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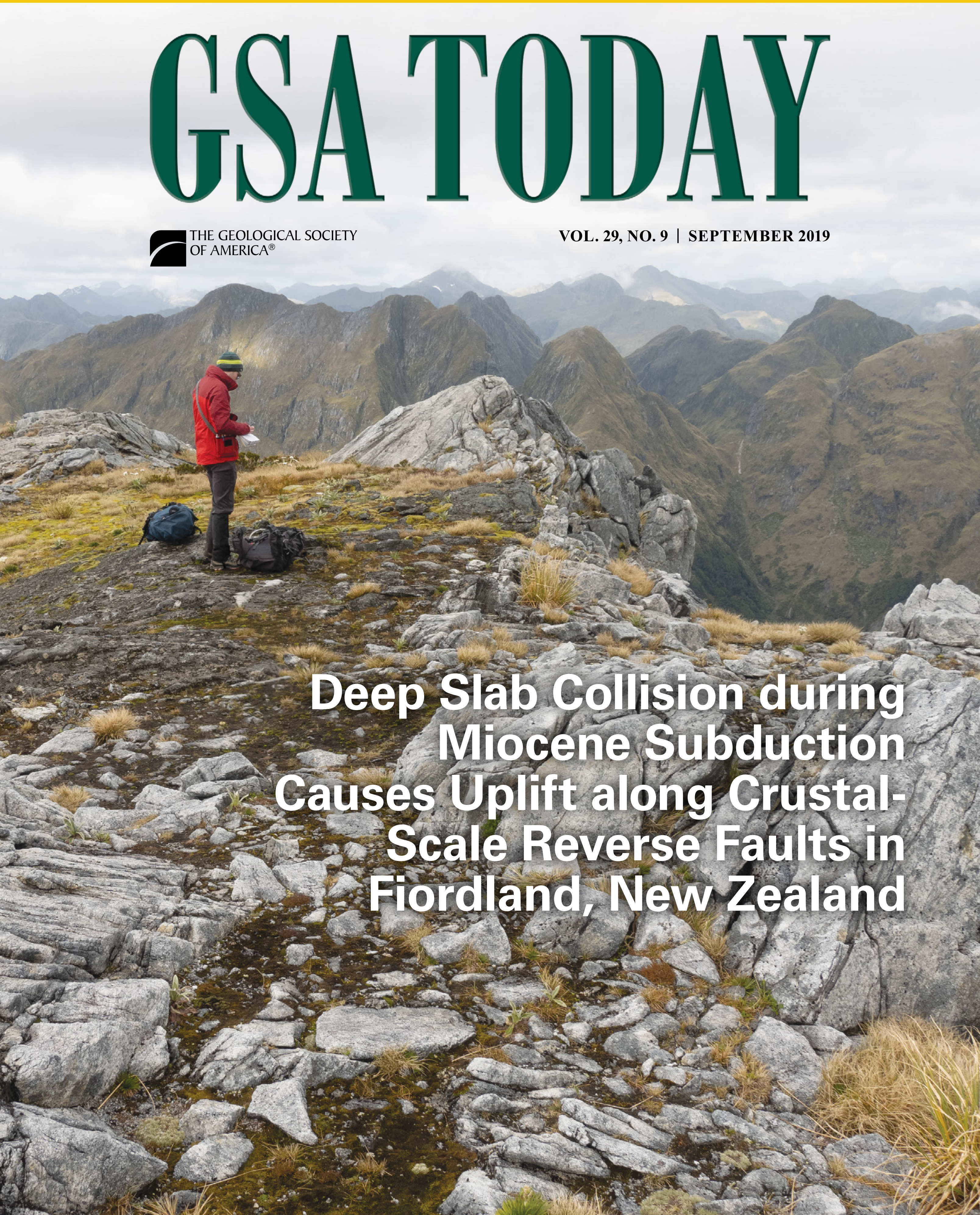

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Deep Slab Collision during Miocene Subduction Causes Uplift along Crustal-Scale Reverse Faults in Fiordland, New Zealand

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ABSTRACT

A new multidisciplinary project in southwest New Zealand that combines geological and geophysical data shows how and why deep lithospheric displacements were transferred vertically through the upper plate of an incipient ocean-continent subduction zone. A key discovery includes two zones of steep, downward-curving reverse faults that uplifted and imbricated large slices of Cretaceous lower, middle, and upper crust in the Late Miocene. Geochemical and structural analyses combined with $^{40}Ar/^{39}Ar$ geochronology and published images from seismic tomography suggest that the reverse faults formed at 8–7 Ma as a consequence of a deep (~100 km) collision between subducting oceanic lithosphere and previously subducted material. This collision localized shortening and reactivated two crustal-scale shear zones from the upper mantle to Earth's surface. The event, which is summarized in a new lithospheric-scale profile, is helping us answer some long-standing questions about the origin of Fiordland's unique lower-crustal exposures and what they tell us about how inherited structures can transfer motion vertically through the lithosphere as subduction initiates.

