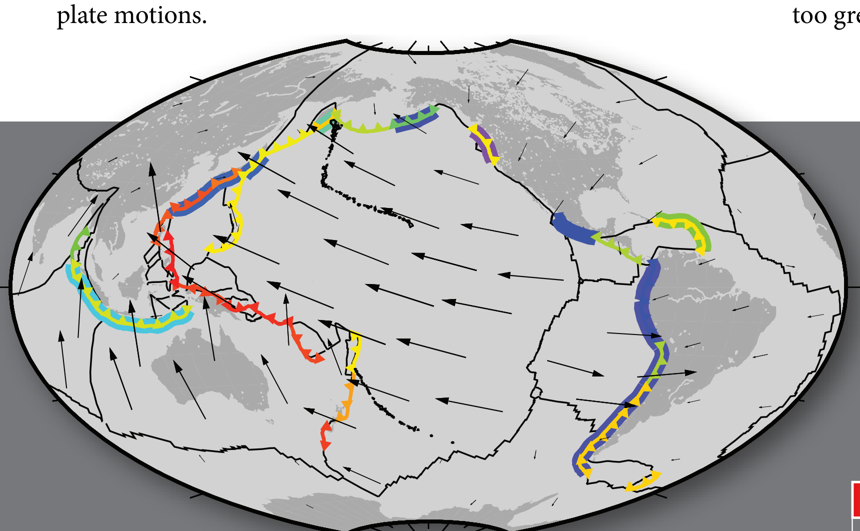
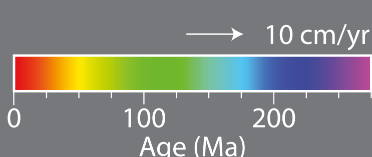


Figure 1. Ages for subduction initiation events centered on the Pacific determined from isotopic ages of arc initiation and stratigraphic, structural, plate tectonic and seismic indicators of subduction initiation. The colors of the trenches represent the latest initiation (reinitiation) age, while those of the underlying thick line represent the long-term age. Plate boundaries and absolute plate motions from Müller et al. (2016). Reprint from Hu and Gurnis (2020) by permission of John Wiley and Sons.



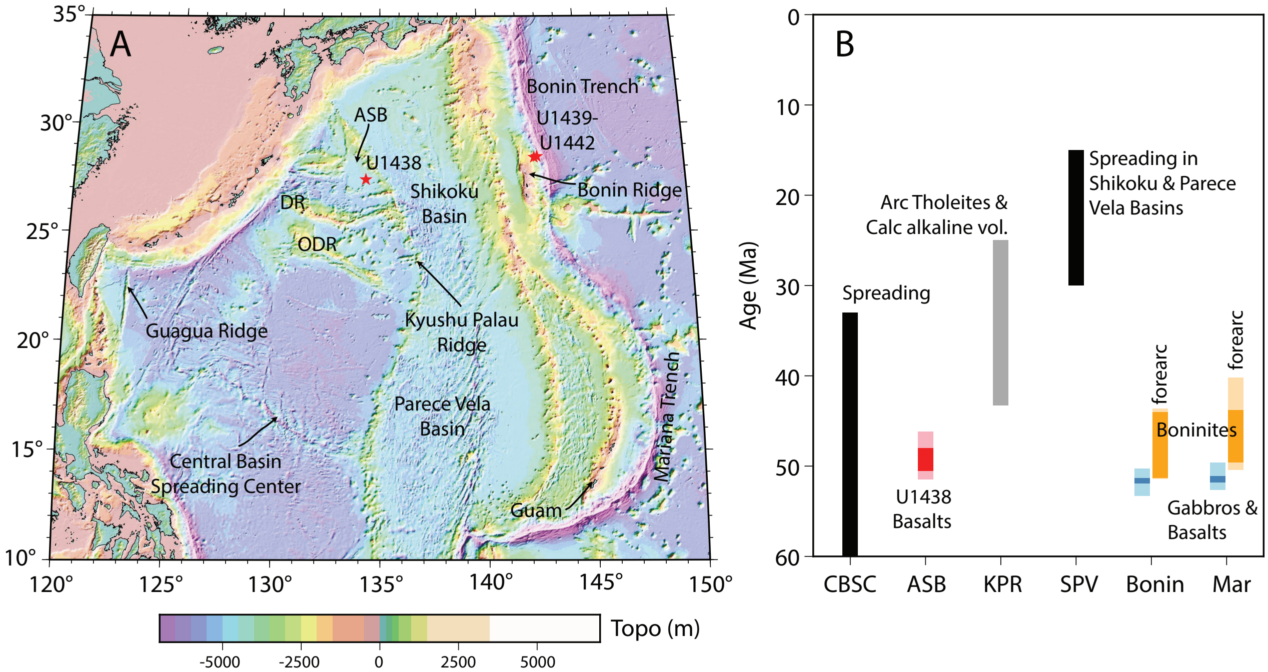


Figure 2. A. Location Map and sites for ages for key events discussed in the text associated with initiation of the IBM system. Uncertainties on the ages of forearc basalts, gabbros and boninites denoted with lighter color shading. Abbreviations are: DR for Daito Ridge; ODR for Oki-Daito Ridge, ASB for Amami Sankaku Basin, CBSC for Central Basin Spreading Center, KPR for Kyushu Palau Ridge, SPV for the Shikoku and Parece Vela Basins, and Mar for the Marianas.

