Illuminating a Contorted Slab with a Complex Intraslab Rupture Evolution during the 2021 M_W 7.3 East Cape, New Zealand Earthquake

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Key Points:

- A moment magnitude 7.3 2021 East Cape, New Zealand intraslab earthquake comprised multiple rupture episodes with different faulting styles
- The complex rupture comprises components of shallow trench-normal extension and unexpectedly, deep trench-parallel compression in slab
- The trench-parallel compression likely reflects stress rotation at a buoyancy contrast that drives slab contortion

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Abstract

The state-of-stress within subducting oceanic plates controls rupture processes of deep intraslab earthquakes. However, little is known about how the large-scale plate geometry and the stress regime relate to the physical nature of the deep-intraslab earthquakes. Here we find, by using globally and locally observed seismic records, that the moment magnitude 7.3 2021 East Cape, New Zealand earthquake was driven by a combination of shallow trench-normal extension and unexpectedly, deep trench-parallel compression. We find multiple rupture episodes comprising a mixture of reverse, strike-slip, and normal faulting. Reverse faulting due to the trench-parallel compression is unexpected given the apparent subduction direction, so we require a differential-buoyancy driven stress rotation which contorts the slab near the edge of the Hikurangi plateau. Our finding highlights that buoyant features in subducting plates may cause diverse rupture behavior of intraslab earthquakes due to the resulting heterogeneous stress state within slabs.

Plain Language Summary

A key type of tectonic boundary is where two plates collide with one sinking into the mantle beneath. These subduction zones generate the world's largest earthquakes. Quantifying stress in the subducting plate ("slab") is important because slabs drive the global plate-tectonic system, and large earthquakes can occur within them. These earthquakes can cause strong shaking, and, when occurring near cities, can lead to damage. However, mapping stress is challenging as we cannot directly "see" inside deep slabs. Our best indications of slab stress come from earthquakes themselves. A magnitude 7.3 earthquake north of New Zealand in 2021 generated a distinct pattern of seismic waveforms at seismometers installed worldwide. We used these seismic records to probe the earthquake, providing a new view of stress in subduction zones. We found the earthquake generated both vertical and horizontal motions along faults, driven by compressional and extensional stresses deep within the slab. The compressional part is oriented 90 degrees from the subduction direction, which is opposite to the usual compression in subduction zones, and has not been observed before. This unusual direction of compression can be explained by subduction of a thickened and buoyant part of the Pacific plate, known as the Hikurangi plateau.

1 Introduction

Complex fault configurations and heterogeneous fault conditions, i.e., stress and strength states, govern earthquake rupture development and propagation (Avouac et al., 2014; Floyd et al., 2016; Elliott et al., 2016; Hamling et al., 2017). Such relations can be inferred from the fault geometry and long-term geodetic observations for shallow active faults (Simons et al., 2002; Williams et al., 2013; Elliott et al., 2016; Arai et al., 2016; Hamling et al., 2017; Hayes et al., 2018; Sippl et al., 2018). However, for intraslab earthquakes occurring below ∼50 km depth, these physical controlling factors are difficult to assess because of challenges to map structure at such depths, and the general lack of seismicity there (Wiens, 2001; Ranero et al., 2005; Page et al., 2016; Dascher-Cousineau et al., 2020; Gomberg & Bodin, 2021). In particular, the internal stress state and its extensional-compression transition regime are often elusive in subducted slabs, although they directly impact intraslab earthquake occurrence and their faulting styles (Astiz et al., 1988; Ammon et al., 2008; Craig et al., 2014; Romeo & Álvarez-Gómez, 2018; Sandiford et al., 2019, 2020; Ye et al., 2021). Thus, imaging the rupture processes of large, deep intraslab earthquakes offers a rare window to investigate the slab configuration, and to understand fault interaction and rupture evolution of these earthquakes, illuminating heterogeneous stress fields.

An intraslab moment magnitude (M_W) 7.3 earthquake occurred offshore the East Cape in northern New Zealand on 4th March 2021, which was followed ∼4 hours later by a series of the M_W 7.4 and M_W 8.1 earthquakes in the Kermadecs (∼900 km to the north) (GeoNet, 2021). The M_W 7.3 2021 East Cape earthquake, which is the focus of this paper, may offer insight into the regional slab geometry because of its location and complex rupture process. The 2021 East Cape earthquake locates at the boundary between the southern end of Kermadec trench and the northern end of Hikurangi margin, where the Pacific plate subducts beneath the Australian plate and its convergence decreases and progressively rotates to oblique motion toward the south (Fig. 1) (Collot et al., 1996, 2001; Lewis et al., 1998; Wallace et al., 2009). The reported centroid depth of the earthquake was ∼50 km (U.S. Geological Survey Earthquake Hazards Program, 2017; Duputel et al., 2012; Dziewonski et al., 1981; Ekström et al., 2012), and the focal mechanism indicates oblique-thrust motion, with the principal stress axis oriented towards the north-south direction (Fig. 1) (U.S. Geological Survey Earthquake Hazards Program, 2017; Duputel et al., 2012; Dziewonski et al., 1981; Ekström et al., 2012). This stress axis suggests the earthquake was not a simple shallow normal- or reverse-faulting event with the strike angle oriented parallel to the trench axis, as is typically seen in many subduction zones (Fig. 1) (U.S. Geological Survey Earthquake

Hazards Program, 2017; Duputel et al., 2012; Dziewonski et al., 1981; Ekström et al., 2012). However, the earthquake produced observable tsunami signals at tide gauges at the northern coast of New Zealand (GeoNet News, 2021), indicating seafloor deformation due to possible shallow slip. All these apparently inconsistent observations (GeoNet, 2021; GeoNet News, 2021) suggest a complex rupture process of the East Cape earthquake, possibly involving multiple faults at different depths.

