

Highly localized upper mantle deformation during plate boundary initiation near the Alpine fault, New Zealand

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ABSTRACT

Peridotite xenoliths entrained in magmas near the Alpine fault (New Zealand) provide the first direct evidence of deformation associated with the propagation of the Australian-Pacific plate boundary through the region at ca. 25–20 Ma. Two of 11 sampled xenolith localities contain fine-grained (40–150 μm) rocks, indicating that deformation in the upper mantle was focused in highly sheared zones. To constrain the nature and conditions of deformation, we combine a flow law with a model linking recrystallized fraction to strain. Temperatures calculated from this new approach (625–970 °C) indicate that the observed deformation occurred at depths of 25–50 km. Calculated shear strains were between 1 and 100, which, given known plate offset rates (10–20 mm/yr) and an estimated interval during which deformation likely occurred (<1.8 m.y.), translate to a total shear zone width in the range 0.2–32 km. This narrow width and the position of mylonite-bearing localities amid mylonite-free sites suggest that early plate boundary deformation was distributed across at least ~60 km but localized in multiple fault strands. Such upper mantle deformation is best described by relatively rigid, plate-like domains separated by rapidly formed, narrow mylonite zones.

INTRODUCTION

The width of plate boundary shear zones in Earth's mantle is a long-standing first-order question in geodynamics (e.g., Vauchez et al., 2012) and a poorly constrained boundary condition for models of major earthquakes and postseismic deformation (e.g., Bürgmann and Dresen, 2008). Teleseismic methods cannot resolve narrow shear zones (<~30 km) but commonly constrain—with poor depth resolution—wide (>100 km scale) zones of anisotropy beneath plate boundaries (e.g., Zietlow et al., 2014). Thus, it is unclear if continental strike-slip faults generally overlay wide deformation zones immediately beneath the Moho (e.g., Collins and Molnar, 2014) or if narrow shear zones penetrate the entire mantle lithosphere (e.g., Ford et al., 2014). Distinguishing between these possibilities using geologic evidence is difficult for a number of reasons, including (1) appropriate rock masses are rarely exposed, (2) microstructures formed during exhumation can be difficult to distinguish from those formed at deep levels, and (3) adequate

barometers are commonly unavailable (e.g., Titus et al., 2007; Vauchez et al., 2012).

We describe a suite of mantle xenoliths from near New Zealand's Alpine fault (Fig. 1), an active continental transform fault (e.g., Norris and Toy, 2015). These xenoliths are unique in that (1) they sampled multiple locations ($N = 11$) near the fault, (2) some samples are mylonites (highly sheared), and (3) their eruption coincided with the onset of plate boundary motion. We present a new approach that allows strain rate, deformation temperature, and shear zone width to be estimated from a xenolith "snapshot" of the critical, earliest moments of faulting.

GEOLOGIC BACKGROUND

The Alpine fault comprises the ~800 km stretch of the Australia-Pacific plate boundary crossing New Zealand's South Island (e.g., Sutherland et al., 2000). Dextral strike-slip motion began at ca. 25–20 Ma following a period of extension and north-propagating rifting (Fig. 1; Sutherland et al., 2000). The mod-

ern transpressional period began at ca. 5–8 Ma (Batt et al., 2004). The trace of the Alpine fault coincides with preexisting structures that may have influenced its position (Sutherland et al., 2000; Lamb et al., 2016).

The studied spinel peridotite xenoliths occur in the Alpine dike swarm (Fig. 1), which also dates to ca. 25–20 Ma (Cooper, 2020). The xenoliths are mainly harzburgites and dunites (olivine $\text{Mg\#}$ [$100 \times \text{Mg}/\{\text{Mg} + \text{Fe}\}$] commonly >90; Scott et al., 2014; Liu et al., 2015). Some xenoliths contain minor hydrous phases (Scott et al., 2014), and calculated H_2O concentrations in olivine are high (~80 ppm; Li et al., 2018). Two-pyroxene thermometry on coarse-grained samples indicates peak or retrograde temperatures ranging from 800 to 1200 °C (Scott et al., 2014, 2016). These temperatures may pre-date deformation, but deformation temperatures are bracketed by these values and lower crustal temperatures of 600–700 °C at the onset of Alpine fault deformation (Vry et al., 2004; Briggs and Cottle, 2018; Kidder et al., 2018). The xenolith source depth exceeded ~25 km based on constraints on paleo-Moho depth (Lamb et al., 2015).