Recent plate reconstructions have continent-ocean plate boundaries accommodating thousands of kilometers of strike-slip during opening and closing of oceans (Dalziel and Dewey, 2019). Actively shearing plate boundaries are weaker than passive margins, so strike-slip motion may precede subduction initiation.

The key reason that consensus on a unified description of subduction initiation has been slow to develop is that initiation is a transient process whose record is generally obscured by subsequent subduction zone processes, most notably burial, overprinting, uplift, and compression and over-thrusting. In contract to rifting, subduction initiation is the seed for the destruction of its own record. Despite these limitations, there is a growing acceptance of a diverse record of Cenozoic subduction initiation events (Fig. 1). Much of the recent work on subduction initiation has exploited the geological, geochemical and geophysical record of these subduction initiation events which represent over half of subduction zones existing today (Gurnis, et al., 2004).

The GeoPRISMS and MARGINS programs targeted primary sites for interdisciplinary research as a means to make accelerated progress. Following the success of MARGINS and the Ocean Drilling Program (ODP), the GeoPRISMS and International Ocean Discovery Program (IODP) 2013-2023 Science Plans highlighted subduction initiation as a key question that would benefit from this concerted, site-focused approach. Four IODP Expeditions and a major seismic experiment all in the western Pacific followed to address these questions. At the same time, these programs have been complemented by expanded focus on other sites, geological synthesis, geochemical analysis, and modelling, which are reviewed here

Izu-Bonin-Mariana (IBM)

The Izu-Bonin-Mariana system with its present-day high convergence rate, simple geometry, and intact geological record has been recognized as an outstanding region for studying the "subduction factory" (Fig. 2). Decades of geophysical research on IBM illustrated its structure and state (Kodaira et al., 2007). The inputs through plate convergence (Kelley et al., 2003; Takahashi et al., 2008) and outputs across the arc and back-arc have been assessed through on-land field work and recovery of samples from the sea floor by diving, dredging, and drilling (Pearce et al., 2005; Kelley, et al., 2010; Heywood et al., 2020). Subduction initiation has been well-studied at IBM because the earliest record of volcanism related to this process is preserved (Stern and Bloomer, 1992; Pearce et al. 1992; Reagan et al., 2010; Li et al., 2019), and the tectonic configuration during the time of initiation has been determined through plate tectonic reconstruction (Hall, 2002; Leng and Gurnis, 2015; Wu et al., 2016).

The IBM subduction zone is on the eastern edge of the Philippine Sea Plate (Fig. 2) and based on the age of igneous rocks in the forearc, the subduction zone initiated at about 52.5 Ma (Reagan et al., 2019). To the west of the present trench, there are several active and rifted arcs, active and relict back arc basins, extinct spreading centers and other tectonic features. The active arc and forearc reconstruct to the position of the Kyushu-Palau Ridge (KPR) at about 33 Ma based on the magnetic lineations and fracture zones within the Shikoku and Parece Vela Basins. KPR, a long N-S feature, is a relict arc of IBM subduction (Ishizuka, et al., 2011a). West of KPR is the West Philippine Sea Basin with features predating- and post-dating subduction initiation.

Most spreading of the generally E-W Central Basin Spreading Center postdates subduction initiation, but initially it was thought to predate it, leading to the hypothesis that subduction initiated along an old fracture zone (Uyeda and Ben-Avraham, 1972).

IODP Expeditions 351 and 352 were mounted to constrain patterns in volcanism and lithosphere generation diagnostic of subduction initiation. Expedition 352 drilled four sites (U1439-U1442) in the forearc to obtain a volcanic record of subduction initiation and with earlier diving showed that earliest volcanism produced distinctive basaltic to boninitic crust with identical ages at locations that are currently 1,700 km apart (Cosca et al., 1998; Reagan, et al., 2010; Ishizuka, et al., 2011b), but may have been about 500 km when they formed (Leng and Gurnis, 2015). Forearc basalts with Ar-Ar and U-Pb zircon ages of 51.9-51.3 Ma are trench-ward (Sites U1440, U1441) of boninites (Sites U1439, U1442) aged 51.3-46 Ma (Reagan et al., 2019).

Expedition 351 Site U1438 just to the west of the KPR cored basaltic crust, finding it younger than Bonin forearc basalts with a Ar-Ar age of 49.9+/- 0.5 Ma (Ishizuka, et al., 2018), overlapping with boninite volcanism in the Bonin forearc. These boninites are thought to represent the first establishment of the volcanic arc (Reagan et al., 2017), and suggests that the basaltic crust drilled at Site U1438 might represent the first IBM backarc basin.

