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Continental-scale geographic change across Zealandia during Paleogene subduction initiation

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ABSTRACT

Data from International Ocean Discovery Program (IODP) Expedition 371 reveal vertical movements of 1–3 km in northern Zealandia during early Cenozoic subduction initiation in the western Pacific Ocean. Lord Howe Rise rose from deep (~1 km) water to sea level and subsided back, with peak uplift at 50 Ma in the north and between 41 and 32 Ma in the south. The New Caledonia Trough subsided 2–3 km between 55 and 45 Ma. We suggest these elevation changes resulted from crust delamination and mantle flow that led to slab formation. We propose a "subduction resurrection" model in which (1) a subduction rupture event activated lithospheric-scale faults across a broad region during less than ~5 m.y., and (2) tectonic forces evolved over a further 4–8 m.y. as subducted slabs grew in size and drove plate-motion change. Such a subduction rupture event may have involved nucleation and lateral propagation of slip-weakening rupture along an interconnected set of preexisting weaknesses adjacent to density anomalies.

INTRODUCTION

Major global plate-motion change occurred between 52 and 43 Ma, as manifested by the Emperor-Hawaii bend (Steinberger et al., 2004; O'Connor et al., 2013), reorientation of mid-ocean ridges (Muller et al., 2000; Steinberger et al., 2004; Cande et al., 2010), and rifting of Antarctica (Cande et al., 2000). This coincided with subduction initiation (Fig. 1) in the Izu-Bonin-Mariana (IBM) system (Arculus et al., 2015; Reagan et al., 2017), and nascent collision of the Indian and Asian plates (Aitchison et al., 2007). Development of western Pacific

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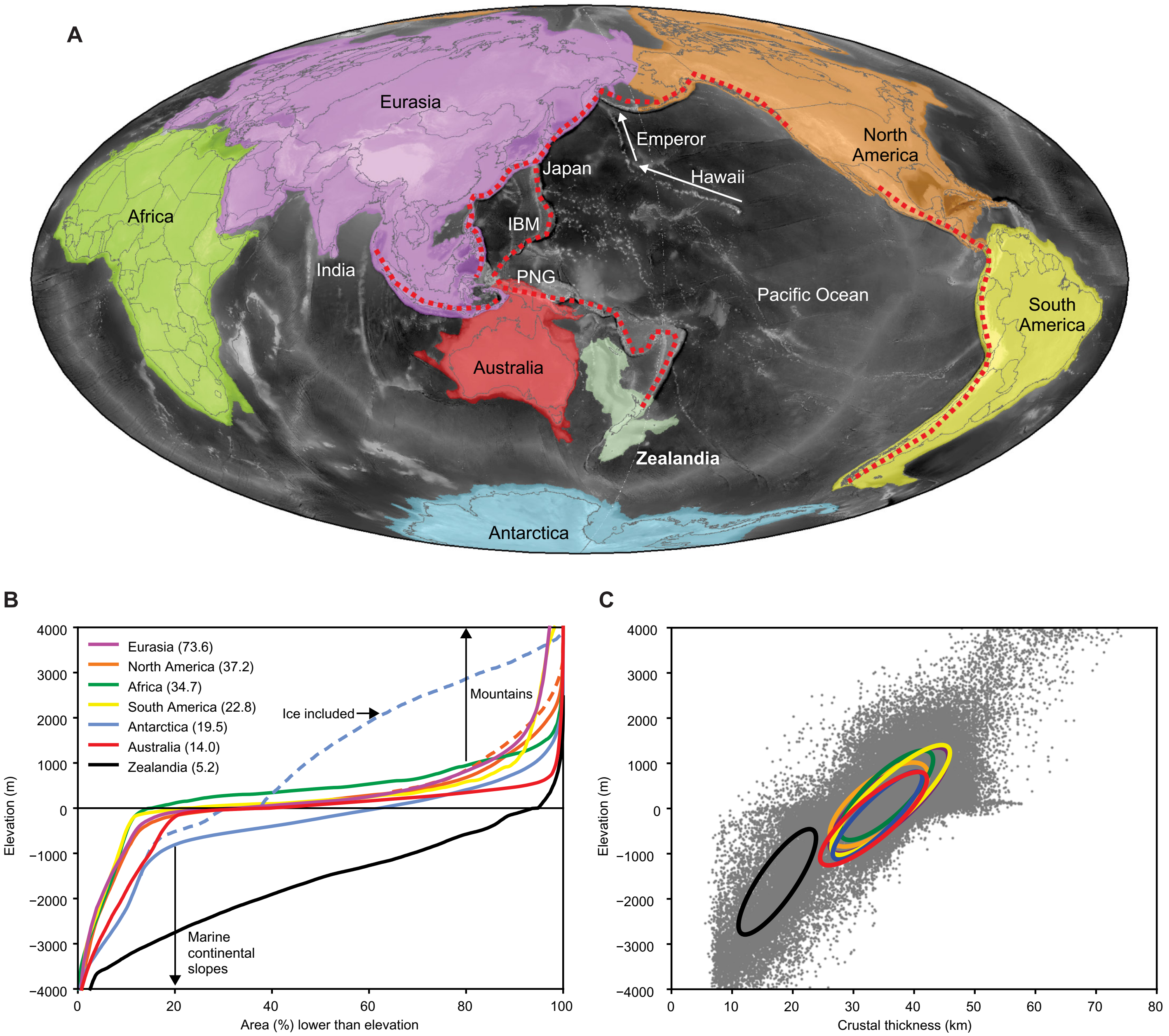