MICROSTRUCTURES

The peridotite xenoliths can be sorted into coarse- and fine-grained types (Fig. 2). Coarse-grained xenoliths (Fig. 2A) make up ~90% of 84 observed samples and occur at all the localities. Coarse-grained xenoliths are dominated by millimeter- to centimeter-scale grains, with grains of size 300–600 μm also found in some samples along grain boundaries.

Fine-grained xenoliths were found at two localities: the 25–20 Ma Moeraki River valley and the 23.3 ± 0.1 Ma Lake Wanaka diatreme (Fig. 1; Cooper, 2020). Fine-grained peridotites

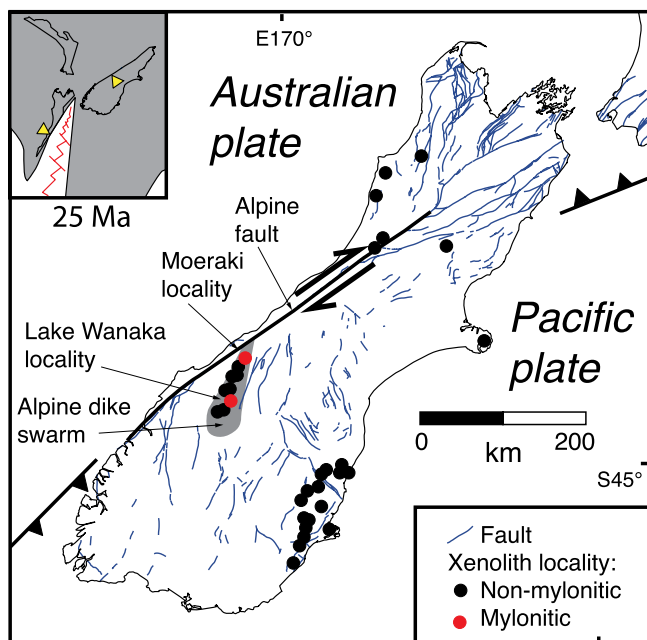


Figure 1. Map of New Zealand's South Island showing features described in the text. Inset shows the location's configuration at 25 Ma (Lamb et al., 2016) with continental crust shaded. The Alpine fault propagated northward from the tip of the Paleogene rift shown in red in the inset, connecting two points marked as yellow triangles. GPS coordinates of sample locations are provided by Scott (2020).

are absent at all 64 other known New Zealand xenolith localities (Fig. 1; Scott, 2020). The fine-grained Lake Wanaka xenoliths are mylonitic and layered and comprise a roughly 50:50 mixture of (1) large, millimeter-scale grains (“relicts”) with aspect ratios as high as 10:1, and (2) zones of fine (40–150 μm) recrystallized grains (grains formed during deformation) made up of olivine or orthopyroxene or mixtures of the two (Fig. 2B). Olivine relicts contain subgrains and undulose extinction. The fine-grained xenoliths at the Moeraki locality are unlayered and comprise a variably proportioned mixture of relicts and pure olivine matrix that also averages 50:50; i.e., overall recrystallized fraction of $\sim 50\%$. The matrix grains in these samples have a size of 100–200 μm and

their boundaries tend to be straight or gently curved and commonly intersect at 120° triple junctions (Fig. 2C).

TIMING OF GRAIN SIZE REDUCTION

The microstructures of the fine-grained xenoliths are typical of highly deformed rocks from shear zones and deformation experiments (e.g., Warren and Hirth, 2006; Cross and Skemer, 2017). Fine-grained areas of such rocks composed of a single phase (e.g., lower part Fig. 2B; Fig. 2C) are energetically unstable and experience grain growth following deformation (e.g., Karato, 1989; Kidder et al., 2016). Using either the wet or dry grain growth equations from Karato (1989) at temperatures of 600–1200 $^\circ\text{C}$ and any initial grain size, we calculate

that the observed grains (Fig. 2C) would have increased beyond 150 μm if formed more than $\sim 20,000$ yr before entrainment. This calculation suggests that the mylonites are not inherited features pre-dating the Alpine fault but instead capture active deformation at the time of entrainment. We note that while the grain growth relationships of Karato (1989) are widely used, they may predict faster growth rates than occur in natural samples (e.g., Speciale et al., 2020). However, both in New Zealand and globally, xenolith localities containing fine-grained spinel peridotite are extremely rare ($n = 7$) and unique to active tectonic areas (Vauchez et al., 2012). We infer that the occurrence of mylonitic xenoliths near the Alpine fault at the moment of its formation is not coincidental but that the xenoliths are representative of the mantle at 25–20 Ma.