The IBM forearc has an overall structure akin to those found in ophiolites (Stern et al., 2012), including depleted peridotites at depth followed progressively by gabbroic, doleritic, and basaltic units. This sequence has been interpreted to represent lithosphere produced during near-trench seafloor spreading immediately after subduction began (Reagan et al., 2010, 2013). The first basalts have compositions rivaling those of the most depleted mid-ocean ridge basalts (Li et al., 2019; Shervais et al., 2019). These compositional traits are shared with Site U1438 basalts and reflect a several hundred million year or longer regional depletion of these mantle sources (Yogodzinsky et al., 2018). With rare exception, fresh pillow-rind basalt glasses sampled during Expedition 352 lack evidence for the involvement of subducted fluids in their genesis (Coulthard et al., 2017). The high SiO_2 concentrations of the forearc suggest generation from mantle with a relatively steep geothermal gradient (Shervais et al., 2019). After less than 1.2 million years and while seafloor spreading was ongoing, water-rich melts became involved in magma genesis, resulting in a transition to low-Si boninite (see Pearce and Reagan, 2019). About the time that seafloor spreading ceased (c. 51.3 Ma) and the arc began to be established, high-Si boninites began erupting (Reagan et al., 2019). Eruption of these boninites migrated away from the trench and continued to about 44Ma, when lava compositions transitioned toward those of a normal volcanic arc (Ishizuku et al., 2011b).

The Puysegur GeoPRISMS site

The Puysegur subduction zone (Fig. 3) at the southern tip and offshore South Island, New Zealand was selected as a GeoPRISMS focus site for studies of subduction initiation. The region is globally unique as subduction is now initiating with well-constrained relative motions between over-riding and subducting plates and antecedent tectonics that are not extensively over-printed.

The Puysegur Subduction zone accommodates oblique convergence with under-thrusting of the Australian below the Pacific Plate along the northern segment of the Macquarie Ridge Complex (Fig. 3A). Cenozoic plate kinematics are well constrained by seafloor magnetic anomalies (Cande and Stock, 2004). After Eocene rifting and seafloor spreading south of New Zealand, a few hundred kilometers of right-lateral strike slip motion juxtaposed continental crust of Fiordland and Miocene age oceanic crust. The seismic Benioff zone, reaching about 150 km depth, can be used to estimate that under-thrusting began in Fiordland at 16 -10 Ma, and at 11-8 Ma near the Puysegur Trench (Sutherland et al., 2006).

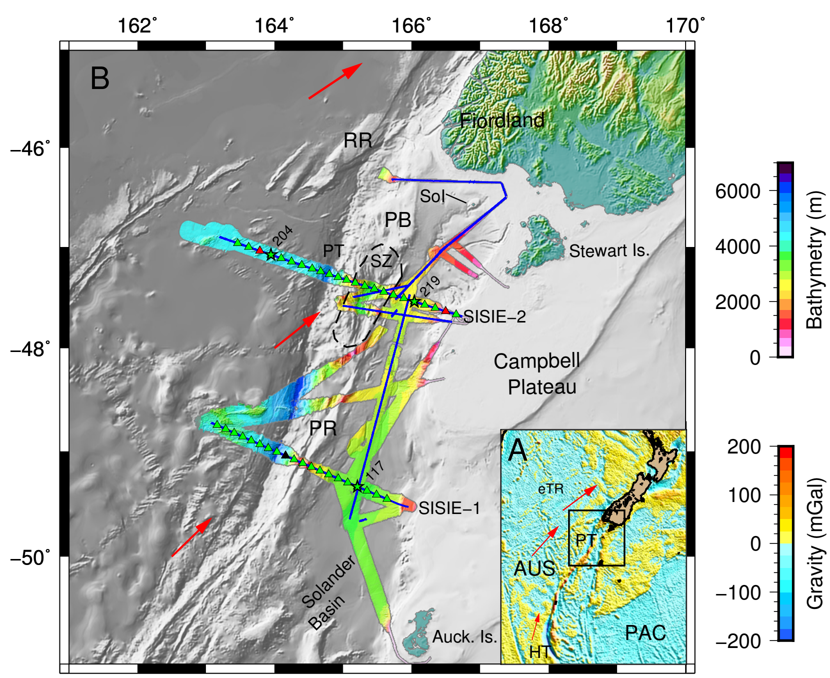


Figure 3. A. Puysegur study region (black rectangle) in the south west Pacific. The Macquarie Ridge Complex is the long narrow gravity high/low feature between the Hjort Trench (HT) and the Puysegur Trench (PT). Base map is free-air gravity. B. MCS lines (blue lines), OBS locations (filled triangles and stars) and swath bathymetry (in color) of Puysegur Ridge (PR) and Trench region acquired as part of the South Island Subduction Initiation Experiment (SISIE) is shown. The combined OBS/MCS lines SISIE-1 and SISIE-2 are labelled. The Snares Zone (SZ) is outlined with a black dashed line, Resolution Ridge is labeled as RR, Solander Island as Sol and Puysegur Bank as PB. Red arrows are the modern relative plate motion with respect to PAC. Reprinted from Gurnis et al. (2019) with permission from Elsevier.