INTRODUCTION

In southwest New Zealand, oceanic lithosphere of the Australian Plate subducts obliquely beneath continental lithosphere of the Pacific Plate at the Puysegur Trench (Fig. 1A). Northeast of the trench, the subducted slab rotates and steepens to vertical below Fiordland, where it joins the Alpine fault (Reyners et al., 2017), an ~850 km transform that has accumulated some 480 km of horizontal displacement since ca. 25 Ma (Sutherland and Norris, 1995). This region has generated great interest among geologists, in part because it is one of only a few places where the surface tectonic record of an incipient ocean-continent subduction zone can be observed directly (Mao et al., 2017). It also represents Earth's deepest exposed example of an Andean-style continental arc (Ducea et al., 2015). Here, we use this unique setting to explore how Fiordland's surface and crust responded to events that occurred deep within the lithospheric mantle since subduction began in the Early Miocene.

Over the past few years, our understanding of the vertical links that develop within the lithosphere has benefitted from improvements in our ability to extract information from the rock record. Innovative approaches to studying fault zones that combine geochemistry and high-precision geochronology with structural analyses, for example, have enhanced our capacity to relate deformation histories to other processes across a wide range of scales (e.g., Haines et al., 2016; Schwartz et al., 2016; Williams et al., 2017). At the same time, new methods in global teleseismic tomography are revealing the geometry and extent of material that was subducted into the mantle millions of years ago in unprecedented detail (Wu et al., 2016; Reyners et al., 2017). These imaged slabs can be integrated with surface geology and plate kinematics to reveal previously hidden tectonic histories. Together, these and many other innovations are providing new opportunities to determine how surface tectonic records connect to processes occurring in the mantle as subduction zones form and develop over time (e.g., Liu, 2015; Liu et al., 2017; Kissling and Schlunegger, 2018).

In this article, we integrate structural, geochemical, and geochronologic data with images of the upper mantle derived from seismic tomography to reconstruct the late Cenozoic tectonic history of Fiordland. The results provide new insights into the process of subduction initiation at continental margins, including the causes and consequences of vertical motions within the overriding plate.

PREVIOUS WORK

Surface Geology

The surficial geology of Fiordland is dominated by exposures of the Median Batholith (Mortimer et al., 1999), which consist mostly of Carboniferous–Early Cretaceous plutons. An eastern (outboard) belt contains Jurassic and older rocks that accreted onto the Gondwana margin during the Early Cretaceous (Tulloch and Kimbrough, 2003; Marcotte et al., 2005). A western (inboard) belt exposes the Early