Although the subduction-related deformation processes in the southern part of the Hikruangi subduction zone have received a lot of scientific attention (e.g., Wallace et al., 2009; Nishikawa et al., 2021), the northern segment of Hikurangi margin, where it transitions to the Tonga-Kermadec arc, is less well understood. In the East Cape region, sporadic deep seismicity (>80-km depth) contrasts with abundant shallow seismicity (<50-km depth) (Dziewonski et al., 1981; Ekström et al., 2012; GeoNet Moment Tensors, 2021; U.S. Geological Survey Earthquake Hazards Program, 2017; GeoNet, 2021). Most of the shallow earthquakes are normal faulting events within the top of the oceanic plate due to trench-normal extensional stress due to slab bending into the trench (Reyners & McGinty, 1999; Henrys et al., 2006; Bassett et al., 2010). With these shallow earthquakes, the plate interface and the surrounding materials have been imaged down to ~20 km depth (Davey et al., 1997; Bell et al., 2010; Bassett et al., 2010, 2016), but the lithospheric structure of the deep slab is poorly resolved. The apparent complex rupture process of the 2021 East Cape earthquake offers a unique opportunity to image the stress regime associated with the deeper subduction process.

Here we show that the rupture process of the 2021 East Cape earthquake involves multiple rupture episodes with a mixture of reverse, strike-slip, and normal faulting mechanisms. These episodes ruptured multiple faults through the subducted oceanic lithosphere at various depths. The earthquake initiated at 70 km depth with an unexpected trench-parallel compressional reverse faulting mechanism, and followed by a slip episode at 30 km depth, which is likely governed by more usual slab-bending trench-normal down-dip extensional stresses. Such a rupture process reflects a heterogeneous stress regime within the subducted slab, in response to a possible geometric change of the slab in depth due to either the subduction of a seamount associated with the Ruatoria debris slide (Lewis et al., 1998; Collot et al., 2001; Lewis et al., 2004), or a sharp change in slab buoyancy at the northern end of the subducting Hikurangi oceanic plateau.