DEFORMATION TEMPERATURE AND STRAIN

To constrain conditions of deformation recorded in the xenoliths, we apply a new technique combining three relationships: (1) a paleopiezometer based on experiments that link recrystallized grain size to differential stress (referred to as “stress” throughout); (2) a flow law that yields strain rate as a function of stress and temperature; and (3) a relationship between finite strain (“strain” hereafter) and recrystallized fraction (percentage of recrystallized grains versus relicts; Cross and Skemer, 2019). Alpine fault history provides a key additional constraint: the earliest likely onset of deformation at ca. 25 Ma and entrainment of mylonites at ca. 23.3 ± 0.1 Ma are separated by < 1.8 m.y. Thus, multiplying strain rates from the flow law by 1.8 m.y. constrains total strain accommodated by the xenoliths. Relationships 2 and 3 can both plot on a graph of temperature versus strain (Fig. 3), with their intersection

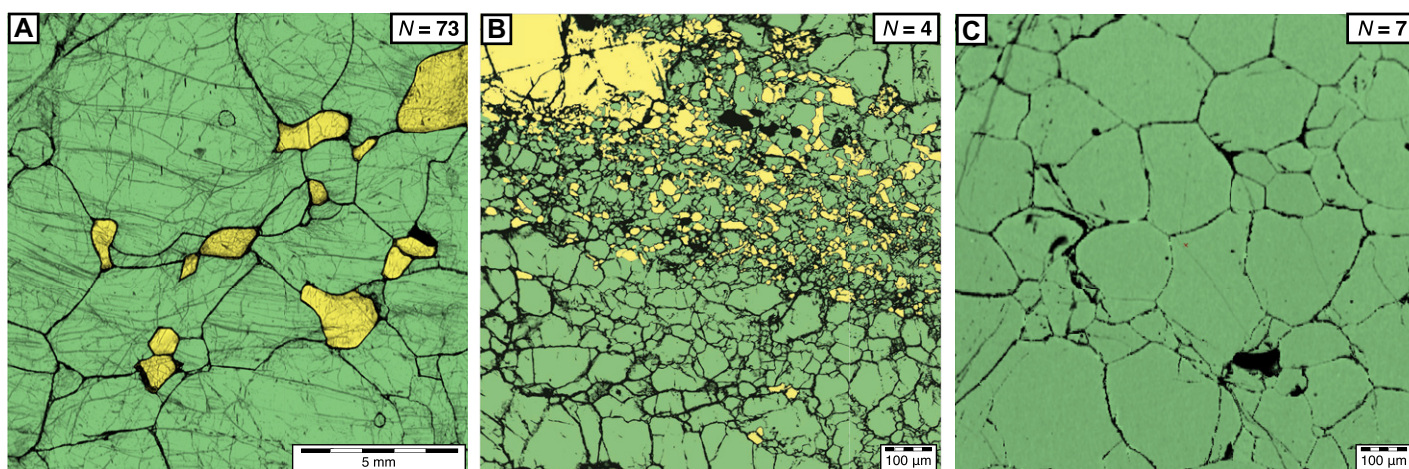


Figure 2. Micrographs of three xenolith types highlighting phase (olivine is false-colored green, pyroxene is yellow) and grain boundaries (darkened). “N” indicates numbers of each sample type. Note that the scale in A is 15 $\times$ that of B and C. (A) Coarse-grained sample (MOE18). (B) Fine-grained mylonite sample (LWA10) containing a mixture of olivine and pyroxene. (C) Fine-grained unlayered sample (MOE 12) showing several 120° triple junctions.