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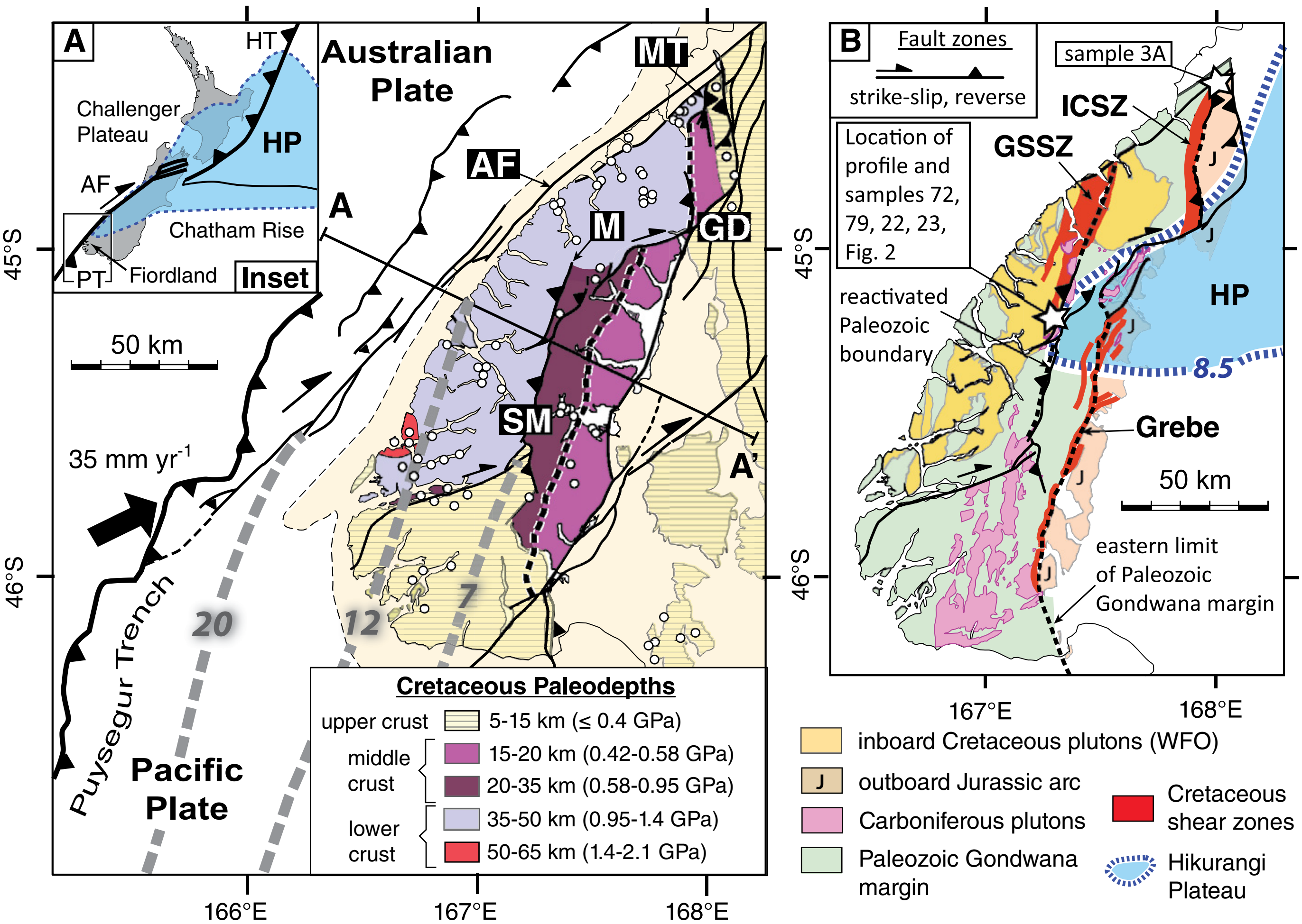

Figure 1. (A) Map of Fiordland showing the imbrication of Cretaceous lower, middle, and upper crust by Miocene reverse faults. Profile along line of section A–A′ is shown in Figure 3. Paleodepth uncertainties are ±0.1 GPa (±3.7 km). Reconstruction of the subducting Australian Plate at 20, 12, and 7 Ma is from Sutherland et al. (2009). AF—Alpine fault; GD—Glade-Darran fault zone; HP—Hikurangi Plateau; HT—Hikurangi Trench; M—Misty fault; MT—Mt. Thunder fault; SM—Spey-Mica Burn fault zone; PT—Puysegur Trench. (B) Map showing position of two Carboniferous crustal boundaries (black dashed lines). The western boundary coincides with the George Sound shear zone (GSSZ) and SM fault zone. The eastern one coincides with the Grebe and Indecision Creek (ICSZ) shear zones, and Mt. Thunder fault. WFO is Western Fiordland Orthogneiss. Locations of three pseudotachylyte samples (22, 23, 3A) dated at 8–7 Ma shown with white stars. Dashed blue line surrounding light blue region represents high Vp (~8.5 km s^{-1}) eclogite crust at the base of the Hikurangi Plateau at ~100 km depth (after Reyners et al., 2017).

Cretaceous Western Fiordland Orthogneiss (WFO), which was emplaced mainly as diorite into Paleozoic plutonic and metasedimentary rocks at the base of a Mesozoic arc (Bradshaw, 1990). Early petrologic investigations showed that the western belt records high metamorphic temperatures ($T \geq 750$ °C) and a depth of exposure that is unique in New Zealand (Oliver, 1976; Blattner, 1976; Bradshaw, 1985). Approximately 35% of the WFO contains high-pressure mineral assemblages indicative of garnet granulite, omphacite granulite, and eclogite facies metamorphism (Turnbull et al., 2010), making it Earth's largest (~4500 km^2) and deepest (to at least 65 km) known exposure of lower crust from a Mesozoic continental arc (Ducea et al., 2015).