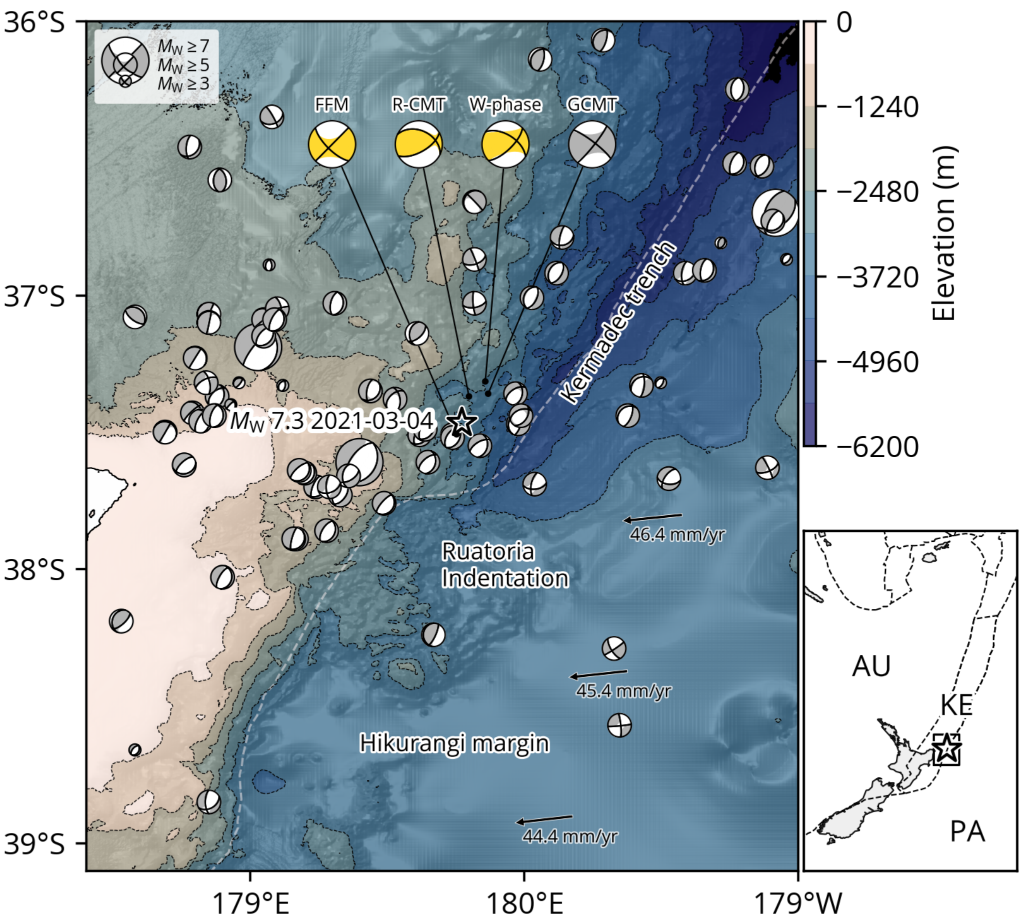

Figure 1. Seismo-tectonic overview of the study region in the East Cape, New Zealand. The star shows the relocated hypocenter of the M_W 7.3 2021 East Cape earthquake. Gray beach balls are the lower-hemisphere stereographic projection of the moment tensor solutions before the 2021 East Cape earthquake (Dziewonski et al., 1981; Ekström et al., 2012). Yellow beach balls are the moment tensor solutions for the 2021 East Cape earthquake obtained by this study (FFM; Finite-fault model, R-CMT; regional centroid moment tensor, W-phase; W-phase moment tensor). Background contours display the bathymetry (Mitchell et al., 2012). The arrows show the relative plate motions with the convergence rate of the Pacific plate (PA) towards the fixed Australian plate (AU) (DeMets et al., 2010). The dashed line gives the approximate location of the subduction trench (e.g., Bassett et al., 2010). The right map shows the wider setting of the study region. The rectangle shows the area of the left map. The star marks the epicenter. The dashed lines are the plate boundaries (Bird, 2003) between the Pacific (PA), the Australian (AU) and the Kermadec (KE) plates.

2 Hypocenter, aftershock relocation, and initial source estimates

We first determined the hypocenter of the East Cape earthquake by non-linear inversion of P- and S-wave arrival times at regional distances using a 1D velocity model appropriate for the East Cape region (Text S1; Fig. S1). Our relocated epicenter lies along the trench axis, and is within 10 km of the GeoNet solution (GeoNet, 2021), and ∼35 km ENE of the U.S. Geological Survey National Earthquake Information Center (USGS-NEIC) solution (U.S. Geological Survey Earthquake Hazards Program, 2017) which is consistent with the USGS-NEIC epicenters being systematically shifted to the down-dip direction in subduction zones (e.g., Ye et al., 2017). Our maximum-likelihood hypocenter depth is 72 km. Although this hypocenter depth may be thought to be inherently uncertain due to the sub-optimal station coverage, it provides an initial hypothesis for testing our results of the more complex rupture configuration later. If we instead fix our hypocentral depth at the fixed GeoNet/USGS estimates of 10–12 km (GeoNet, 2021; U.S. Geological Survey Earthquake Hazards Program, 2017), the root-mean-square residual of arrival times at the closest stations (<200 km) increases by 0.3 s, suggesting that a shallow depth is less compatible with the observations. However, no depth phases were reported in the International Seismological Centre Bulletin for this earthquake (International Seismological Centre, 2021), presumably due to interference with the long source-time function.

Next, we used the `COMPLOC` package (Lin & Shearer, 2005, 2006) to relocate earthquakes near the mainshock hypocenter. The algorithm uses the source-specific station term (SSST) method to relocate the earthquakes, which can greatly improve the relative locations of nearby events because of implementing empirical corrections to neutralize the 3D velocity effects (Richards-Dinger & Shearer, 2000; Lin & Shearer, 2005). We focus on events occurring from January 1, 2021 to May 1, 2021 near the source region of the 2021 East Cape earthquake as there were few events in the region prior to the earthquake. These events are relocated using both P- and S-wave phase picks from GeoNet (2021) and a 1D velocity profile taken from the NZW2.2 model (Eberhart-Phillips et al., 2010, 2020). We selected the L1-norm as the traveltime-residual misfit measure, and obtained locations for 3484 events (Fig. S2). We find that the distribution of aftershocks from one week after the mainshock (1556 events) is spread across the whole lithosphere, from the seafloor down to ∼100 km in depth. In particular, the deep aftershocks corroborate our deep mainshock hypocenter hypothesis, and the aftershock distribution indicates a possible multi-fault rupture process of the East Cape earthquake.

Using a Bayesian bootstrapping centroid-moment tensor (CMT) inversion of low-frequency (2.0–8.5 mHz) teleseismic waveforms for a single-point source (Text S2), we find a mean centroid depth of 53 km, with a centroid position shifted 18 km NNE of the epicenter, and time shift from the origin time of +5 s (Fig. S3). However, the CMT solution has a large non-double couple component (DC=15%). Such a low DC component is likely caused by geometric complexities of the earthquake that may involve multiple faults within the subducted Pacific plate near the Hikurangi trench.

