Scale dependence of oblique plate-boundary partitioning: New insights from LiDAR, central Alpine fault, New Zealand

Nicolas C. Barth1*, Virginia G. Toy1, Robert M. Langridge2, and Richard J. Norris1

1DEPARTMENT OF GEOLOGY, UNIVERSITY OF OTAGO, P.O. BOX 56, DUNEDIN, NEW ZEALAND
2GNS SCIENCE, P.O. BOX 30-368, LOWER HUTT, NEW ZEALAND

ABSTRACT

We combine recently acquired airborne light detection and ranging (LiDAR) data along a portion of the Alpine fault with previous work to define the ways in which the plate-boundary structures partition at three different scales from <10⁶ to 10⁴ m. At the first order (<10⁶–10⁴ m), the Alpine fault is a remarkably straight and unpartitioned structure controlled by inherited and active weakening processes at depth. At the second order (10⁴–10³ m), motion is serially partitioned in the upper ~1–2 km onto oblique-thrust and strike-slip fault segments that arise at the scale of major river valleys due to stress perturbations from hanging-wall topographic variations and river incision destabilization of the hanging-wall critical wedge, concepts proposed by previous workers. The resolution of the LiDAR data refines second-order mapping and reveals for the first time that at a third order (10³–10⁰ m), the fault is parallel-partitioned into asymmetric positive flower structures, or fault wedges, in the hanging wall. These fault wedges are bounded by dextral-normal and dextral-thrust faults rooted at shallow depths (<600 m) on a planar, moderately southeast-dipping, dextral-reverse fault plane. The fault wedges have widths of ~300 m and are bounded by and contain kinematically stable fault traces that define a surface-rupture hazard zone. Newly discovered anticlinal ridges between fault traces indicate that a component of shallow shortening within the fault wedge is accommodated through folding. A fault kinematic analysis predicts the fault trace orientations observed and indicates that third-order fault trace locations and kinematics arise independently of topographic controls. We constructed a slip stability analysis that suggests the new strike-slip faults will easily accommodate displacement within the hanging-wall wedge, and that thrust motion is most easily accommodated on faults oblique to the overall strike of the Alpine fault. We suggest that the thickness of footwall sediments and width of the fault damage zone (i.e., presence of weaker, more isotropic materials) are major factors in defining the width, extent, and geometry of third-order near-surface fault wedges.

INTRODUCTION

In the past 10 yr, airborne light detection and ranging (LiDAR) technology has been demonstrated to be an effective tool for identifying active faults and assessing seismic hazards in a wide range of environments, including urban areas (northern Taiwan—Chan et al., 2007; Houston, Texas—Engelkemeir and Khan, 2008), grassland and scrub (California—Arrowsmith and Zielke, 2009; Zielke et al., 2010; Hunter et al., 2011), and densely vegetated forests (Washington—Harding and Berghoff, 2000; Haugerud et al., 2003; California—Zachariasen and Prentice, 2008; Slovenia—Cunningham et al., 2006). In particular, the ability of LiDAR to image the land surface beneath thick vegetative covers at a resolution of centimeters to meters has allowed the topographic features of these landscapes to be examined in revolutionary new ways.

Airborne LiDAR data were collected in July 2010 in a 1.5-km-wide by 34-km-long swath encompassing a portion of the heavily vegetated Alpine fault (the major plate-boundary structure in the South Island of New Zealand; Fig. 1) to better understand seismic hazards in the region. The LiDAR survey extends roughly between the townships of Franz Josef (which straddles a known surface trace of the Alpine fault) and Whataroa. Within the study area, about 75% of the terrain is covered by dense temperate rain forest, with the remaining 25% dominated by lightly populated active river floodplains. Within the latter, any evidence for a surface rupture of the most recent Alpine fault earthquake in A.D. 1717 (Yetton, 1998; Yetton et al., 1998) has already been erased. The prospect of a 30% chance of a surface-rupturing, M~8 Alpine fault earthquake in the next 50 yr (Sutherland et al., 2007; Berryman et al., 2012a) poses a significant national hazard to the country of New Zealand, and better understanding of surface rupturing along the fault is sorely needed. By incorporating interpretations of the new LiDAR data with aerial photo interpretation and decades of previous geologic mapping, we explore the significance of several orders of magnitude of shallow transpressional partitioning observed on the oblique-slip central Alpine fault and propose a new model for the geometry of structures observed at 10³–10⁰ m scales.