Figure 1. (A) Global continents on a shaded elevation model (ETOPO1, https://www.ngdc.noaa.gov/mgg/global/), Izu-Bonin-Mariana margin (IBM), Papua New Guinea (PNG), and "Pacific Ring of Fire" (red dots). Arrows show plate movement during formation of Emperor-Hawaii seamounts. (B) Hypsometric profiles of continents (area in legend, ×10⁶ km²). Ice (dashed) and rock (solid) surfaces are shown for Antarctica and North America (includes Greenland). (C) Crustal thickness (CRUST1.0, https://igppweb.ucsd.edu/~gabi/crust1.html) versus surface elevation. Ellipses show one standard deviation for each continent (same legend as in B).

slab pull explains the sense of plate-motion changes (Gurnis et al., 2004).

Zealandia, a distinct but mostly submerged continent (Mortimer et al., 2017), has a low median elevation (Fig. 1), which is primarily an isostatic response to its relatively thin crust (~18 km on average). Between 83 Ma and 79 Ma, Zealandia separated from Gondwana (Gaina et al., 1998; Sutherland, 1999), and much of the continent has been below sea level since, as documented by now-uplifted marine stratigraphic records in New Zealand and New Caledonia (Paris, 1981; Laird and Bradshaw, 2004) and submarine sections recovered by the Deep Sea Drilling Program (DSDP; Fig. 2; Burns and Andrews, 1973).

However, the topographic history of Zealandia is not straightforward. Seismic reflection surveys and geological mapping reveal widespread Eocene deformation in northern Zealandia (Bache et al., 2012; Browne et al., 2016). This has been coined the "Tectonic Event of the Cenozoic in the Tasman Area" (TECTA; Sutherland et al., 2017), and it appears to have begun about the same time as cessation of spreading in the Tasman Sea (Gaina et al., 1998) and subduction initiation near or east of Norfolk Ridge (Fig. 2; Gurnis et al., 2004; Cluzel et al., 2006; Sutherland et al., 2010; Bache et al., 2012; Matthews et al., 2015).

International Ocean Discovery Program (IODP) Expedition 371 (Sutherland et al., 2019) was designed to determine the Cenozoic paleogeography of northern Zealandia, and how and why this large region (~3 × 10⁶ km²) evolved over time. We discuss the evidence collected and reasons for topographic change, and we propose a new framework for understanding subduction initiation.