Finally, to test the hypothesised rupture complexity, we investigated the rupture process of the earthquake with a multi-point centroid moment tensor (R-CMT) inversion method using regional seismic waveforms (Text S3; Figs. S4 to S6). The approach can resolve the first-order features of a complex rupture with few assumptions. Due to the low-velocity accretionary wedge, the later part of the <25 s period surface waves on the horizontal components at stations within ∼400 km epicentral distance are poorly fit (Figs. S5 and S6) due to basin resonance effects (Kaneko et al., 2019). We find that the East Cape event can be best explained by two sub-events, with the largest sub-event (M_W ∼7.3) at 50–70 km depth occurring 8–10 s after the origin time, and the second sub-event at 7–12 km depth and 6–8 s after the first sub-event. The second sub-event significantly increases waveform variance reduction by 16–23%. The first sub-event has an oblique-reverse mechanism. Given the inclination of the deep aftershocks near the hypocenter (Fig. S2), the fault plane is possibly dipping north and striking along the east-west faulting plane. Conversely, the second sub-event has a normal faulting mechanism. The shallow aftershock lineation (10–30 km depth) dips to the west (Fig. S2), which suggests the fault plane is likely oriented along the trench axis. Overall, our R-CMT solution corroborates a complex rupture scenario involving at least two sub-events separated by ∼40 km in depth: one in the top of the Pacific plate, the other deep within the slab.

3 Intermittent complex multiple rupture episodes with various focal mechanisms

To better understand the rupture development, we applied a finite-fault potency-density inversion method (Shimizu et al., 2020) to estimate the slip evolution of the 2021 East Cape earthquake (Text S4). The method can flexibly accommodate multiple faults with different geometries rupturing during the same event, which are inferred from the spatiotemporal distribution of five-basis double-couple components of the potency-density tensors (Kikuchi & Kanamori, 1991; Ampuero & Dahlen, 2005). The method has proven effective at resolving complex earthquake ruptures in a variety of tectonic settings (Shimizu et al., 2020, 2021; Okuwaki et al., 2020; Tadapan-

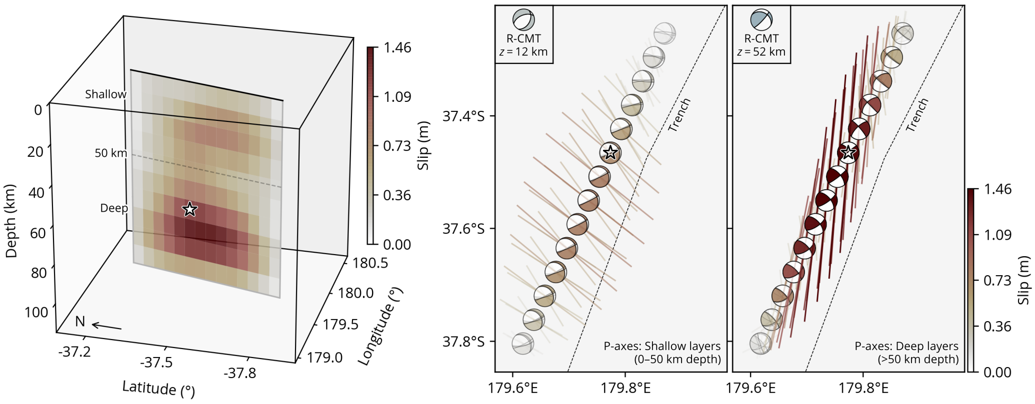

Figure 2. Static slip distribution. The left panel shows the total slip distribution in a 3D view, viewed from the south-west. The star represents our hypocenter. The black line shows the top of the model fault. The right panels show the map view of the slip distribution from shallow (<50 km) and deep depths (≥50 km), with beach balls representing double-couple components (Fig. S7), and corresponding P-axis azimuths (bars scaled by slip). The P-axis azimuth is extracted from the resultant double-couple solution for each sub-fault, which is represented by a lower-hemisphere stereographic projection. We show the beach balls from the slip patch corresponding to the fault element with the maximum slip within each given depth range. The inset shows the corresponding R-CMT solutions annotated with their depths (z). The dashed line is the subduction trench (Bird, 2003).

sawut et al., 2021; Yamashita et al., 2021). In practice, we parametrize a 2D vertical model domain along a 200° strike extending from 7- to 107-km depth with a total of 140 source elements (sub-faults) (Fig. 2). This parameterization is guided by the observed cluster of the near-trench-parallel aftershocks (Fig. S2). In the 2D model domain, we solve the fault-normal and shear-slip vectors at each source element, which are independent of the model domain geometry. In other words, we solve distributed sources in the model domain that may have any types of faulting mechanism required by the data. The model domain therefore allows multiple faulting episodes of the earthquake and does not necessarily indicate a single fault plane cutting through the lithosphere a continuous rupture. Our preferred slip model suggests that the earthquake initiated at 72 km depth (Fig. S12) corroborating the relocated hypocenter and the R-CMT solution.