Rock Uplift and Topographic Growth

Sutherland et al. (2009) documented the onset of rapid exhumation in SW Fiordland at 25–15 Ma, coincident with the initiation of subduction south of New Zealand. During the 15–5 Ma period, zones of high exhumation rates broadened and expanded into the interior of Fiordland, although exhumation occurred mainly in the west. These patterns, which include an estimated 12–15 km of total rock uplift, are thought to be associated with the development of elevated topography. They also have been interpreted to result from either a combination of crustal shortening and dynamic uplift above the subducting slab (Sutherland et al., 2009) and/or glacial erosion coupled with high (>8 m/yr^{-1}) precipitation rates (Jiao et al., 2017). Although Sutherland et al. (2009) postulated that age-elevation relationships and spatial variations in exhumation rates were caused by reverse faulting, their relationship to specific faults was unresolvable with existing data.

Subsurface Imaging

A regional 3D seismic velocity model derived from seismic tomography studies by Eberhart-Phillips et al. (2010) has recently allowed geophysicists to image the subsurface extent of the partially subducted Hikurangi Plateau beneath New Zealand (Fig. 1, inset) (Reyners et al., 2011; Davy, 2014). This oceanic plateau formed ca. 122 Ma (Neal et al., 1997) and was underthrust beneath the continent twice. The first underthrusting occurred ca. 100 Ma when Fiordland formed part of Gondwana; the second occurred in the late Cenozoic driven by convergence between the Pacific and Australian plates (Davy, 2014; Reyners et al., 2011, 2017). Currently, the western edge of the plateau lies below central and northern Fiordland where it impacts the geometry of the subducting Australian Plate (Reyners et al., 2017). South of the line of section shown in Figure 1A, the subducting plate parallels the Puysegur Trench and dips at ~68° below 50 km depth (Reyners et al., 2011). North of this line, the slab twists to the NE (040°) and is vertical below 75 km (Reyners et al., 2017).

INTEGRATED GEOLOGICAL STUDIES

Reconstructing Fiordland

Many advances in our understanding of Fiordland's deep-crustal exposures have come from efforts to distinguish the age and significance of various episodes of magmatism, metamorphism, and deformation. In particular, the application of multiple geochronometers (e.g., Klepeis et al., 2016; Schwartz et al., 2016, 2017; Stowell et al., 2017; Tulloch et al., 2010, 2019), combined with an improved understanding of metastability in igneous and metamorphic mineral assemblages (Allibone et al., 2009a; Bhattacharya et al., 2018), have enhanced our ability to correlate tectonic events across thousands of square kilometers. These improvements have allowed us to reconstruct Fiordland's crustal architecture with increased accuracy.

Figure 1A shows a new compilation of Cretaceous paleodepths that provides a snapshot of Fiordland crust ca. 115 Ma, when it reached its maximum thickness of ≥65 km. It also is the first to delineate the boundaries of the various crustal blocks. The data derive from mineral assemblages that represent the peak of Early Cretaceous metamorphism and estimates of the emplacement depths of plutons whose age and history are known (see Table DR1 in the GSA Data Repository[1]). Our reconstruction shows large blocks of Cretaceous upper, middle, and lower crust, all of which are bounded by faults.

