Compressional faulting associated with forced Tonga-Kermadec subduction initiation

Supplementary information

Supporting information is provided for each site labeled in Fig. 1 of the main text. We use existing high-level seismic-stratigraphic nomenclature (Bache et al., 2014a) in which Late Cretaceous and Paleogene strata folded by the Eocene event are assigned to seismic unit 2a, syn-tectonic (Eocene) strata to seismic unit 1b, and strata that lie above these two units are assigned to seismic unit 1a. Ages are based on the New Zealand Geological Timescale (Cooper, 2004).

Table S1. Reinga Basin fossils in dredge samples referred to.

<table>
<thead>
<tr>
<th>ID</th>
<th>Fossil type</th>
<th>Brief description</th>
</tr>
</thead>
<tbody>
<tr>
<td>TAN1312-d06B</td>
<td>Radiolaria</td>
<td>Co-occurrence of Lychnocanium bellum (First Occurrence 53 Ma), Buryella tetradica (Last Common Occurrence, 51 Ma), Phormycyrtis striata striata and Lithochytris archaea – (Last Occurrences, 48 Ma). Age control based on ref (Norris et al., 2013).</td>
</tr>
<tr>
<td>SE35170/f0001</td>
<td>Foraminifera</td>
<td>The presence of planktics Morozovella lensiformis, Acarinina primitiva and benthics Bulimina subbortonica, and Buliminella browni gives an Eocene age of 56 – 46 Ma. The benthic fauna contains Buliminella browni, Melonis maorica, and Discorbinella apposite, indicating that paleodepth was probably uppermost bathyal (200 – 400 m). Larger foraminifera were also recovered (Asterocyolina) indicating that material from the photic zone is present, possibly shallower than 150 m.</td>
</tr>
<tr>
<td>F44852</td>
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<tr>
<td>TAN1312-d06E</td>
<td>Foraminifera</td>
<td>The presence of Acarinina collactea and Acarinina primitiva and absence of Globigerinatheka index, ubiquitous in the New Zealand Bortonian stage, indicate an age older than Bortonian. Morozovella and Elphidium saginatum are absent. Combined with the benthic Vulvulina zespinosa this indicates an Early to Middle Eocene age of 56 – 43 Ma.</td>
</tr>
<tr>
<td>SE35170/f0002</td>
<td></td>
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<tr>
<td>P83170</td>
<td></td>
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<tr>
<td>TAN1312-d08D</td>
<td>Foraminifera</td>
<td>Four specimens of Globigerinatheka index and a single Acarinina collactea were found. If the Acarinina collactea is contamination or reworked then G. index with Globigerina brevis (quite common), indicates an age of 36-34 Ma. However, there are a number of benthics that have younger age ranges: Discorotalia tenuissima, Bolivina lapisus, Bolivina anastomosa, Buliminella missilis, and Victoriella conoidea. The best interpretation is that most of the sample has a Late Eocene or Early Oligocene age of 36–30 Ma, with a component of reworked Eocene material of age 43–38 Ma. The benthic fauna is dominated by shallow shelf forms such as Amphistegina sp, Lepidocyclina sp., Mississippina concentrica, Wadella globiformis, Victoriella conoidea, Discorotalia tenuissima, Cribrorotalia sp., Elphidium charlottense and others.</td>
</tr>
<tr>
<td>SE35170/f0003</td>
<td></td>
<td></td>
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<tr>
<td>P83175</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TAN1312-d19B</td>
<td>Foraminifera</td>
<td>Four specimens of Globigerinatheka index and a single Acarinina collactea were found. If the Acarinina collactea is contamination or reworked then G. index with Globigerina brevis (quite common), indicates an age of 36-34 Ma. However, there are a number of benthics that have younger age ranges: Discorotalia tenuissima, Bolivina lapisus, Bolivina anastomosa, Buliminella missilis, and Victoriella conoidea. The best interpretation is that most of the sample has a Late Eocene or Early Oligocene age of 36–30 Ma, with a component of reworked Eocene material of age 43–38 Ma. The benthic fauna is dominated by shallow shelf forms such as Amphistegina sp, Lepidocyclina sp., Mississippina concentrica, Wadella globiformis, Victoriella conoidea, Discorotalia tenuissima, Cribrorotalia sp., Elphidium charlottense and others.</td>
</tr>
<tr>
<td>SE34169/f0001</td>
<td></td>
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<td>P83197</td>
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<tr>
<td>TAN1312-d27H</td>
<td>Dinoflagellates</td>
<td>Taxa identified: Cerodinium dartmoorum, Cordosphaeridium fibrospinosum, Cordosphaeridium inodes, Hystrichosphaeridium tubiferum, Impagidinium cavea, Palaeoperidinium pyrophorum (very common), Senegalinion dlwynense, Trithyrodinium evitti (one specimen; questionable identification), and several unknown taxa. This indicates an Early Paleocene age of 65-61 Ma and fully marine conditions distal from land.</td>
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<tr>
<td>SE34165/f0002</td>
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<tr>
<td>L27764</td>
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</tbody>
</table>
Figure S1. Location map of seismic-reflection lines and boreholes (circles; DSDP site numbers shown) used in this study. Crosses show where significant dredge samples were collected on the TAN1312 voyage (only representative results presented here). Bold lines show sites described in this text. 1000 m isobath interval (blue lines).
**Site 1: Reinga Basin**