Our preferred finite-fault model suggests that most slip occurred at 55 to 100 km depth and ∼15 km south of the hypocenter, releasing 69% of the total moment (Fig. 2). Another patch of slip is observed at 20–40 km depth, much shallower than the hypocentral depth and comprising 31% of the total moment. The deeper slip is dominated by an oblique strike-slip faulting mechanism. The shallow slip involves a mixture of normal and strike-slip faulting mechanisms. The finite-fault model leads to a moment estimate of 1.7×10^{20} Nm (M_W 7.4).

The rupture process of the East Cape earthquake involved at least four distinct episodes (E1 to E4) with the deep- and shallow-slips corresponding to different faulting types. The earthquake initiated as a reverse faulting with a strike-slip component for the first 5 s (E1, Fig. 3). The rupture then propagated towards the south at 60–100 km depth, releasing 20% of the total moment and lasting for about 5 s (E2, Fig. 3). This episode was dominated by thrust faulting. The third episode (E3) simultaneously ruptured several fault patches from 10 to 15 s, including a shallow patch at ∼25 km depth and a deep patch ∼70 km depth (Fig. 3). The shallow part of E3 ruptured with a normal faulting mechanism, while the deep patch of E3 had a strike-slip mechanism. The last major episode (E4) ruptured a fault patch beneath the hypocenter for about 5 s with a dominant strike slip focal mechanism (Fig. 3). The remaining 26% of the total moment was released by slips at both shallow and deep regions, and the earthquake lasted for about ∼30 s.

The four rupture episodes are compact in size and are spatially distinct from each other. Given the varying focal mechanisms, the chaotic episodes likely do not result from the same continuous rupture front, but more likely represent segmented slip on different faults that may have interacted with, and triggered, each other.

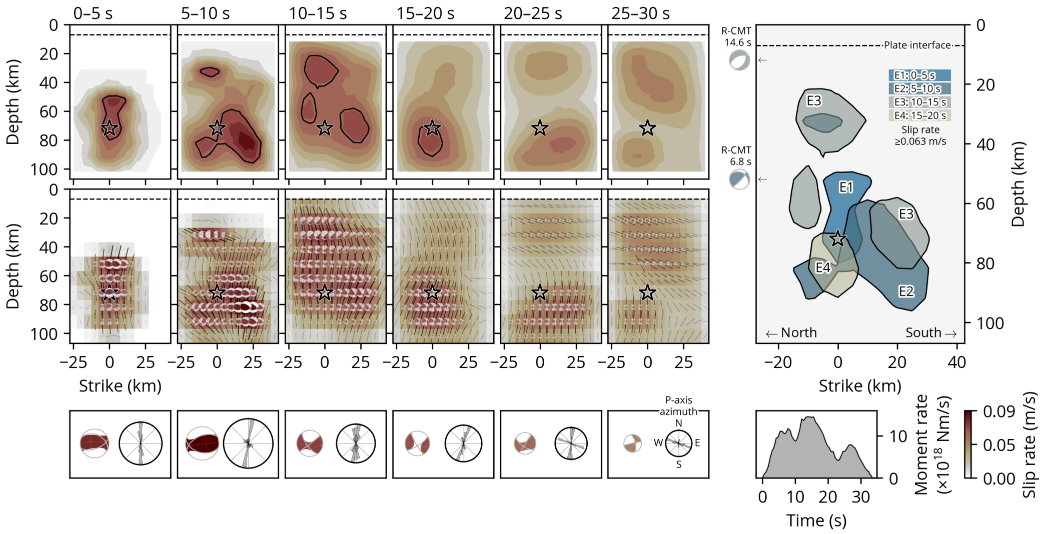

Figure 3. Slip evolution. The left panels show the cross sections of the spatio-temporal distribution of slip rate and the resultant moment-rate tensor solution, given in 5 s long windows. The star represents the hypocenter. The dashed line is the top of the subducting plate (Bassett et al., 2010). The black contour highlights faster slip rates (≥0.063 m/s; ≥70% of maximum slip rate). The centroid moment tensor for each time window is shown at the bottom, together with the rose diagram of P-axis azimuths weighted by slip rate. All the beach balls of the moment-tensor solution are represented as a lower-hemisphere stereographic projection, not rotated according to the model geometry, but in map view. The right panel summarizes the slip-rate evolution. The color for each episode (E1 to E4) corresponds to the time window. The minor slip-rate events within the final two time windows (20–30 s) are not slipping fast enough to plot a contour on the right panel. R-CMT solutions are also shown at the corresponding depths, with their time shift given relative to the hypocentral time. The right-bottom inset is the total moment-rate function from the finite-fault model.

4 Intraslab stress rotation in depth

The source process of the 2021 East Cape earthquake is characterized by spatiotemporally disconnected, multiple episodes rupturing from deep to shallow within the subducted slab. For the shallow slip episode, its focal mechanism shows a mixture of the normal faulting with a strike-slip component. The general trend of the aftershock distribution (Fig. S2) suggests that the fault plane striking toward the northeast-southwest direction likely ruptured during the later phase of the earthquake. It is noteworthy that some aftershocks (U.S. Geological Survey Earthquake Hazards Program, 2017; Dziewonski et al., 1981; Ekström et al., 2012; GeoNet Moment Tensors, 2021) share similar focal mechanisms to the shallow rupture episode (Fig. S8). Given the near-trench location of the East Cape earthquake, there is some ambiguity regarding the exact faulting configuration. However, the aftershock distribution indicates that the shallow slip episode likely ruptured a normal fault within the downgoing plate. Additionally, in the absence of clear shallow slip with a reverse-faulting mechanism, this normal faulting episode likely caused the observed tsunami.