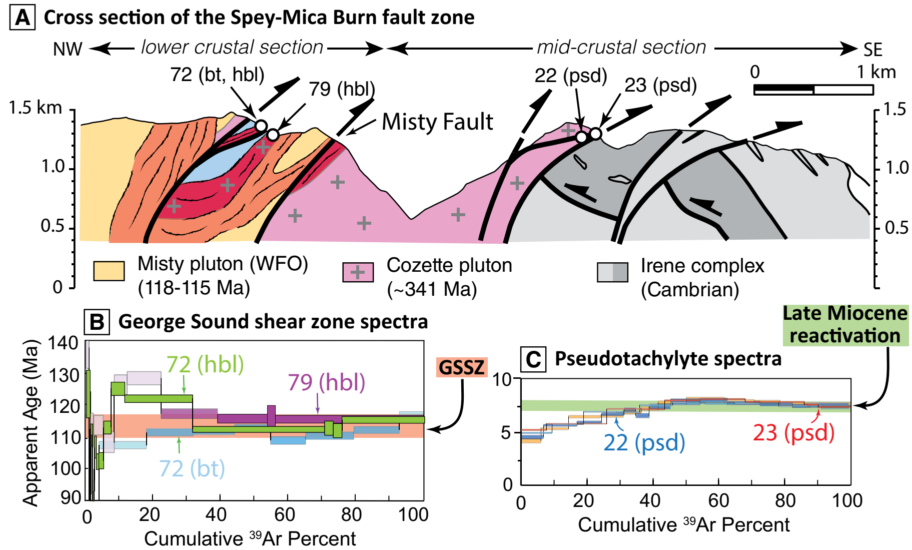

Figure 2. (A) Cross section of the Spey-Mica Burn fault zone (location in Fig. 1A). Profile shows steep reverse faults (dark black lines) that uplifted and imbricated the George Sound shear zone (orange-red-lined patterns), placing Cretaceous lower crust to the SE over Cretaceous middle crust. Yellow and blue represent undeformed portions of the Misty pluton and older Jurassic–Early Cretaceous igneous rock, respectively. Orange-lined pattern represents sheared Misty pluton; dark red-lined pattern with plusses represents sheared Cozette pluton (samples 72 and 79). (B) Apparent $^{40}Ar/^{39}Ar$ age spectra from hornblende (hbl) and biotite (bt) from sample 72 and hornblende from sample 79 indicate George Sound shear zone (GSSZ) deformation occurred at 117–110 Ma (dots are dated samples). (C) Apparent $^{40}Ar/^{39}Ar$ age spectra from 8 to 7 Ma pseudotachylyte (psd) within splays of the Spey-Mica Burn fault zone (two runs each of samples 22 and 23). Similar ages were obtained from pseudotachylyte in the Mt. Thunder fault (Figs. DR2 and DR3 in the GSA Data Repository [see text footnote 1] show detailed spectra and a detailed map of the Spey-Mica Burn fault zone, respectively).

These crustal divisions are important because they provide an improved framework for determining how the characteristics of magmatism, metamorphism, and deformation change vertically within the lithosphere.

One of the most significant outcomes of our study is the discovery of a narrow zone of steep, downward-curving reverse faults that placed a large, irregular slice of lower crust up and to the east over the middle and upper crust (Figs. 1A and 2A). The Spey-Mica Burn fault system, which is well-exposed in central Fiordland, extends for ~80 km and joins the Misty fault (new name) along the eastern boundary of the lower crustal block. The fault zone then steps to the east in a series of oblique-slip faults that connect with another system of reverse faults, including the Mt. Thunder fault (new name) and the Glade-Darran fault zone (Fig. 1). This discovery is the first to confirm that the last 12–15 km of the uplift and exhumation of Fiordland's unique exposures is directly related to late Cenozoic reverse faulting rather than to an older period of Cretaceous extension. Consequently, it has sparked new investigations aimed at determining the age of faulting and its relationship to Miocene subduction and zones of high exhumation rates.

Reactivating Ancient Structures

Determining the age and history of faulting in Fiordland has been challenging, mainly because the surface expression of faults typically is narrow and eroded or concealed by sediment and dense vegetation. To solve this problem, we walked the surface traces of faults and found high-quality exposures that preserve kinematic information (Fig. DR1, Table DR2 [see footnote 1]). Two especially informative localities (stars in Fig. 1B) expose pseudotachylyte-bearing reverse faults at and near the eastern boundary of the lower crustal block. These sites show that the reverse faults reactivated two ancient crustal boundaries that coincide with large, ductile shear zones. The western boundary, which is centered on the

[1]GSA Data Repository item 2019195, $^{40}Ar/^{39}Ar$ analytical methods and data tables, paleodepth data, and fault-slip data, is online at www.geosociety.org/datarepository/2019.

George Sound shear zone, is marked in part by a linear belt of Late Carboniferous granites (Ramezani and Tulloch, 2009) within the lower crustal block (Fig. 1B). The eastern boundary coincides with the old Carboniferous edge of Gondwana (Marcotte et al., 2005; Allibone et al., 2009b; Scott et al., 2011; McCoy-West et al., 2014) and is deformed by both the Grebe and the Indecision Creek shear zones (Fig. 1B). All of these structures were infiltrated by magma and reactivated multiple times since the late Carboniferous (e.g., Marcotte et al., 2005; Scott et al., 2011) (Fig. 1B), indicating that they represent long-lived zones of crustal weakness.

Figure 2A provides a detailed view of the superposed deformations caused by the repeated reactivation of the western boundary. It shows that the Carboniferous Cozette pluton (pink) was intruded by the Early Cretaceous (mainly 118–115 Ma) Misty pluton (yellow), both of which are deformed by the George Sound shear zone (red-lined pattern). This same zone also was the site of repeated magma infiltration during the 170–128 Ma interval (blue) (Allibone et al., 2009b). Two phases of steep reverse faulting then imbricated the shear zone, placing lower crust to the east over middle crust.