Reinga Basin is geologically similar and semi-continuous with Taranaki and Northland basins of western New Zealand (Isaac et al., 1994; King and Thrasher, 1996). The first high-quality seismic-reflection data from Reinga Basin were collected in 2009 by the petroleum industry and New Zealand government, and these data are now open-file (available from New Zealand Petroleum and Minerals). We interpreted these data across Reinga Basin (Bache et al., 2012), and dredged rock samples during the TAN1312 voyage from key locations identified on the basis of those interpretations (Table S1) (Bache et al., 2014c; Browne et al., 2016).

Cretaceous rift faults were reactivated during Cenozoic time in western Reinga Basin as reverse faults and fault-propagation folds (Bache et al., 2012). Rock samples dredged from several locations indicate that the uppermost folded sediments (seismic units 2a and 1b), which are inferred to have been deposited before or during the early stages of deformation, have ages in the range 53-43 Ma. Seismic unit 1b is shown by benthic foraminifera to have been deposited in relatively shallow water (<150-400 m, d6E). On the crests of some deformed ridges, folded strata are truncated by erosion surfaces and overlain by undeformed limestones e.g. dredge TAN1312-d19, which was deposited in shallow water (<100 m) and has age 36-30 Ma (Fig. S1). Flat erosion surfaces indicate: (1) uplift and subareal or wave erosion; followed by (2) subsidence and limestone deposition (Bache et al., 2014b).

![Figure S2](image-url)  
*Figure S2.* (A) Examples of TAN1312 dredge sites that sampled seismic unit 1b (shaded), in the context of high-quality seismic-reflection data (B). These specific dredge samples yielded biostratigraphic ages (foraminifera, radiolaria) that indicate a stratigraphic age of 53-48 Ma.
Site 2: Southern New Caledonia Trough

Folding was previously identified in the southern New Caledonia Trough on seismic lines 114-02 and 114-04, and ties to petroleum wells in Taranaki Basin used to infer folding during the period Middle Eocene to Oligocene (49-23 Ma) (Sutherland et al., 2010). We dredged the first rock samples from folded strata within the basin (seismic unit 2a), 400-800 m stratigraphic thickness below the top of the folded unit (Fig. S3). Some of these samples contained a rich dinoflagellate assemblage and yielded an Early Paleocene age (65-61 Ma), consistent with our previous interpretation.

Figure S3. (A) Southern New Caledonia Trough line drawing of part of seismic line 114-04. (B) Dredge TAN1312-d27 contained Early Paleocene fossils (65-61 Ma). (C) Cenozoic folding tied to Taranaki basin boreholes, Waka Nui-1, and DSDP-206.
Site 3: Southern Lord Howe Rise

We collected new high-resolution seismic-reflection data in the vicinity of DSDP sites 207 and 592 during the TAN1409 voyage (Figs. S1 and S4). Our objective was to tie and understand the stratigraphy near these significant boreholes. We discovered that Eocene reverse faulting and volcanic activity is evident in proximity to these sites. The syn-tectonic unit 1b can be tied back to DSDP 207 (Burns and Andrews, 1973; Burns et al., 1973) and DSDP 592 (Kennett et al., 1986). At DSDP 207, the top of unit 2a has a Middle Eocene age (49-37 Ma). The upper part of unit 1b and lowest part of unit 1a are tied to Late Eocene and Early Oligocene strata (37-28 Ma) in DSDP 592.