The varying focal-mechanisms of the four slip episodes (E1–E4) show the compressional stress orientation (the P-axis orientation) of the East Cape earthquake rotated from the northwest-southeast direction to the north-south direction with a gap in slip and approximate stress transition depth at ∼50 km (Figs. 2 and 3). The normal faulting of the shallow slip episodes striking toward the northeast-southwest direction agrees well with the extensional stress in the upper part of the subducted plate due to the expected plate bending and pulling process (e.g., Astiz et al., 1988; Ammon et al., 2008; Craig et al., 2014; Romeo & Álvarez-Gómez, 2018; Sandiford et al., 2020). Such a bending process seems to have caused most of the background seismicity in this region, which has predominant normal faulting mechanisms (Fig. 1; Reyners & McGinty, 1999; Bassett et al., 2010). If the deep slip at 50–100-km depth during the East Cape earthquake was driven by the same bending-related process, we would expect a trench-normal P-axis orientation, which is typical for similar events at other subduction zones, where deep trench-parallel reverse faulting is observed (e.g., Okada & Hasegawa, 2003; Ohta et al., 2011; Ye et al., 2012; Todd & Lay, 2013; Ye et al., 2021). However, the deep slip patches of the East Cape earthquake (E1 and E2, and R-CMT Sub-event 1) have oblique-thrusting mechanisms, resulting in a trench-parallel compression. This perplexing P-axis orientation indicates an additional regional factor that may have modulated the rupture process of the East Cape earthquake.

The interactivity between various faulting episodes is a puzzling part of the East Cape earthquake. Subduction zone earthquakes may involve multiple disconnected subevents with different faulting types that can trigger and interact with each other (Ammon et al., 2008; Lay et al., 2013; Hicks & Rietbrock, 2015; Lay et al., 2020). For the East Cape earthquake, our preferred finite-fault model does not show a continuous rupturing path from the deep to shallow episodes (Figs. 2 and 3). The shallow rupture E3 is separated by ∼40 km from the deep episodes and started ∼5 s later (Fig. 3), suggesting an apparent rupture speed of ∼8 km/s if the rupture was continuous. Such a rupture speed would be close to the local *P*-wave speed (Table S1), which is unlikely. More likely, slip episodes E1 and E2 triggered the following shallow episode E3 due to either the static and/or dynamic stress change from the initial deep rupture. Additionally, the aftershock distribution (Fig. S2) shows a gap at ∼50-km depth in-between the deep and shallow rupture episodes, which may reflect the neutral stress transition between the shallow extension and deep compression. A stress transition or strength contrast within the slab can work as an inhomogeneous barrier (Das & Aki, 1977; Aki, 1979) to smooth propagation from deep to shallow rupture during the East Cape earthquake. Therefore, the rupture evolution of the earthquake may have developed as discontinuous jumps by means of stress triggering (Miyazawa & Mori, 2005; Sleep & Ma, 2008; Fischer, Sammis, et al., 2008; Fischer, Peng, & Sammis, 2008) across the apparent stress/strength barrier between the deep and shallow rupture areas.

Large intraplate earthquakes within the downgoing plate in subduction zones are typically caused either by the down-dip bending and unbending of the slab (e.g., Astiz et al., 1988; Craig et al., 2014; Sandiford et al., 2020), the reactivation of major oceanic fabrics, including fracture zones (e.g., Abercrombie et al., 2003; Meng et al., 2012; Yue et al., 2012), or the tearing of the slab (e.g., Tanioka et al., 1995). However, the orientation and rupture complexity of the 2021 East Cape event deviates from these typical events. Two events with apparently similar deep trench-parallel compression in the slab include 2003 M_W 7.9 Enggano and 2009 M_W 7.6 Padang earthquakes, offshore Sumatra (Abercrombie et al., 2003; Wiseman et al., 2012). However, these events likely ruptured pre-existing fabrics in the downgoing plate (Abercrombie et al., 2003), such as fracture zones (Wiseman et al., 2012). Both earthquakes potentially represent the continuation of the diffuse deformation within the Wharton basin, and both consistently ruptured orthogonal fabrics toward the top of the downgoing plate both updip and downdip from the trench, where highly oblique convergence inherently causes a rotated state of the stress in the slab. In contrast, the 2021 East Cape earthquake, which occurred deeper beneath the top of the slab, does not align with the expected oceanic fabric, and is not obviously part of a wider, plate-scale, deformation field, where there is no obvious oblique convergence nor are fracture zones of an orientation consistent with the observed mechanisms subducted (Fig. 1). Instead, the rupture processes may represent a unique case, highlighting a different type of stress transition within the subducted slab.