These findings have allowed us to formulate many new questions, such as: How old is the crustal imbrication? Why do faults deform only parts of the Late Carboniferous boundaries? Our collaborative study aims to answer these questions and, in doing so, determine how the Paleozoic–Mesozoic history of Gondwana influenced Fiordland's late Cenozoic tectonic history.

Unraveling the Timing of Fault Reactivations

An especially useful approach to distinguishing the age of superposed events at the boundaries of Fiordland's lower crustal slice has been through the use of $^{40}Ar/^{39}Ar$ age spectra derived from step-heating experiments (Tables DR3 and DR4 [see footnote 1]). For example, hornblende from the George Sound shear zone where it deforms the Carboniferous Cozette pluton (sample 79, Fig. 2B) yields a 116.1 ± 1.1 Ma (1σ) plateau age after an initial complex release pattern. A second sample from where the shear zone deforms this same pluton (sample 72, Fig. 2B) yielded similar hornblende spectra and a 111.14 ± 0.76 Ma biotite plateau age. These ages help establish that Cretaceous magmatism and transpression overlapped in space and time, with pluton emplacement occurring mainly at 118–115 Ma (Schwartz et al., 2016) and deformation occurring at 117–110 Ma (Fig. 2B). They also help establish this zone as a long-lived boundary that was in place prior to subduction initiation at the Puysegur Trench during the Miocene.

To determine the age of the reverse faults, we collected two samples of pseudotachylyte from a well-exposed segment of the Spey-Mica Burn fault zone (samples 22, 23, Fig. 2A) and a third pseudotachylyte sample (3A) from the Mt. Thunder fault (location in Fig. 1B; results shown in the GSA Data Repository [see footnote 1]). Multiple runs of all three samples helped us cross check the reproducibility of the apparent age spectra and interpreted ages. The results indicate that the pseudotachylytes all range in age from 8 to 7 Ma, indicating that faulting occurred approximately simultaneously within both fault zones.

Probing the Deep Roots of Faults

One of the outcomes of the crustal configuration shown in Figures 1A and 1B is an improved framework for determining how structures and tectonic processes are expressed at different depths within the lithosphere. For example, our work shows that it is possible to walk continuously along the boundary between the Paleozoic Gondwana margin and the outboard Jurassic arc from its location in upper crustal exposures at the southern end of the Grebe shear zone to its lower crustal expression in the Indecision Creek shear zone (Fig. 1B). This physical relationship shows how narrow zones of Cretaceous faulting in the upper crust gradually change into thick zones of ductile shear in the lower crust (Fig. 1B). In addition, the systematic mapping and dating of plutons along the length of the shear zones shows that magmatism and deformation were synchronous within them at all levels of the crust (Marcotte et al., 2005; Klepeis et al., 2016; Schwartz et al., 2017). This close association is important because it allows us to use the geochemical signatures and source regions of plutons to determine how deep the George Sound and Indecision Creek shear zones once penetrated.

Over the past few years, several studies (Decker et al., 2017; Milan et al., 2017) have investigated the deep source regions of the WFO batholith using isotopic systems and geochemical data. Decker et al. (2017) showed that Early Cretaceous plutons emplaced into the crustal boundary marked by the George Sound shear zone (Figs. 1B, 2, and 3) were sourced below the continental crust. Structural studies indicate that deformation aided magma ascent (Betka and Klepeis, 2013; Klepeis et al., 2016). Further work using oxygen and hafnium isotopes (Andico et al., 2017) indicates that strong isotopic differences in the lower crust existed across these shear zones during the Jurassic and Cretaceous, indicating they extended to lower crustal depths during, and prior to, these times. This work is important for understanding Fiordland's current crustal architecture because it implies that the Spey-Mica Burn fault system, which reactivated two ancient crustal-scale shear zones in the Late Miocene, also transects the crust and penetrates into the upper mantle.

CONNECTING SURFACE GEOLOGY TO DEEP LITHOSPHERIC STRUCTURES

Our ability to investigate vertical connections between Fiordland's surface and the deep lithosphere requires a detailed knowledge of crustal architecture, including when and how it was assembled. Figure 3 shows a new profile that combines information from Fiordland's rock record with recently published tomographic models of the deep crust and upper mantle (Eberhart-Phillips et al., 2010; Reyners et al., 2017). The profile shows two narrow zones of reverse faulting directly above the region where the subducting Australian Plate steepens to vertical against the Hikurangi Plateau. This discovery not only enhances our ability to reconstruct Fiordland's subduction history, it also suggests a new mechanism by which Fiordland's crustal architecture and surface record are linked to processes occurring at the base of the lithosphere.