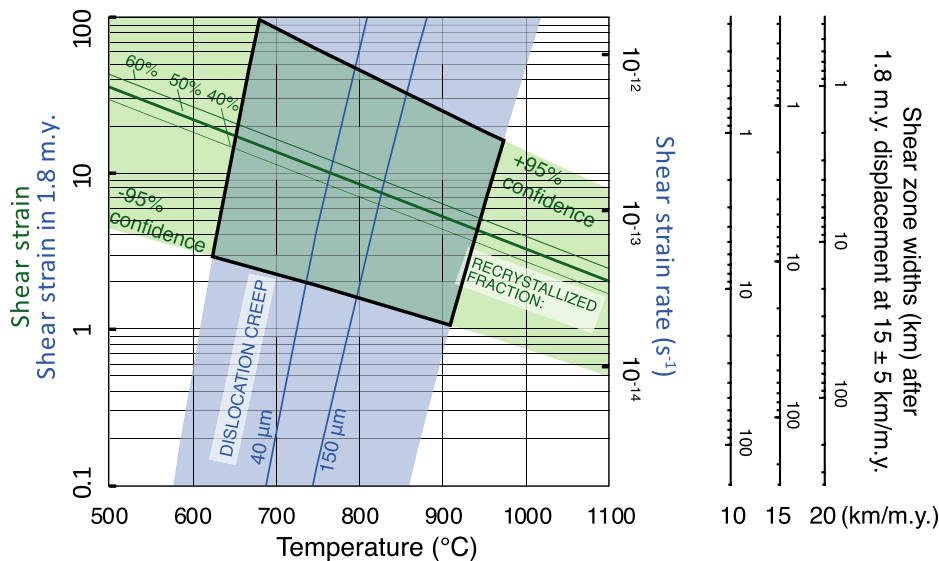


Figure 3. Relationships 2 and 3 plotted on a graph of temperature versus strain. Black-outlined area shows calculated deformation temperature, strain, and shear zone width based on the intersection of wet dislocation creep flow law (blue) and recrystallization relationship (green). Flow law (blue area) uses recrystallized grain sizes from fine-grained xenoliths (40–150 μm) and uncertainties in flow law and piezometer formulations. Shear strains were calculated from flow law-derived axial strain rates by multiplying by: (1) 1.8 m.y. over which deformation occurred, and (2) $\sqrt{3}$ (to convert axial to shear strain rate). Variations in recrystallization relationship due to variable recrystallized fraction (40%–60%) are shown to be relatively small. Alternative scales for shear zone width correspond to plausible 25 Ma Alpine fault offset rates of 10–20 km/m.y. (Sutherland et al., 2000).

constraining the temperature, strain, and strain rate of a plate boundary shear zone in the mantle within 1.8 m.y. of its initiation.

Relationship 1: Paleopiezometer

Recrystallized grain size is inversely proportional to stress (e.g., Twiss, 1977). To bracket reasonable stresses, we employed the olivine piezometer of Van der Wal et al. (1993) using recrystallized grain sizes from the coarsest and finest observed zones: a 150 μm grain size of a region that likely experienced post-deformation grain growth (e.g., Fig. 2C) corresponds to a stress of 21^{+6}_{-4} MPa; a 40 μm grain size (e.g., Fig. 2B) provides a stress of 57^{+21}_{-13} MPa. The higher stress value is a maximum constraint because it comes from a phased-mixed zone (e.g., Fig. 2B); such zones are routinely finer grained than coexisting pure-phase regions (e.g., Cross and Skemer, 2017). We used a stereologic correction factor of 1.75 in these calculations (Van der Wal et al., 1993).

Relationship 2: Viscous Flow Law

Using the stresses from the piezometer, we calculated strain rates as a function of temperature using the wet dislocation creep flow law for olivine (Fig. 3; Hirth and Kohlstedt, 2003). This flow law was chosen based on the evidence of wet conditions and microstructures indicative of dislocation activity in the mylonites. The other common deformation mechanism involving dislocations (dislocation-accommodated grain boundary sliding [disGBS]; e.g., Warren and

Hirth, 2006) is slower than dislocation creep at the conditions in Figure 3 (Hansen et al., 2011).

Relationship 3: From Recrystallized Fraction to Finite Strain

Cross and Skemer (2019) demonstrated that recrystallized fraction is a largely material-independent function of strain and homologous temperature (the fraction of the material melt temperature). To plot this relationship for the xenoliths and estimate uncertainties (Fig. 3), we used the Cross and Skemer (2019) database to fit a new curve with the *Polyfit* function in Matlab (<https://www.mathworks.com/help/matlab/ref/polyfit.html>; see the Supplemental Material¹) using only samples containing similar recrystallized fractions as the xenoliths (50% $\pm$ 10% recrystallized).