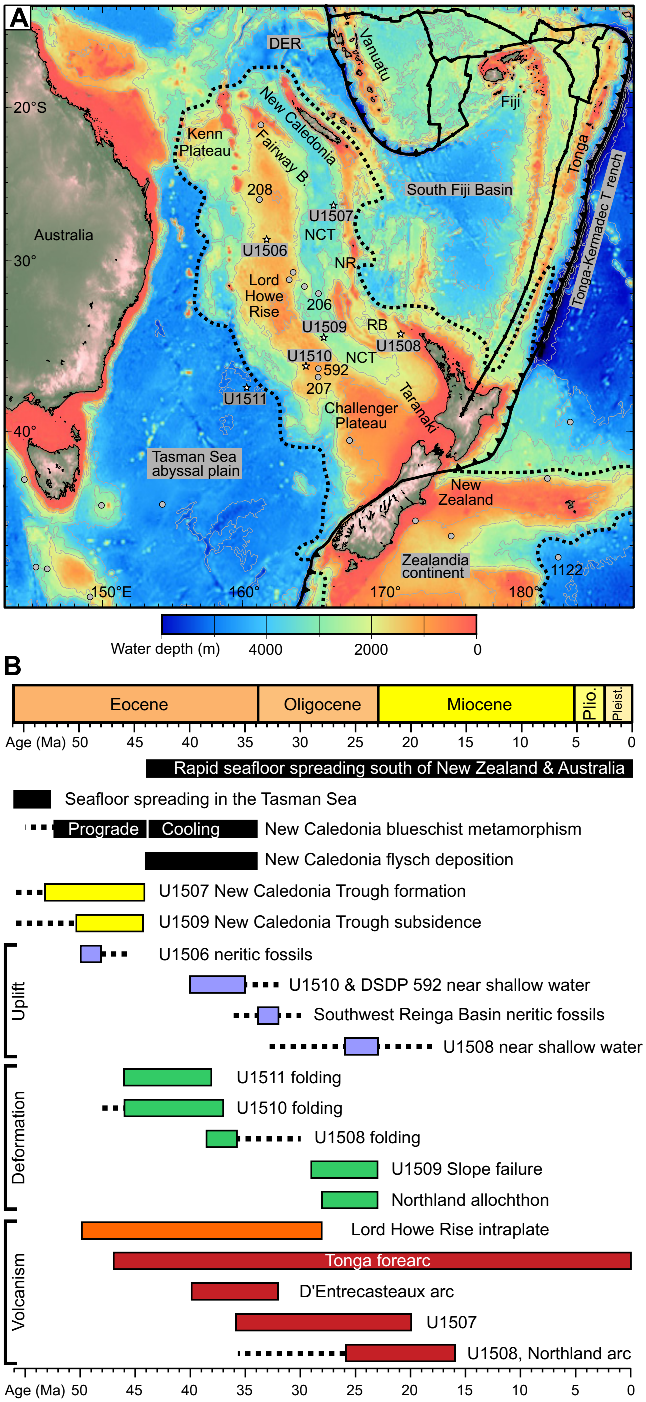

Figure 2. (A) Zealandia bathymetry (m), new (stars) and existing (circles) drill sites, New Caledonia Trough (NCT), Norfolk Ridge (NR), D'Entrecasteaux Ridge (DER), Reinga Basin (RB), and outline of Zealandia (dotted). B.—Basin. (B) Timing of events inferred from integrated analysis (see the Data Repository [see footnote 1]). Plio.—Pliocene; Pleist.—Pleistocene; DSDP—Deep Sea Drilling Project.

DRILLING RESULTS

Before IODP Expedition 371, only three boreholes, DSDP Sites 206–208, each with limited core recovery, penetrated strata in northern Zealandia beneath the TECTA unconformity. We drilled six sites in the context of seismic reflection surveys (Fig. 2; Figs. DR1 and DR2 in the GSA Data Repository[1]). We classified paleodepth (meters below modern sea level [mbsl]) into the following categories (Van Morkhoven et al., 1986): neritic (<200 mbsl), upper bathyal (200–600 mbsl), middle bathyal (600–1000 mbsl), lower bathyal (1000–2000 mbsl), and abyssal (>2000 mbsl). We discovered Paleogene fossils indicative of nearby neritic conditions at sites now far below sea level (Fig. DR3).

Parts of northern Zealandia were transiently uplifted and then subsided. IODP Site U1506 on northern Lord Howe Rise rose close to sea level with a shallow carbonate platform at ca. 50 Ma, and subsided to a bathyal environment (~600 mbsl) by 45 Ma. Neritic fossils of Eocene (ca. 50 Ma) age at Site U1506 are now ~1770 mbsl. At DSDP Site 208 (Fig. 2), middle Eocene (45–43 Ma) cores contain benthic foraminifers indicative of middle bathyal conditions, but planktic-benthic ratios in Paleocene (65–56 Ma) cores indicate shallower conditions, and unconformities separate Paleocene from older and younger strata (Burns et al., 1973).