Figure S4. New seismic-reflection data from the southern Lord Howe Rise, showing folding of seismic unit 2a and basal 1b.
Site 4: Tasman Sea abyssal plain

The TAN1409 voyage collected eight high-resolution seismic-reflection lines across deformed ocean crust in the Tasman Sea that was identified during our compilation and interpretation phase.

Three seismic units are identified (Fig. S5A). Units TASS-U2 and TASS-U3 are conspicuously folded, indicating a convergent tectonic event. Dips on the steepest limbs of folds are in the range 10-20°. The upper part of unit TASS-U2 thickens away from the crests of anticlines in some places, suggesting that it may be partly syn-tectonic. Unit TASS-U1 drapes topography that was created by the folds, and its thickness is positively correlated with depressions created by synclines. Regions with an anomalously thin unit TASS-U1 (Fig. S5B) typically have an anomalously thick unit TASS-U3 (Fig. S5C), leading to the conclusion that normal faults that were active during deposition of sediments imaged as TASS-U3, were reactivated as reverse faults during or after deposition of TASS-U2. The strongly-preferred WNW-ESE orientations to depocentres imaged within TASS-U3 likely reflect primary abyssal hill fabric. This interpretation is consistent with previous interpretations of regional magnetic and gravity data (Gaina et al., 1998), and the alignment of magnetic anomalies that we recorded.

The age of sediments that are imaged is constrained by magnetic interpretations of the Tasman Sea (Gaina et al., 1998), and results from DSDP 283 (Kennett et al., 1974), which is located on conjugate ocean crust in the western Tasman Sea. Borehole DSDP 283 contained only 13 m of Oligocene-Quaternary sediment; but 575 m of Paleocene to Eocene abyssal sediments (Fig. S6). The thickness of sediments at DSDP 283 (588 m) is comparable to that imaged at the TASS site. The mean sonic velocity at DSDP 283 was 1680 m s⁻¹, and the total thickness of sediments at the TASS site is in the range 400-850 m. Of particular significance at DSDP 283 is a distinct Late Eocene (37-34 Ma) sediment unit that is diatom-rich, about 160 m thick, and contained an indurated nannofossil-rich layer towards its base. This appears to correlate well with seismic unit TASS-U2, which is 130-280 ms thick and has a strong reflector at its base.

Figure S5. Abyssal hill normal faults on the Tasman Sea abyssal plain were reactivated as reverse faults. (A) Seismic section TAN1409-02 is used to identify three seismic units;
(B) thickness in milliseconds two-way travel time of seismic unit TASS-U1; and (C) thickness in milliseconds two-way travel time of seismic unit TASS-U3.
Figure S6. Summary stratigraphy from DSDP 283 (Kennett et al., 1974), with correlations to TASS seismic units.

Site 5: Gippsland Basin, Australia
The Gippsland Basin of southeast Australia is a productive petroleum province with many boreholes and high-quality seismic-reflection data. The basin formed during Cretaceous time and experienced compressional inversion of Cretaceous rift faults during Cenozoic time. Eocene inversion events created many structures that now host petroleum. The onset of folding and reverse faulting of the Latrobe Group occurred during the Middle Malvacipollis diversus pollen zone (51.5-53.5 Ma). This initial phase of inversion produced the Marlin Unconformity and was completed by the end of the Early Eocene (49 Ma) (Johnstone et al., 2001). A second more intense phase of Eocene basin inversion occurred during the period 44-40 Ma (Middle Eocene) and was responsible for the Top Latrobe Unconformity that is the cap for many petroleum accumulations (Holdgate et al., 2003). There is also evidence for minor compressional inversion since the Middle Miocene (16-0 Ma) (Swierczek et al., 2013).
Site 6: New Caledonia

Continental basement rocks in New Caledonia are similar to those found in New Zealand. They formed in the forearc of the Mesozoic Gondwana subduction margin and detrital zircon studies show that subduction ceased at c. 95 Ma (Adams et al., 2009; Cluzel et al., 2010; Mortimer, 2004). The Mesozoic Gondwana arc is located west of New Caledonia, based on magnetic anomalies and rock samples dredged from the flank of the New Caledonia Trough (Mortimer et al., 1998; Mortimer et al., 1997; Sutherland, 1999), so subduction was west-dipping beneath the Gondwana continent.