The intersection of relationships 2 and 3 in Figure 3 indicates deformation temperatures in the range 625–970 $^{\circ}\text{C}$ and shear strains of 1–100. If deformation began more recently than 25 Ma (i.e., an interval shorter than 1.8 m.y. between deformation and entrainment), then the plotted flow-law lines would shift slightly to the right; e.g., an order of magnitude shorter time causes a $+50^{\circ}$ change in temperature.

¹Supplemental Material. Supplemental figures, data, and code related to shear zone width estimates. Please visit <https://doi.org/10.1130/GEOLOGY.14605269> to access the supplemental material, and contact editing@geosociety.org with any questions.

DISCUSSION

Narrow Upper Mantle Shear Zones

When combined with an estimated $\sim 20^{\circ}\text{C}/\text{km}$ paleo-geothermal gradient (Scott et al., 2014), the calculated deformation temperatures indicate a depth of no more than 50 km. Oligocene–Miocene crustal thickness is estimated at ~ 25 km (Lamb et al., 2016), thus the mylonites formed in the uppermost mantle (25–50 km).

Mantle shear zone widths can be estimated if strains in the xenoliths (Fig. 3) are representative of a strike-slip shear zone deformed at 10–20 km/m.y. (Sutherland et al., 2000) for 1.8 m.y. For shear strains of 1–100, calculated widths are 0.2–32 km (Fig. 3). If the interval between the initiation of deformation and xenolith entrainment was shorter, estimated widths are reduced, e.g., a time interval of 0.2 m.y. results in widths of 0.02–3 km (see the Supplemental Material for examples).

The upper mantle within 60 km horizontal distance of the fault (or perhaps $\sim 30\%$ – 40% larger given likely Neogene crustal shortening; e.g., Little et al., 2002) was thus characterized by at least two narrow shear zones within minimally deformed wall rock. This interpretation is supported by four observations. First, the region affected by mylonitization (>120 km, assuming symmetry across the fault) is one or two orders of magnitude larger than the calculated shear zone widths. Second, several sites with exclusively coarse-grained xenoliths lie between sites containing evidence of mylonitization (Fig. 1). Third, a locality displaying exclusively coarse-grained xenoliths is found ~ 10 km distant from the fault (Fig. 1). Thus, from geometric arguments alone, if a highly localized main fault strand was centered over the present-day surface expression of the fault, its width was <20 km. Fourth, fine-grained, mixed-phase shear zones (e.g., Fig. 2B) are generally dominated by diffusion creep rather than dislocation creep, making the above strain rate estimates minima and estimated shear zone widths an upper bound (e.g., Cross and Skemer, 2017; Mulyukova and Bercovici, 2019).

These observations are consistent with multiple, highly localized upper mantle fault strands running sub-parallel to the early Alpine fault trend in a region ~ 150 km wide (Fig. 4A). Such an array may have linked to more-distributed deformation at depth; e.g., Collins and Molnar (2014) interpreted from Pn wave anisotropy a modern 100–200-km-wide zone of penetrative deformation at depths of 40–60 km. Alternatively, the Alpine dike swarm may have intruded along a lithosphere-scale Riedel shear zone (e.g., Cooper, 2020), and the xenoliths could thus preserve deformation associated with this structure (Fig. 4B). Either way, these rocks indicate that upper mantle deformation associated with the early Australian-Pacific plate boundary was highly localized.