There have been large vertical motions of the Puysegur Ridge along strike as the boundary evolved from transpression to incipient subduction. The southern Puysegur Ridge experienced uplift, whereas the northern Puysegur Ridge first uplifted and then subsided by about 1.8 km within the Snares Zone, a region with several strike faults and a negative free air-air gravity anomaly as strong as an oceanic trench (Fig. 3). The uplift migrated to the north during the Miocene consistent with about 2 km of dynamic support within Fiordland (House et al., 2002). South of Fiordland, adakitic volcanism on Solander Island commenced within the last 1 Myr (Mortimer et al., 2013).

As part of GeoPRISMS, the South Island Subduction Initiation Experiment (SISIE) was successfully completed in February and March 2018 using the *R/V Marcus G. Langseth*. Seismic reflection and refraction data were acquired across the Puysegur Trench and Ridge and the Solander Basin (Fig. 3B). For the multichannel seismic (MCS) imaging, the Langseth used a 12.6 km long streamer for much of the 1,300 km of lines acquired. A group of 28 ocean-bottom seismometers (OBSs) from the University of Texas Institute of Geophysics (UTIG) were used at 43 sites on two refraction lines. One refraction/MCS line targeted the more juvenile part of the Puysegur Ridge (SISIE 1) while the other targeted the more evolved part (SISIE-2). Two lines of onshore seismic receivers and several broadband seismometers on islands were deployed by New Zealand collaborators.

With the new seismic data, much of the crust immediately to the east of the Puysegur Trench was found to be rifted continental crust (Gurnis et al., 2019; Fig. 4) and not oceanic crust as interpreted along the entirety of the MRC. This is an important new observation, because the density difference across an ocean-continental margin is substantially larger than that across an ocean-ocean margin. A plate tectonic reconstruction shows that the density difference across the plate boundary rapidly increased during strike-slip

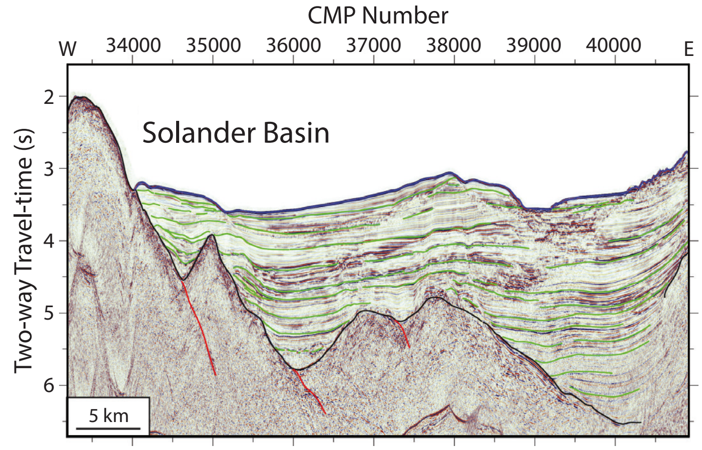


Figure 4. Details for the Solander Basin just east of the Puysegur Ridge from SISIE-2 seismic line (see Fig. 3 for location of SISIE-2). The seismic images clearly showed that the over-riding plate during the initiation of subduction was stretched continental crust and not oceanic crust as expected for SISIE. The top panel shows interpretation of time-migrated multichannel seismic line. Lines indicate: top of sediments (blue), basement (black), sedimentary horizons (green), and faults (red). For upper part of section V.E. ~4:1 @ 2km/s. For depths for basement with faults V.E. ~2:1 @ 4 km/s. Reprinted from Gurnis et al. (2019) with permission from Elsevier.

motion between 18 and 15 Ma, just before subduction initiation, and supporting a role for compositional differences in the initiation of Puysegur subduction. During initiation, a large fault (Tauru Fault, Fig. 3B) within the northern Solander Basin, inverted from normal to reverse. Using sequence stratigraphy with the N-S MCS lines and an existing petroleum exploration well, Patel et al. (2020) constrained the compressional event between 12 and 8 Ma. Using a seismic tomographic model with OBS-inferred velocities mapped to density, Hightower et al. (2019) showed that the crust below the Snares zone was thicker compared to the Puysegur Ridge to the south even though it was topographically depressed. This likely reflects a strong change in the vertical force balance along strike.