Estimates of crustal thickness beneath Fiordland, derived from isovelocity plots of $Vp = 7.5$ km s^{-1} (Eberhart-Phillips et al., 2010; Reyners et al., 2017), suggest that Moho depths vary from ~30 km below the WFO to more than 50 km below the outboard batholith (Fig. 3).

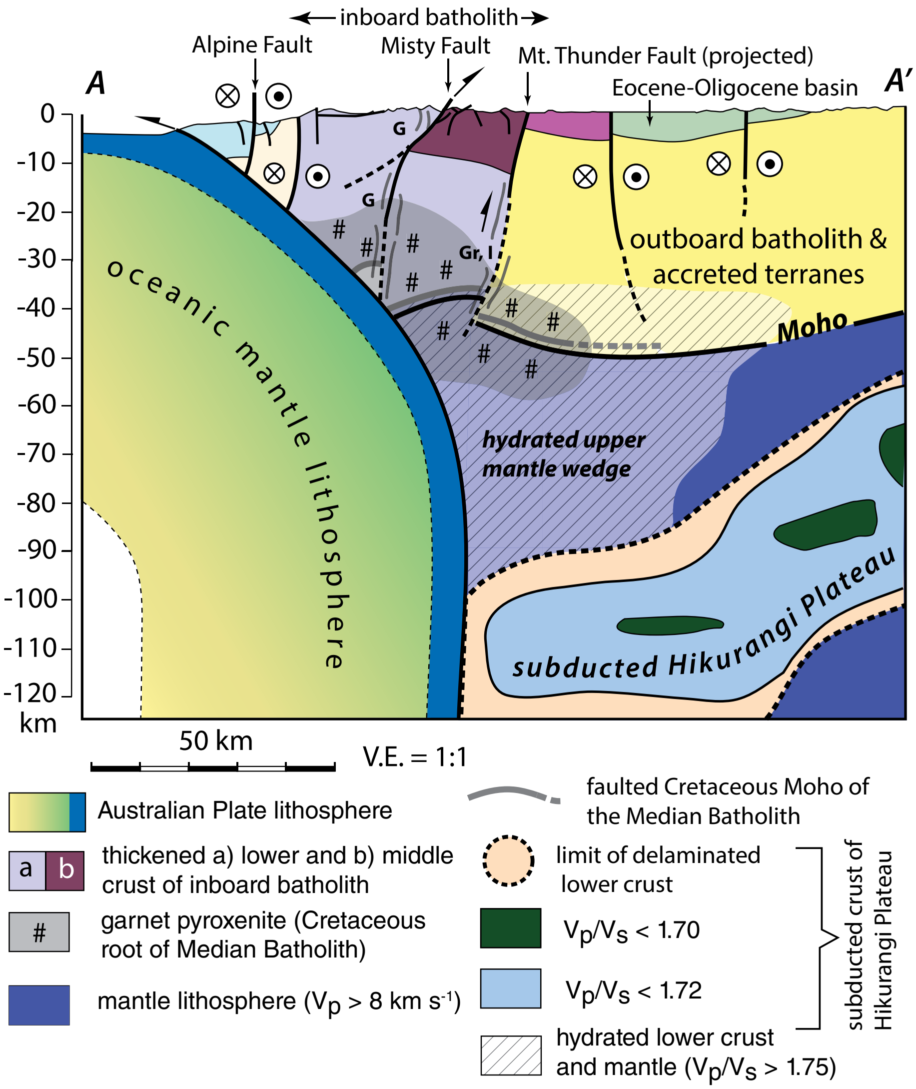

Figure 3. Vertical profile that combines new geological information with published geophysical images (location in Fig. 1A). Colors match those in Figure 1A except where noted. The location and geometry of the subducted Australian Plate is from relocated hypocenters (Reyners et al., 2017). The location of the subducted Hikurangi Plateau is from Eberhart-Phillips et al. (2010) and Reyners et al. (2017). Gray lines are Cretaceous shear zones that penetrate the lower crust: G—George Sound shear zone; I—Indecision Creek shear zone; Gr—Grebe shear zone.