Southern Lord Howe Rise experienced later transient uplift. Beneath an unconformity at IODP Site U1510 (1238 mbsl), upper Eocene (41–37 Ma) siliceous chalk was deposited at middle bathyal depths, and neritic fossils indicate downslope transport. Site U1510 is ~80 km from DSDP Site 592 (1088 mbsl), where an unconformity separates lower Miocene (23–19 Ma) chalk from lower Oligocene (33–32 Ma) ooze (Kennett et al., 1986). Fossils indicate a lower or middle bathyal environment since the late Eocene at Site 592, but lower Oligocene strata contain layers of coarse (1–4 cm) mollusk (*Ostrea*) fragments (Kennett et al., 1986), consistent with nearby shallow water. DSDP Site 207 (Fig. 2) subsided from upper bathyal to middle bathyal depths during the Paleocene to middle Eocene, but an unconformity separates Eocene (43–38 Ma) from middle Miocene (15–13 Ma) strata, and inclusion of slumped upper Eocene (38–36 Ma) material along the unconformity is consistent with peak regional uplift in the latest Eocene and early Oligocene (36–32 Ma). The crest of southern Lord Howe Rise has a current depth of 900–1000 mbsl.

Bioclastic limestone dredged from ~1750 mbsl in southwest Reinga Basin (Fig. 2) contains neritic benthic foraminifers with ages of 36–30 Ma, and reworked Eocene (43–38 Ma) planktic species (Browne et al., 2016; Sutherland et al., 2017). At IODP Site U1508 (1609 mbsl), in the eastern Reinga Basin, onlap indicates deformation started at ca. 39 Ma (Figs. DR1, DR2, and DR4), and Oligocene (26–23 Ma) chalk contains a middle to lower bathyal fauna mixed with shallow-water ostracods and benthic foraminifers, along with palynoflora indicating downslope transport from land. Reinga Basin and Lord Howe Rise sample locations have erosional unconformities identified on seismic reflection profiles (Fig. DR4).

At IODP Site U1509 (2911 mbsl), in the southern New Caledonia Trough, we drilled into Cretaceous Fairway–Aotea Basin strata (Fig. 2; Collot et al., 2009). Pleistocene to Oligocene ooze and chalk contain lower bathyal to abyssal benthic foraminifers. Eocene assemblages indicate lower bathyal paleodepths. Paleocene and Cretaceous assemblages indicate a paleo–water depth of ~1000 m. Cretaceous claystones contain plant fragments and fern spores that indicate coastal proximity. Combined data suggest ~2000 m of Cenozoic subsidence, with most accomplished after 59 Ma and before 45 Ma.

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[1] GSA Data Repository item 2020110, geological and geophysical data; New Caledonia geology; paleontological evidence used to infer paleogeography; and Figures DR1–DR4, is available online at http://www.geosociety.org/datarepository/2020/, or on request from editing@geosociety.org.

At IODP Site U1507 (3568 mbsl), we drilled sediments of the northern New Caledonia Trough for the first time. Fossils from the oldest drilled sediments (864 m below seafloor [mbsf]) indicate lower bathyal depths at 41 Ma (Sutherland et al., 2019). Sedimentation rates increase downhole from 10 m/m.y. to 40 m/m.y. (Fig. DR2), and extrapolation to the base of the unit, determined from seismic reflection data to be ~1300 mbsf, indicates a Paleogene age for the basin.

GEOGRAPHIC CHANGE

Cretaceous rifting from Gondwana likely thinned the crust of Zealandia, but large elevation changes (1–3 km) across a wide region (Fig. 3) occurred during the Paleogene. Lord Howe Rise uplifted by at least 1 km, with a southeast migration in this motion from 50 to 35 Ma. New Caledonia Trough subsided 1–3 km, starting at ca. 55–45 Ma, with no resolvable difference in timing between north and south. The East Reinga Basin records deformation at ca. 39 Ma with peak uplift at ca. 26–23 Ma (Fig. 2; details of fossil evidence are given in the "Paleogeography" section of the Data Repository).