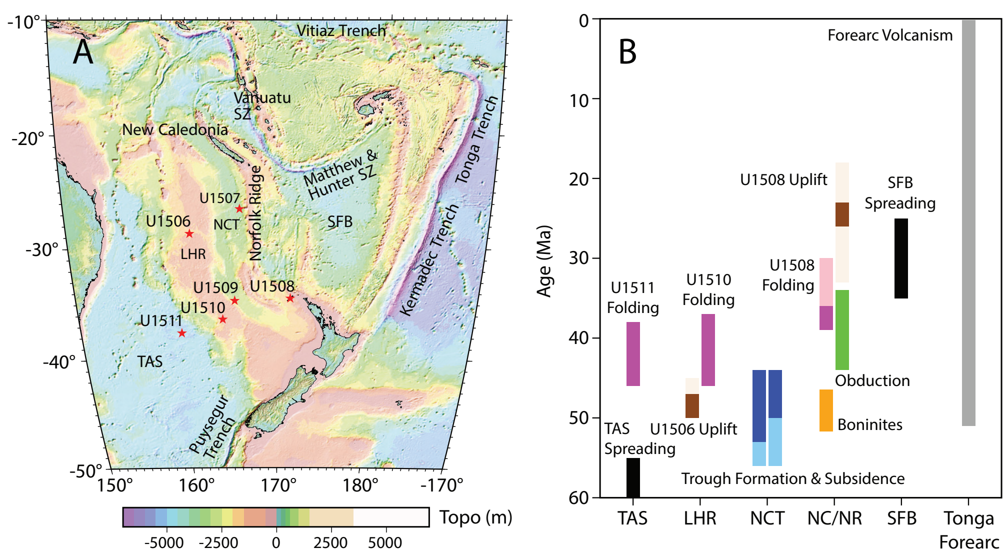


Figure 5. A. Location map for features associated with Tonga-Kermadec subduction initiation. B. Ages for key events associated with initiation of the Tonga-Kermadec subduction zone. Uncertainties on folding, uplift and subsidence denoted with lighter color shading. Recent IODP Expedition 371 drilling shown with red stars. The small black line at U1508 is the trace of the seismic line shown in Figure 6. Abbreviations are: TAS for Tasman Sea oceanic crust, SFB for South Fiji Basin, LHR for Lord Howe Rise, NCT for New Caledonia Trough, and NR for Norfolk Ridge.

Other sites and observational programs

Complementing the IBM and Puysegur work has been research undertaken on Tonga-Kermadec subduction initiation using three sources of information from: the Tonga forearc, ophiolitic terrains of New Caledonia, and the sediments and structure of northern Zealandia (that is, Norfolk Ridge, New Caledonia Trough and Lord Howe Rise) (Fig. 5).

Initiation of Tonga-Kermadec, like IBM, dates to about 50 Ma as revealed through analysis of samples recovered from the Tonga forearc. Dredge samples, primarily tholeiitic basalts, have ages from 51 Ma into the Miocene, with one late Mesozoic age (Meffre et al., 2013). An IBM-type forearc volcanic stratigraphy, with Boninites upslope from basalts, has not been found and the volcanism reflects a longer period and not just a brief burst as at IBM.

New Caledonia, at the northern end of the narrow Norfolk Ridge (Fig. 5), has several obducted terrains, including a Poya terrain with dolerites, basalts and abyssal sediments dating from 83 to 55 Ma (Cluzel et al., 2001). On top of Poya lies an ultramafic Peridotite Nappe with boninite and felsic dykes intruding it (Cluzel et al., 2016). Within the serpentinite sole of the ophiolite are boninite-series felsic dikes with ages of ca. 54 Ma, while two boninitic dykes have $^{40}Ar/^{39}Ar$ ages of 50.4 +/1 1.3 Ma and 47.4 +/- 0.9 Ma.

Throughout northern Zealandia (Fig. 5A), as evident in multichannel seismic profiling (Fig. 6), is broad-scale folding, thrusting and vertical motions broadly dating to the Eocene and Paleocene (Sutherland et al., 2017). Refining the timing of this compression and vertical motion was the objective of IODP Expedition 371 (Sutherland et al., 2020; Fig. 5A). Analysis of the recovered cores showed that Lord Howe Rise rose from about 1 km water depth to sea level and then subsided back, with peak uplift at 50 Ma in the north (west of New Caledonia) and between 41 and 32 Ma in the south (Fig. 5B). The New Caledonia Trough, between Lord Howe Rise and Norfolk Ridge, subsided 2–3 km between 55 and 45 Ma, but whether the trough resulted from rifting or crustal delamination remains unclear.

The evidence for Tonga-Kermadec initiation from the Tonga forearc, ophiolitic nappes in New Caledonia, and compression throughout northern Zealandia points to an inception of around 50 Ma. The longer-term history of eastern Australia and Zealandia has long-term subduction from early Mesozoic but without subduction between about 110 Ma and 50 Ma (Mortimer et al., 2017). The modern Tonga-Kermadec formed at the boundary of this older Mesozoic subduction zone and the initiation was associated with broad-scale compression (Sutherland et al., 2017), local eruption of boninites and formation of a trough in-board of the new trench.