5 A contorted slab structure due to slab buoyancy variations?

A key question is why does this part of the Hikurangi subduction zone exhibit an atypical stress regime, as manifested in the rupture process of the 2021 East Cape earthquake? Slab models of this region (Hayes, 2018; Hayes et al., 2018; Williams et al., 2013) show a homogeneous planar structure (Fig. S9) which would be expected to lead to a trench-normal compression in the deeper part of the slab. However, these slab models are poorly constrained near the East Cape earthquake, largely because of a lack of plate interface thrust earthquakes in the region (Fig. 1). The rupture process of the East Cape earthquake therefore potentially offers new insight into the local slab structure.

One possible explanation is that the slab surface warps downward north of the hypocenter, forming a depression at the plate interface (Fig. 4). The warping is likely a response to the buoyancy gradients in the subducting plate, which allows the less buoyant parts of the slab to sink more rapidly than the buoyant parts. The internal stress field from such a slab topology would be complex, leading to strong 3-D stress rotations around the localized downwarp in a manner as shown in the 2021 East Cape earthquake (Fig. 2). One contribution to the buoyancy gradients might be the subduction of a large-scale seamount. About 30 km south-west from the epicenter, the Quaternary Ruatoria seamount was obliquely subducted at the margin (Lewis et al., 1998; Collot et al., 2001; Lewis et al., 2004), forming the characteristic bathymetry of the Ruatoria indentation (Fig. 1). The Ruatoria seamount could deflect and bend the slab, causing the intraslab stress state to rotate from trench-normal compression to trench-parallel compression across the hypocentral area. Numerical models of slab stress in the presence of subducted buoyant features in the oceanic plate support such a stress rotation and lateral spreading mechanism (e.g., Mason et al., 2010).

An alternative explanation may arise from the location of the East Cape earthquake with respect to the transition between the Kermadec trench and Hikurangi margin, marked by the edge of the Hikurangi plateau, which is represented by a clear bathymetric scarp running along its northern boundary (Davy & Collot, 2000). This transition from the subduction of normal oceanic lithosphere to the north, to the subduction of the thickened oceanic crust associated with the igneous Hikurangi plateau likely leads to a pronounced, short-wavelength flexural warping at the plateaus edge. The superposition of this N-S flexural stress field with the stress field related to the down-

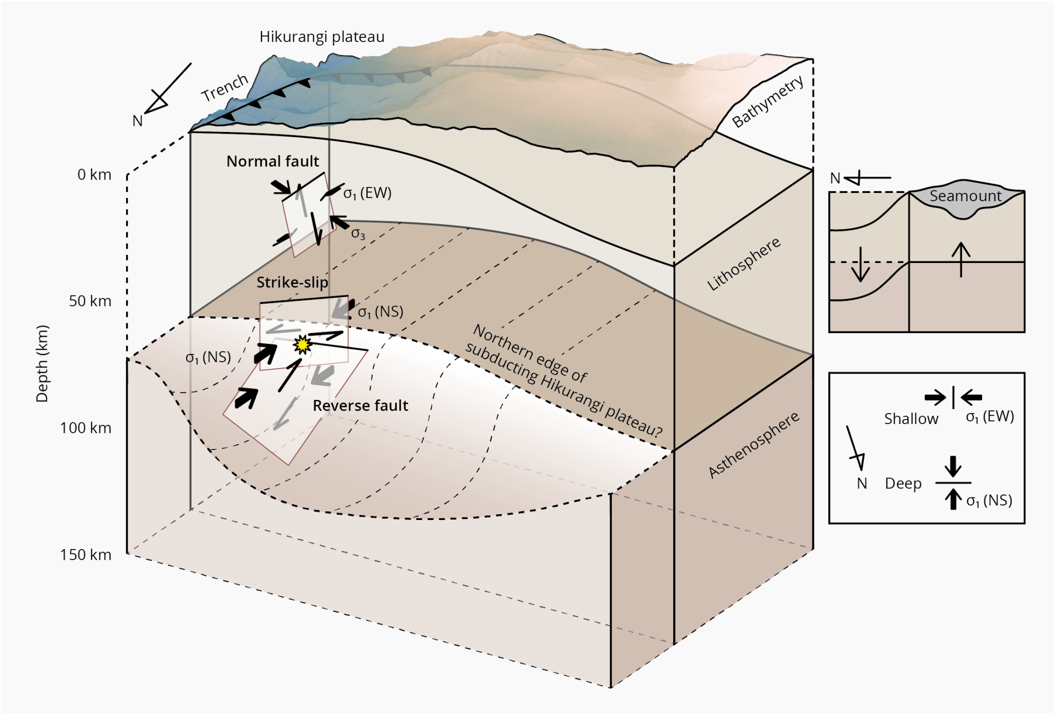

Figure 4. Schematic figure showing the inferred slab geometry, stress regimes and faulting styles based on our observations of the 2021 East Cape earthquake. The yellow marker shows the hypocenter. The arrow shows the stress orientations. The one-side arrow represents the fault motion. The bathymetry is from Mitchell et al. (2012) with its height being exaggerated ×15. The upper right panel is a cross-section with the arrows showing the relative force applied in the slab. The lower right panel shows the expected principal stress (σ_1) orientations in a top view.

dip bending would produce a complex pattern that varies at short-length scales within the subducted slab, and could impact on the rupture process seen in the compound East Cape earthquake.