Flexure would not produce the magnitude, wavelength, nor timing of observed elevation changes, so we suggest crustal delamination and slab formation by reactivation of a west-dipping Cretaceous subduction zone (Fig. 4; Sutherland et al., 2010) to explain the observed features. Thermal isostatic and dynamic forces (upwelling) are inferred to have driven uplift of Lord Howe Rise, while delamination of basaltic lower crust, minor local extension, and dynamic forces (downwelling) caused New Caledonia Trough to subside.

SUBDUCTION INITIATION

Subduction initiation can be spontaneous if gravitational instability and a weakness are juxtaposed (Stern, 2004), or it can be induced if gravitational instability grows during convergence across a fault (Gurnis et al., 2004). We propose an additional case: A stable gravitational anomaly may exist but will founder to produce a slab if failure occurs. Time scales,

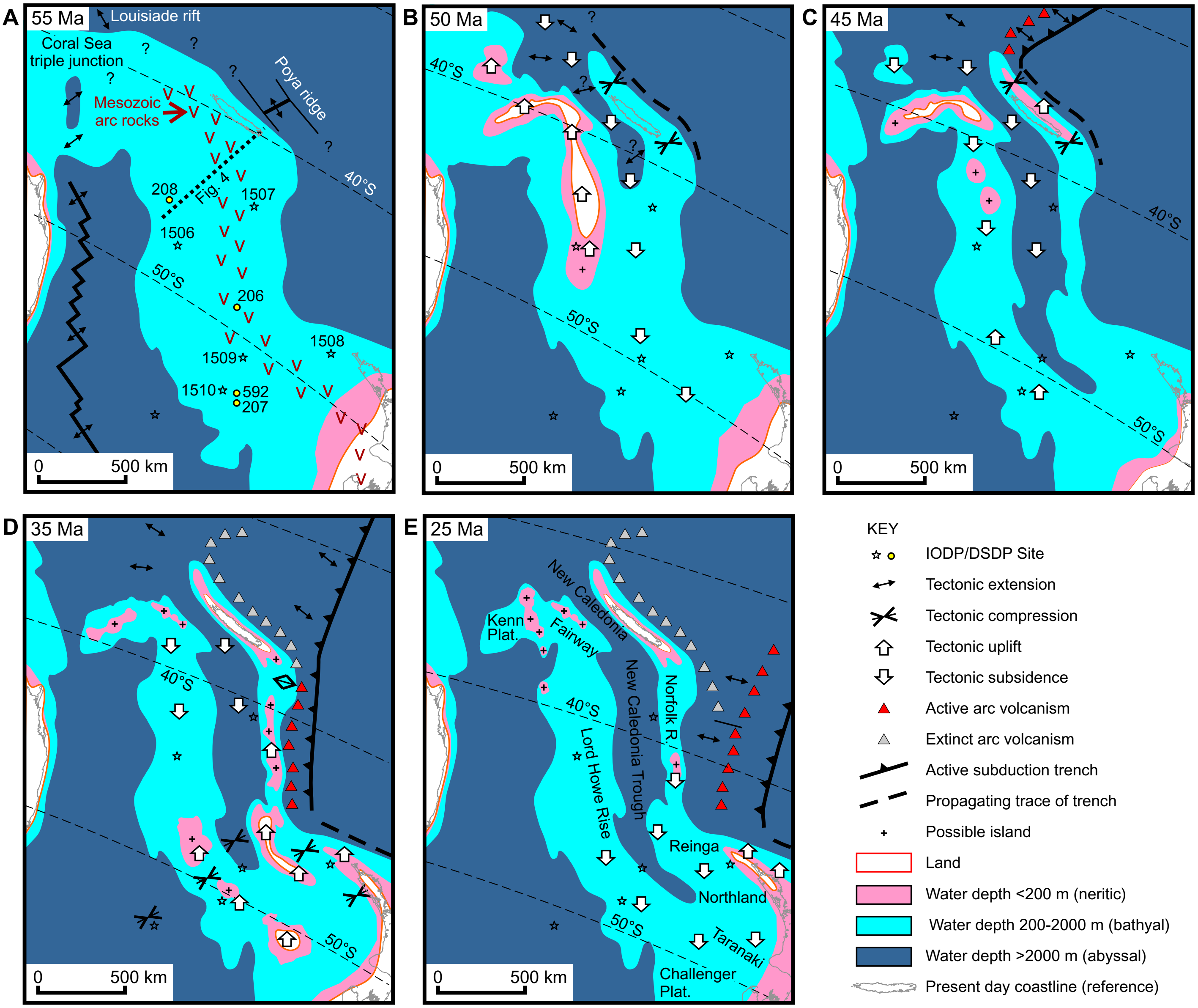

Figure 3. Paleogeographic reconstructions at 55, 50, 45, 35, and 25 Ma. Dark blue is >2000 m water depth, cyan is 2000–200 m, pink is 200–0 m, and white is land. Stars are new drill sites. Present coastline (gray) is shown for reference. Filled arrows show uplift (up) or subsidence (down). Open arrows show