Vanuatu also provides two examples of subduction initiation. One is the nucleation ~15-12 million years ago through a polarity reversal along the Vitiaz Trench and is significant because of the large amount of rollback and back arc opening which transpire right after initiation (Pelletier et al., 1993). In addition, the < 2 Ma Matthew-Hunter subduction zone formed east of the south end of the Vanuatu Trench, potentially as it collided with the Loyalty Ridge (Patriat, et al., 2019). The trench is migrating southwestward and southward, opening a series of sinistral trans-tensional basins proximal to the trench (Patriat et al., 2015). A diverse suite of magmas, including boninites, adakites and basalts, have erupted within this extensional environment and Patriat et al. (2019) have argued that the resulting terrane is a modern analogue for supra-subduction zone ophiolites.

A possible candidate for intra-oceanic subduction initiation may be the N-S Gagua Ridge east of Taiwan (Fig. 2A), separating Cretaceous oceanic crust to the west with the crust of the West Philippine Sea Basin. Reconstructions (Hall, 2002) suggest that Paleogene relative plate motion was strike-slip, and that the Gagua Ridge was likely a long-offset transform fault (Deschamps et al., 1998) until initiation of compression. Marine seismic data show that the younger crust is deformed at the Gagua Ridge, where it thickens to 15-18 km (Eakin et al., 2015) with younger lithosphere underthrusting the neighboring plate by ~10 km, without leading to subduction. The failed subduction along the Gagua Ridge suggests that subduction may not easily initiate between oceanic plates with normal crustal thicknesses. The Laxmi Basin, west of India, may also be an example of failed subduction initiation based on similarities between the compositions of basement lavas recovered during IODP Expedition 355 and IBM forearc lavas (Pandey et al., 2019).

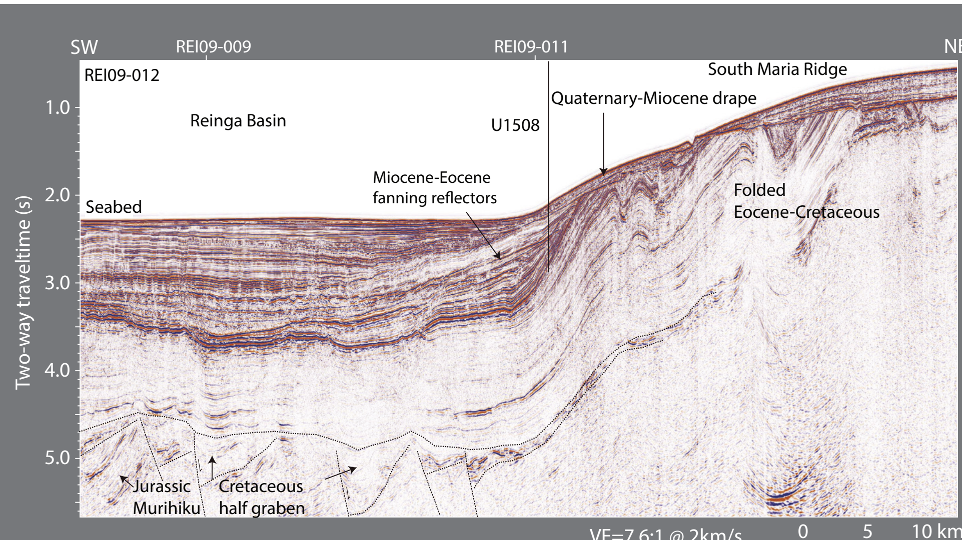


Figure 6. Seismic line for U1508 from IODP Expedition 371 showing the intense compression and subsequent tectonic subsidence interpreted as part of Tonga-Kermadec subduction initiation. Regional seismic reflection Line REI09-012 near Site U1508 with interpretation of stratal age and structure Location of seismic line and U1508 Site shown in Figure 5A. VE = vertical exaggeration. From Sutherland, et al. (2019)