These estimates closely match those we obtained for Cretaceous crustal thicknesses using metamorphic mineral assemblages combined with estimates of the vertical offset across faults. This similarity suggests that the Cretaceous Moho approximately coincides with the position of the current Moho, which has been difficult to image using geophysical techniques. It also suggests that the apparent shallowing of both the Cretaceous and the current Moho from east to west beneath Fiordland is a consequence of Late Miocene reverse faulting. This interpretation is compatible with the steep orientation of the reverse faults, their reactivation of inherited crustal-scale shear zones, and estimates of 12–15 km of late Cenozoic uplift within their hanging walls.

Below the base of the crust, tomographic images show the 3D structure and subsurface extent of the subducted Hikurangi Plateau (Reyners et al., 2011, 2017; Davy, 2014). Images of Vp and Vp/Vs show that the plateau within the Pacific Plate mantle is an ~35-km-thick zone of seismicity with a layer of high Vp (~8.5 km s^{-1}) eclogite crust at its base (Fig. 3). Above this layer, high Vp/Vs ratios (~1.75) probably reflect the presence of a hydrated mantle wedge, which may contribute to the poorly defined Moho. The plateau's southwest edge lies below central and northern Fiordland, where it appears to step to the northeast. Interestingly, the pattern of Miocene reverse faults at the surface mimics this east-stepping geometry of the plateau at depth (Fig. 1B), which provides an explanation for why the two ancient crustal boundaries were reactivated in different places at 8–7 Ma.

In their tomographic studies of the subsurface, Reyners et al. (2011, 2017) concluded that a late Cenozoic collision between the subducting Australian Plate and the western Hikurangi Plateau caused the underthrust plate to steepen to vertical below 75 km (Fig. 3). A reconstruction of the forward progress of this slab since ca. 25 Ma (Fig. 1A) shows that the time when its leading edge first encountered the plateau margin coincides with both the surface location and the timing of reverse faulting at 8–7 Ma. This relationship suggests that the collision localized shortening and caused the reactivation of two Cretaceous shear zones as reverse faults. Their steep orientations meant that the displacements were partitioned mostly into vertical motion, suggesting that this event also should be visible in Fiordland's exhumation history.

In their compilation of Fiordland's record of surface uplift, Sutherland et al. (2009) inferred that topographic growth and exhumation since ca. 25 Ma were associated with the inception of subduction and the downward deflection of the Australian slab. However, one problem in trying to relate this history of uplift and exhumation to crustal shortening is that neither topographic features nor zones of high exhumation rates could be linked to specific faults. Our discovery of major reverse faults at the edge of Fiordland's lower crustal block helps to solve this problem. In particular, the close spatial and temporal agreement between vertical fault motions at 8–7 Ma and the abrupt expansion of zones of rock uplift and high exhumation rates into eastern and northern Fiordland suggests that these uplift patterns were caused by reverse faulting. We therefore conclude that fault-related uplift and topographic growth in the Late Miocene were direct consequences of the collision between the subducting Australian Plate and the Hikurangi Plateau.

CONCLUSIONS

The integration of surface and subsurface data sets from southwest New Zealand shows how the history of deformation, exhumation, and fault-related topographic growth above a young ocean-continent subduction zone is linked to events occurring near the base of the continental lithosphere. New geologic mapping and $^{40}Ar/^{39}Ar$ dates show that crustal-scale reverse faults reactivated two ancient shear zones at 8–7 Ma, placing an irregular slice of Cretaceous lower crust up and to the east over the middle and upper crust. The size, age, location, and style of these faults suggest that they formed as a direct consequence of a Late Miocene collision between the leading edge of the subducting Australian Plate and previously subducted oceanic crust of the Cretaceous Hikurangi Plateau. This collision, which occurred at ~100 km depth, localized shortening and caused the subducting slab to steepen to vertical. It also drove the reactivation of inherited structures, resulting in crustal imbrication and 12–15 km of vertical motion. Integrated structural and geochemical analyses suggest that the reverse faults penetrate the entire crust and offset the Moho. The irregular geometry of the Hikurangi Plateau at depth provides a plausible explanation for why two ancient shear zones were reactivated simultaneously in different places at 8–7 Ma. For the first time, this study shows when, how, and why Earth's largest and deepest known exposure of lower crust from a Mesozoic continental arc was uplifted, imbricated, and exhumed to the surface above the Puysegur subduction zone. It also illustrates how inherited zones of crustal weakness facilitate the transfer of displacements between Earth's surface and the upper mantle during the early stages of subduction.

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