Whilst there have been many studies on the impact of subducting buoyant features on subduction megathrust coupling and interface seismogenesis (e.g., Wang & Bilek, 2011; Nishikawa & Ide, 2014), there have been far fewer studies that have considered their impact on intraslab seismicity. The rarity of deep intraslab earthquakes in the northern Hikurangi subduction zone makes it difficult to distinguish between the seamount and plateau models of stress rotation. However, it is also possible that both features play a concurrent role, with stress rotations superimposed from both.

6 Conclusions

We determined the rupture geometry of the 2021 M_W 7.3 East Cape, New Zealand earthquake using a novel finite-fault inversion technique. Our method does not require a-priori knowledge of the fault geometry and can flexibly resolve complex faulting styles in large earthquakes. Therefore, it can uniquely illuminate the heterogeneous stress state near the earthquake. We show that the East Cape earthquake has at least four rupture episodes and likely ruptured multiple faults with various faulting styles. We find distinct rupture episodes within the shallow (~30 km) and deep (~70 km) parts of the subducted oceanic plate, with distinct mechanisms of normal and a mixture of strike-slip and reverse faulting, respectively. The deep and shallow episodes likely reflect components of a flexural stress field, separated by a low-stress barrier in the middle of the plate. The rotation of P-axes suggests that the intraplate stress state is locally rotated from trench-normal compression to trench-parallel compression. Such a stress rotation in depth requires the slab geometry to change sharply, which may have been induced by a subducted seamount or the additional buoyancy of the Hikurangi plateau. Our study suggests that understanding the generation of intermediate and deep intraslab seismicity requires a detailed treatment of localized variations in slab geometry caused by the subduction of heterogeneous features, such as ocean plateaus and seamounts.

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Data Availability Statement

All the materials presented in this paper are archived and available at https://doi.org/10.5281/zenodo.5068091. All seismic data were downloaded through the IRIS Wilber 3 system (https://ds.iris.edu/wilber3/find_event) or IRIS Web Services (https://service.iris.edu), including the following seismic networks: the GT (Global Telemetered Seismograph Network (USAF/USGS); Albuquerque Seismological Laboratory (ASL)/USGS, 1993); the IC (New China Digital Seismograph Network; Albuquerque Seismological Laboratory (ASL)/USGS, 1992); the IU (Global Seismograph Network (GSN - IRIS/USGS); Albuquerque Seismological Laboratory (ASL)/USGS, 1988); the GE (GEOFON Seismic Network; GEOFON Data Centre, 1993); the AU (Australian National Seismograph Network (ANSN); Geoscience Australia (GA), 1994); the HK (Hong Kong Seismograph Network; Hong Kong Observatory, 2009); the G (GEOSCOPE; Institut De Physique Du Globe De Paris (IPGP) & Ecole Et Observatoire Des Sciences De La Terre De Strasbourg (EOST), 1982); the NZ (New Zealand National Seismograph Network; Institute of Geological & Nuclear Sciences Ltd (GNS New Zealand), 1988; Petersen et al., 2011); the AI (Antarctic Seismographic Argentinean Italian Network - OGS; Istituto Nazionale Di Oceanografia E Di Geofisica Sperimentale, 1992); the II (IRIS/IDA Seismic Network; Scripps Institution Of Oceanography, 1986); the C (Chilean National Seismic Network; Universidad de Chile Dept de Geofisica (DGF UChile Chile), 1991); the PS (Pacific21

(ERI/STA); University of Tokyo Earthquake Research Institute (Todai ERI Japan), 1989). We used ObsPy (Beyreuther et al., 2010, version 1.1.0; https://doi.org/10.5281/zenodo.165135), Pyrocko (The Pyrocko Developers, 2017, https://pyrocko.org/), matplotlib (Hunter, 2007, version 3.0.3; https://doi.org/10.5281/zenodo.2577644), Generic Mapping Tools (Wessel & Luis, 2017, version 6.1.0; http://doi.org/10.5281/zenodo.3924517); and Scientific colour maps (Crameri, 2018; Crameri et al., 2020, version 6.0.4; http://doi.org/10.5281/zenodo.4153113) for data processing and visualisation. The `NonLinLoc` software used for hypocenter relocation is available at http://alomax.free.fr/nlloc/. The `Grond` software (Heimann et al., 2018) used for W-phase CMT inversion is available at https://pyrocko.org/grond/docs/current/. The `ISOLA` software used for R-CMT inversion is available at http://seismo.geology.upatras.gr/isola/. The `COMPLOC` earthquake location package (Lin & Shearer, 2005, 2006) for aftershock relocation is available at https://sites.google.com/view/guoqing-lin/products/comploc.

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