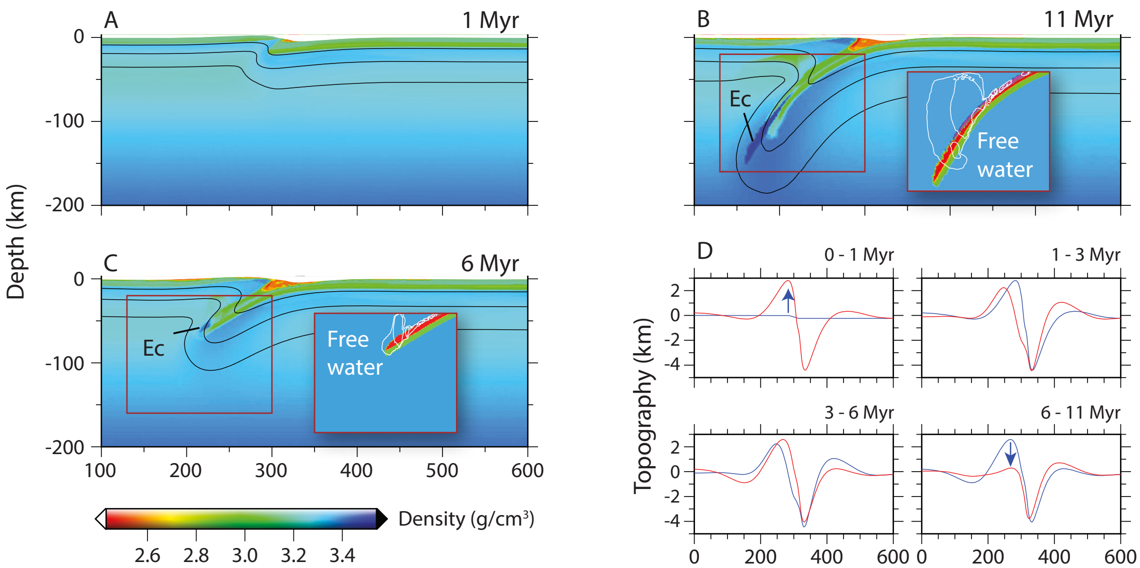


Figure 7. Development of a new subduction zone in transition from forced to a self-sustaining state. A-C Total density with temperature contours (black). Eclogite (Ec in B and C) formation starts at ~ 6 Myr. Free water release shown in insets as white contours. D Evolution of surface topography (blue lines at start of interval, red at end) in which ridge rapidly forms within ~ 1 Myr but then subsides when the system becomes self-sustaining through a combination of thermal buoyancy and transformation of basalt to eclogite. From the models in Mao et al. (2017).

Some ophiolites, subaerial slivers of oceanic lithosphere found within continental suture zones, have geochemical signatures of a subduction-related setting (Shervais, 2001). A key geochemical marker of ophiolite formation in a subduction initiation setting is the presence of low-Ca or high-Si boninites (Pearce and Robinson, 2010). Type section boninites from the IBM forearc have these compositions, and they have been interpreted to reflect extreme prior mantle depletion caused by genesis of forearc basalts (Stern and Bloomer, 1992). Ophiolites bearing high-Si boninites are no older than 2 Ga, suggesting that rigid plate subduction initiation accompanied by near trench sea-floor spreading may have started about this time (Pearce and Reagan, 2019). The most studied ophiolite belts are Tethyan from the Alps to the Himalaya and in age range from Jurassic to Cretaceous. Some have compositional and/or stratigraphic affinities with the IBM forearc, suggesting that they may represent IBM-like subduction initiation events (e.g. Pearce and Robinson, 2010; Reagan et al., 2010). Others have more complex compositional patterns and age ranges, suggesting formation in more complex tectonic settings, such as Hunter-Matthew, where subduction is occurring beneath the northern end of the Lau Basin (Embley and Rubin, 2018), or south of the Mariana Trough where forearc rifts propagate close to the trench (e.g. Ribeiro et al., 2013).

Computational studies

Theoretical and computational approaches have been used to investigate the mechanics of subduction initiation, the expected geochemical expression as subduction starts, and the role of volatiles among many other factors. The thermal age of oceanic plates, compositional variations across the nascent boundary, convergence rate and in–plane stress (Gurnis, et al., 2004; Nikolaeva, et al., 2010) and fault strength, fault weakening and plate bending (McKenzie, 1977; Toth and Gurnis, 1998) have been shown to be the key factors that drive and retard initiation. Independent of initiation scenarios, driving forces must overcome frictional resistance between plates and bending of the high effective viscosity plate. During the nucleation of a new trench, oceanic lithosphere should act as an elastic plate (McKenzie, 1977; Toth and Gurnis, 1998); this means that older plates might be less favorable to subduction initiation (Cloetingh et al., 1989). If the plate boundary does not weaken sufficiently fast, the oceanic plate will not slide into the mantle to allow the negative thermal buoyancy to grow (Gurnis et al., 2004). Constitutive models with strain-weakening, due to grain size reduction, grain damage, or volatile ingestion can lead to plate instability (Bercovici and Ricard, 2014). During the incipient phase, as crust on the newly underthrust plate is subjected to greater pressures, it will transition to eclogite. Eclogite will not only have a higher density which enhances subduction initiation, but the phase transition releases water which decreases the creep strength (Fig. 7) leading to more favorable conditions to overcome resisting forces (Mao et al., 2017). Alternative very large vertical forces at the edges of a plate, such as from an adjacent slab, can induce large vertical velocities and near field extension (Maunder et al., 2020).

If the forces resisting subduction at the plate boundary can be overcome, one outcome is an oceanic plate that starts to founder and move vertically downward. The downward motion will lead to back-arc opening and trench rollback (Hall et al., 2003; Zhou, et al., 2018). The initial evolution during initiation leads to both local tectonic changes and changes in the forces which drive plate motions. If the plate founders, the energy released by the descending slab goes into bending and deforming the plate with no change in absolute velocity of the subducting plate (Leng and Gurnis, 2011). However, without foundering and trench rollback, the energy released by subduction goes into pulling the plate forward. Consequently, the combination of local tectonics (structural style, vertical motions and volcanism) of new plate boundaries and changes in plate kinematics can be diagnostic of how plate forces changed during subduction initiation.