active convergent or divergent crustal deformation. Triangles show active (red) or extinct (gray) arc volcanic activity. Black line with teeth is a suggestion for trench location, but alternate hypotheses exist. Plat.—Plateau; R.—Ridge; IODP—International Ocean Discovery Program; DSDP—Deep Sea Drilling Project.

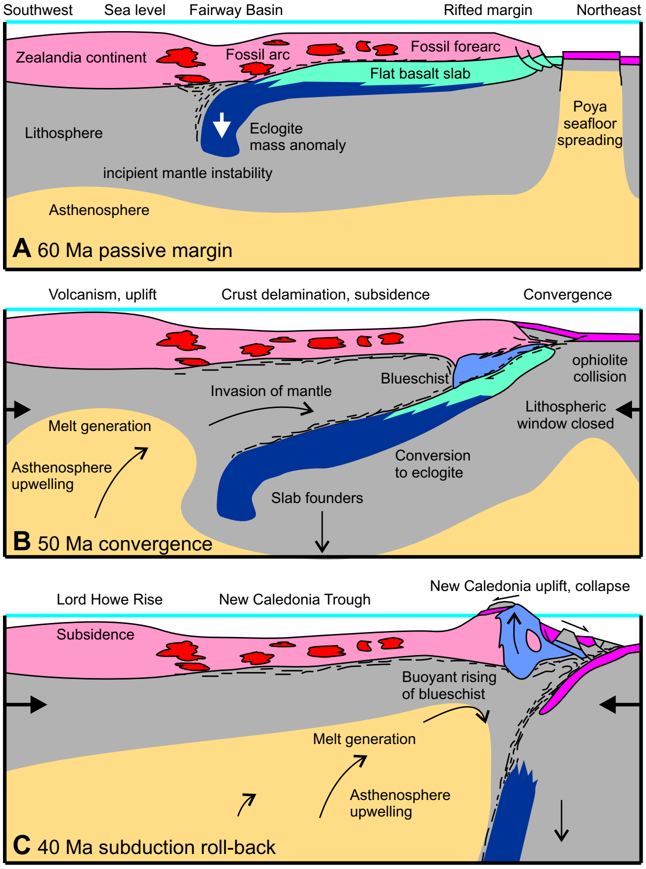

Figure 4. Cartoon cross sections illustrating the transition from Paleocene rifted margin to Eocene subduction. Line is between northern Lord Howe Rise and southern New Caledonia (Fig. 3A). Pink—continental crust; red—arc plutons; green—Cretaceous subducted slab (dark blue where it is eclogite); purple—ocean crust, gray—mantle lithosphere, and yellow—asthenosphere.

length scales, and processes may differ, but the idea has similarities to velocity-weakening behavior on a fault during an earthquake. We propose the term subduction rupture event (SRE) to describe the nucleation and lateral propagation of the onset of fault slip and slip-weakening on lithospheric faults during subduction initiation. Induced subduction initiation requires regional forcing, whereas an SRE requires only local forcing (nucleation of initial failure) and slip-weakening processes that facilitate lateral propagation.