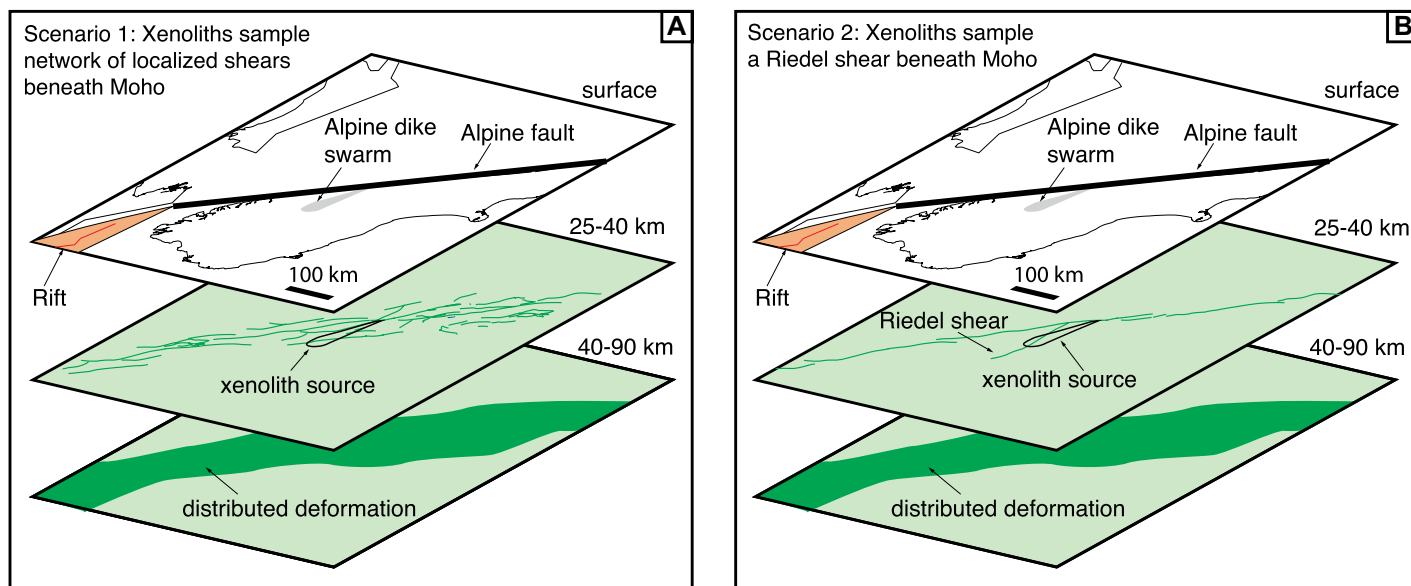


Figure 4. Cartoon showing two scenarios consistent with highly localized deformation in sub-Moho mantle lithosphere at ca. 23 Ma. The upper crust (white) is the same in both panels and is based on reconstructed paleogeography (Fig. 1 inset). Mantle is shown in green. Distributed deformation in the deep lithospheric mantle (40–90 km) is based on modern-day seismic anisotropy (e.g., Collins and Molnar, 2014). (A) Scenario 1: xenoliths sample an ~150-km-wide, Alpine fault-parallel, heterogeneous zone containing both localized shear zones and coarse-grained rocks relatively unaffected by shearing. (B) Scenario 2: xenoliths sample an isolated fault splay (Riedel shear).

Relevance to Modern Strike-Slip Faults

Seismic anisotropy occurs at poorly constrained depths in the present-day mantle beneath the modern Alpine fault, with a fast direction oriented within 5°–25° of strike (e.g., Collins and Molnar, 2014; Zietlow et al., 2014). Such anisotropy results from the preferred orientation of olivine crystals in zones wider than ~50 km (e.g., Vauchez et al., 2012; Skemer and Hansen, 2016). Thus, mylonite zones such as those sampled are too narrow to affect seismic anisotropy.

The modern degree of mantle localization may also differ from that recorded in the xenoliths due to crustal thickening and extensive deformation since 25 Ma, but if a narrow shear zone persisted, it could explain the sharp change in lithospheric thickness across the Alpine fault (Hua et al., 2018).

In terms of Moho depth and rates of plate motion, the 25–20 Ma Alpine fault was similar to the modern San Andreas fault (California, USA; e.g., Ford et al., 2014). Mylonites are not present at the single known xenolith locality adjacent to the San Andreas fault (Titus et al., 2007). The absence of mylonites at one locality should not be considered evidence against a highly localized shear zone, however: for the early Alpine fault example, only 18% of localities contain mylonites. It appears most likely that a single xenolith locality would not sample a highly localized shear zone.

CONCLUSIONS

The xenoliths provide rare samples of an initiating continental transform fault at mantle depths and the earliest-known physical evidence

of Alpine fault deformation. Within ~1.8 m.y. of likely fault initiation, mantle deformation was focused in narrow, highly localized shear zones with a total width of 0.2–32 km. These findings support the view that the upper mantle lithosphere consists of relatively rigid, plate-like domains separated by rapidly developed zones of focused deformation (Bercovici and Ricard, 2014; Ford et al., 2014).

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