Synthesis

Our understanding of the kinematics and dynamics of subduction initiation has progressed enormously during MARGINS and GeoPRISMS. Observations of the IBM and Tonga-Kermadec systems have helped refine age constraints on the timing of initiation, while new data from Puysegur have dramatically improved knowledge of subsurface structure. Subduction initiation is a frequent process with nearly all ocean-ocean subduction zones initiating in the Cenozoic and ocean-continent subduction zones reinitiating at plate boundaries that experienced subduction in the past (Fig. 1). A key message is that there is no single tectonic pathway which gives rise to a new subduction zone, and either extension or compression occurring in the near field during initiation. IBM is an example of rapid and near-field extension, while Tonga-Kermadec and Puysegur are examples of near- and far-field compression. Hunter-Matthew is an example of near-field transtension. Progress has also been made on the antecedent tectonic conditions that must exist regionally. A history of previous subduction likely must have existed in the region of the nucleating boundary. Nucleation of the IBM system occurred adjacent to relic Mesozoic arcs, Tonga-Kermadec and Puysegur Trenches formed along old Cretaceous subduction zones, and Hunter-Matthew propagated south- and east-ward from a Miocene subduction zone. Different factors contributing to subduction initiation may include the added buoyancy of the relict arc, hydration and weakening of lithospheric mantle, and the development of shear zones. Ancient shear zones may have reduced grain sizes, fabrics generated in low-friction phyllosilicates, or produced significant degrees of micro-cracking and dislocations. These factors contribute to low strength, which could lead to reactivation as the tectonic conditions or state of stress change.

The connection between Pacific Plate motion and the initiation of subduction during the Eocene remains a tantalizing window into how plate tectonics works. The mechanics are being addressed as the observational record has improved. On the surface, the connection between plate motion and subduction initiation seems straightforward: The Hawaiian-Emperor seamount Bend (HEB) and initiation of the two largest, fully-oceanic subduction zones, IBM and Tonga-Kermadec, all date to ~50 Ma. Questions raised are whether there was a synchronous change in absolute Pacific Plate motion, and if that change was a cause or consequence of subduction initiation.

Traditionally, HEB represents a change in absolute Pacific Plate motion with respect to a Hawaiian mantle plume fixed in the lower mantle with no motion between plumes globally (Clague and Dalrymple, 1987; Sharp and Clague, 2006). However, there is no strong readjustment in relative plate motions along Pacific spreading centers at this time (Norton, 1995) but there is a substantial change of the paleo latitudes of Emperor Seamounts from about 81 to 47 Ma consistent with southward motion of the Hawaiian hot-spot (Tarduno, 2003). Global geodynamic models with plate motions show that the Hawaiian plume can move rapidly southward during this interval, slowing down at 50 Ma (Hassan, et al., 2016). Nevertheless, global plate reconstructions still show a substantial component in the change in absolute motion at about 50 Ma (Müller et al., 2016; Torsvik et al., 2017). In other words, HEB may represent a simultaneous combination of changes in absolute plate motion and plume motion at depth, raising the question of whether these two processes could be coupled.

Future prospects

The prospects for refining our understanding of subduction initiation remains bright through continued observationally campaigns linked with commensurate improvements in understanding kinematics and dynamics. The mechanical details of how oceanic lithosphere transitions to a new subduction zone and how faults nucleate, grow and evolve during transition to a fully self-sustaining system (driven entirely by local slab pull) remain unresolved and will require evidence from multiple subduction initiation events at different stages of initiation or which have particularly well-resolved features.

Targeting different subduction zones remains essential and there are important targets that could be accessed with offshore and onshore work. The Puysegur subduction zone remains a clear target for future work given the globally unique aspects of being in the process of initiation while having both interpretable antecedent tectonics as well as high precision plate kinematic constraints. The GeoPRISMS Puysegur work acquired high quality seismic data that can now be used to target sample collection, especially through deep sea drilling. Important targets could place precise constraints on the timing of in-plane compression and growth of the Puysegur Ridge as the new subduction interface nucleated. The evolution of volatiles likely plays an essential role during initiation as it is associated with both the change in forces, by the reaction of basalt to eclogite, and reduction in the effective viscosity of the mantle wedge (Fig. 7). With Puysegur showing different stages of initiation along strike, we predict an along strike variation in volatile injection and hence electrical conductivity which could be tested with a focused magnetic tellurics experiment combined with deployment of broadband OBS for deeper imaging and earthquake locations. The forearcs of the Aleutian, Tonga-Kermadec, and Vanuatu subduction zones all remain essentially unsampled compared to the IBM record. All of these subduction zones evolved in different ways compared to IBM and so the expansion of this vital observational record is essential to develop a comprehensive understanding of the geodynamics of subduction initiation.

Synthesizing these recently acquired and future observations and linking them to the geodynamics of plate motions will remain a substantial challenge but which becomes more tractable with the ongoing explosion in computational and information sciences. A key direction will be three-dimensional studies that track viscoelastoplastic materials incorporating volatile transport and magmatic processes from nucleation to self-sustaining subduction as plate motions change. The domain of inverse geodynamics is starting to unfold, which will allow direct incorporation of observational constraints into process-based models.

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