Extension and volcanic activity associated with IBM subduction started at 53–52 Ma (Arculus et al., 2015), and the onset of metamorphism in New Caledonia was at 55–50 Ma (Pirard and Spandler, 2017; Vitale-Brovarone et al., 2018; Fig. 2; see the Data Repository). In the Tonga forearc, the oldest plagiogranites have ages ca. 51–50 Ma, and arc activity is evident after ca. 48 Ma (Meffre et al., 2012). Seafloor spreading in the Tasman Sea also ended at ca. 52 Ma (Gaina et al., 1998). The Emperor-Hawaii bend records onset of Pacific plate-motion change at ca. 50 Ma, with a time of maximum curvature at ca. 48–47 Ma (O'Connor et al., 2013), and magnetic anomalies record rapid seafloor spreading south of Australia and New Zealand after 45–43 Ma (Sutherland, 1995; Cande and Stock, 2004). These major tectonic changes in the western Pacific were broadly synchronous with subsidence of the New Caledonia Trough and transient uplift of the northern Lord Howe Rise, and we interpret them to have been caused by initial slab formation.

Geological evidence from New Zealand, New Caledonia, and magnetic data show that a fossil Mesozoic arc lies beneath the New Caledonia Trough, and the Norfolk Ridge contains forearc accretionary complexes (Paris, 1981; Sutherland, 1999; Mortimer, 2004). Collision of a young large igneous province caused Cretaceous flat-slab subduction death and hence underplating of a thick basaltic lower crust (Davy et al., 2008). We propose that metamorphism of delaminated lower crust to eclogite provided a density anomaly that led to slab formation during the Eocene (Fig. 4).

Suitable conditions for reactivation might exist in an extinct subduction zone, including weakness of the subduction fault zone, and gravitational instability of buoyant arc rocks and serpentinized mantle set against dense eclogite of the slab and/or root of the arc, in addition to thermal contrasts (Leng and Gurnis, 2015). Subducted sediment or continent slivers may also play some role. Subduction zones have high continuity, so resurrection could propagate over a large distance.

Subduction initiated along ~10,000 km of the western Pacific between 55 and 50 Ma and seemingly preceded major plate-motion change. In our SRE hypothesis, subduction was induced as slip laterally propagated to resurrect extinct subduction zones. The rate of lateral propagation (>1 m/yr) was about two orders of magnitude faster than typical plate-motion rates.

After the SRE, forces, topography, and volcanism evolved in response to local conditions. The ca. 48 Ma change in Pacific plate direction and speed toward the western Pacific occurred earlier than the ca. 44 Ma acceleration in Australia toward Indonesia. The ~4–8 m.y. delay before plate motions changed reflects progressive growth of slabs and reductions in fault resistance. The North Pacific evolved fastest, but the SRE may have nucleated elsewhere. The oldest evidence for SRE activity that we are aware of is in Papua New Guinea, where ophiolites were emplaced at ca. 58 Ma (Lus et al., 2004).

There has been one major kinematic change during Earth history for which we know plate motions through magnetic anomalies, hotspots, and now regional topographic changes: the Eocene event of the western Pacific. We suggest that subduction initiation involves: (1) an SRE, and (2) development of forces as slabs grow and faults weaken. Fossil subduction margins provide the right ingredients for this to happen: lateral continuity, weakness, and density contrasts. The Pacific "subduction resurrection" context contrasts with the Mediterranean, where subduction initiation was induced by Oligocene continental collision (Handy et al., 2010), but prolonged (>30 m.y.) slab foundering had limited impact on global plate motions, perhaps due to limitations of suitability and continuity of inherited geology.

Subduction initiation beneath northern Zealandia altered geography, crustal thickness, and likely also crustal composition. It may be that other continents were shaped at a similar time (e.g., thin continental parts of Indonesia and South China Sea). As there has been only one major plate-motion change event since 83 Ma, the frequency-magnitude relationship for SRE events over geological time is hard to determine. It is plausible, though, that between 40 and 100 such events have occurred since the onset of plate tectonics. The unstable dynamical behavior we infer challenges the principle of uniformitarianism for plate tectonics because there is likely no modern analogue for the SRE processes that occurred at ca. 55–50 Ma. However, the geographical, geological, and geochemical evolution of continents and mantle probably was affected by these infrequent events. The records in Zealandia provide unique insight for recognizing and understanding them, and may even be a basis for prediction of favorable geological conditions: subduction resurrection.

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