Late Cretaceous and Paleocene sedimentary rocks (84-56 Ma) indicate passive subsidence into deep water bathyal environments, and then Early Eocene (56-48 Ma) turbidites signal the onset of a new phase of tectonic activity (Maurizot, 2011). A thick sequence of Eocene sediment gravity flows were deposited as extensive deformation occurred, culminating in ultramafic-derived sediments in the Late Eocene (38-34 Ma) (Aitchison et al., 1995). High-pressure low-temperature metamorphism (blueschist facies) associated with this new phase of subduction-related tectonics is evident in northeastern New Caledonia, where thermochronology reveals peak metamorphism at 44 Ma and un-roofing was nearly complete by 34 Ma (Baldwin et al., 2007).

Eocene deformation and metamorphism in New Caledonia was accompanied by southwestward-directed emplacement of the Poya Terrane along low-angle faults (Cluzel et al., 2001). The Poya Terrane is composed of oceanic basalts and associated deep water sediments that formed near a spreading ridge that was active from the latest Cretaceous to the Upper Paleocene (84-56 Ma) (Eissen et al., 1998). Structurally above this mafic terrane is a peridotite nappe that caps the highest topography of the island (Cluzel et al., 2001; Paris, 1981). Amphibolite nappes dated at 56 Ma are found at the base of the Peridotite Nappe, and mafic and felsic dykes dated at 53 Ma are found within the Peridotite Nappe. The inferred pressure-temperature conditions of recrystallization suggest that the amphibolites formed by anomalous faulting activity near a spreading ridge (Cluzel et al., 2012). The dykes and amphibolites have been interpreted as the earliest pre-cursor signs of a new phase of subduction (Cluzel et al., 2006), consistent with the sedimentary evidence (Aitchison et al., 1995), though exact local details of vergence and geometrical evolution of the new subduction system remain hotly debated.

In summary, there is strong evidence for a long history of Paleozoic and Mesozoic subduction in New Caledonia and New Zealand, and this phase of Gondwana subduction ended at c. 95 Ma (Cluzel et al., 2010). There is conclusive evidence for seafloor spreading during the interval 83-53 Ma both northeast (Poya Terrane) (Eissen et al., 1998) and southwest (Tasman Sea) (Gaina et al., 1998) of New Caledonia. There is no plate kinematic requirement for a convergent plate boundary during the same interval (Matthews et al., 2015), and there is no conclusive direct rock evidence for subduction, but it has been widely speculated that a subduction zone may also have been active at this time (Cluzel et al., 2001; Cluzel et al., 2012; Cluzel et al., 2006; Crawford et al., 2004; Whattam et al., 2008). Eocene subduction initiation events, starting at c. 56-53 Ma re-occupied a zone close to the abandoned Gondwana subduction zone, but geometrical details of its early evolution remain debated. Inception may have re-activated the west-dipping Gondwana subduction interface (Gurnis et al., 2004) or may have formed through initiation of an east-dipping zone (Aitchison et al., 1995; Cluzel et al., 2001). For the purposes of our work the initial vergence of subduction is relevant to our understanding, but not our conclusion. It is clear that a major tectonic phase started in New Caledonia at the time we
are considering, and the phase involved creation of a new subduction zone that ultimately evolved into the Tonga-Kermadec system. There is general agreement that subduction initiation started in New Caledonia at c. 53 Ma and evolved through a phase with peak high pressure-low temperature metamorphism at 44 Ma and tectonics were complete by 34 Ma. This corresponds in time with the phase of widespread intra-plate convergence that we observe farther south.

References


Sutherland et al.: Subduction initiation


Sutherland, R., 1999, Basement geology and tectonic development of the greater New Zealand region; an interpretation from regional magnetic data: Tectonophysics, v. 308, no. 3, p. 341-362.