GEOLOGIC AND TECTONIC SETTING

The Alpine fault is the ~850-km-long (~600 km onshore) major active transpressive plate-boundary structure in the South Island of New Zealand (Fig. 1). It currently accommodates ~75% of total motion between the Pacific and Australian plates (Berryma et al., 1992; Norris and Cooper, 2001; Sutherland et al., 2006; Barnes, 2009; Langridge et al., 2010). Along with the North Anatolian fault in Turkey and the San Andreas fault in California, the Alpine fault is commonly cited as one of the major continental strike-slip faults in the world (e.g., Frankel and Owen, 2013; Molnar and Day, 2010; Sylvester, 1988).
In the study area, the Alpine fault is the geologic boundary between the granitic and gneissic Western Province (Australian plate) and gneissic and schistose rocks (Alpine Schist and Alpine Schist–derived mylonites) of the Pacific plate (Reed, 1964; Cox and Barrell, 2007), across which 480 km of cumulative strike-slip motion has taken place (Wellman[1949] in Benson, 1952). Dip-slip rates vary along strike of the Alpine fault. Only its central part experiences very high hanging-wall uplift rates, giving rise to the Southern Alps. In the vicinity of the LiDAR study area, the fault is a relatively planar, moderately southeast-dipping, dextral-reverse fault accommodating ~27 mm/yr of strike-slip motion and up to ~10 mm/yr of dip-slip motion (Norris and Cooper, 2001; Little et al., 2005; Sutherland et al., 2006). The fault is thought to rupture in large to great (M ~8) earthquakes with a mean long-term recurrence interval of ~300 yr, and it last ruptured in A.D. 1717 (Wells et al., 1999; Yetton, 1998; Yetton et al., 1998; Sutherland et al., 2007; Berryman et al., 2012a). In terms of single-event displacement, Alpine fault earthquake events have generated 6–9 m of dextral displacement and throw of up to 2 m (Cooper and Norris, 1995; Yetton and Nobes, 1998; Berryman et al., 2012b). Evidence from fault trenches and tree-ring chronologies suggest that at least 375 km strike-length of the fault ruptured in the A.D. 1717 earthquake (Wells et al., 1999).

The Alpine fault forms a particularly striking lineament visible from space, extending for hundreds of kilometers (Fig. 2A). While much of the fault has a relatively straight and uncomplicated surface expression, the central section exhibits sequences of transpressional oblique-thrust and strike-slip faults (Fig. 2B) dubbed "serial partitioning" by Norris and Cooper (1997, 1995). These zigzag sequences of north-northeast–striking, thrust/dextral-thrust faults and east-northeast–striking, dextral faults repeated over lengths of 1–10 km have been interpreted to form as a result of an angle of obliquity of 16° between the 071°-trending relative Pacific–Australian plate-motion vector (DeMets et al., 1994) resolved on the 055°-striking central Alpine fault, as well as local stress field perturbations due to topographic effects of a steep range front with deeply incised river valleys (Norris and Cooper, 1997, 1995). Norris and Cooper (1995) constructed transpressional sandbox experiments simulating the Alpine fault with and without valleys to support the topographic influence on serially partitioned fault segments. Serial partitioning here is confined to the upper ~1–2 km of the crust along ~100 km of the central Alpine fault.

An alternate geometry, parallel partitioning, in which oblique motion is accommodated on parallel-striking thrust and strike-slip faults, is more common globally (e.g., Molnar and Dayem, 2010; McCaffrey, 1996, 1992; Wentworth and Zoback, 1989). Parallel partitioning has been documented in detail on the Alpine fault offshore Fiordland by Barnes et al. (2005), where multiple fault splays ~1–2 km apart are interpreted to link into a single through-going fault at depth. At Darnley and Gaunt Creeks in the LiDAR study area, structural mapping by Easterbrook (2010) revealed two subvertical hanging-wall dextral faults thought to root into a southeast-dipping, dextral-thrust fault at shallow depths to form an ~200-m-wide zone of parallel partitioning. These two examples in Easterbrook’s study are the first suggestion of parallel partitioning on the central Alpine fault in the same area where serial partitioning was previously identified. A requirement of serial partitioning is that equal amounts of slip are accommodated on sequenced thrust and strike-slip fault segments, whereas varying degrees of slip partitioning are possible between parallel-partitioned thrust and strike-slip faults.

Imbricate out-of-sequence thrusts form as rapid river incision reduces the wedge taper below its critical value so that they internally imbricate (Norris and Cooper, 1997). The best known example of this is the Waikukupa River–Hare Mare Creek thrust system, where the wedges can be >1 km wide. A 30°-dipping basal plane requires a negative surface slope to render the wedge subcritical and therefore likely to imbricate in this way (Norris and Cooper, 1997). Negative surface slopes (i.e., toward the range) are only likely to occur where deep incision by rivers has taken place, hence the close relationship to valleys. Other prominent examples of abandoned thrusts of the Alpine fault are at Ward Hill near Paringa, 60 km southwest of the study area (Simpson et al., 1994), and near Simon Slew and Robinson Creek, 85 km southwest of the study area (Department of Geology, University of Otago, 2012, Alpine fault map Web site).

It should be emphasized that despite the complex surface-rupture patterns, all evidence suggests the fault is a single planar structure at depths greater than 500–1000 m, and that shallow partitioning does not appear to hinder the propagation of earthquakes through this region (Norris and Cooper, 1995). Along its entire onshore length, the fault exhibits no step-overs or discontinuities in the fault plane greater than 1 km, at depth (Sutherland et al., 2007). Active faults within the Western Province are rare in the central Alpine fault zone (Cox and Barrell, 2007). As the Alpine fault dips shallowly to moderately southeast with depth, fault traces south and east of the Alpine fault are rooted within the base of the Pacific plate (the main Alpine fault plane). Thus, the main trace of the Alpine fault tends to correspond to the most basinward (basal) fault trace, which still accommodates the most slip at the surface, with partitioning occurring only in the hanging wall.

Typical exposures along the central Alpine fault (e.g., Hare Mare Creek, 4 km southwest of study area; Gaunt Creek) consist of Pacific plate fault rocks thrust obliquely over fluvioglacial sediments on the Australian plate. The Pacific plate section typically consists of a centimeter-thin ultracataclasitic clay gouge, a 20–30-m-thick hydrothermally altered, highly fractured fault rock (commonly referred to as “cataclasite”), and a sequence of progressively less-fractured ultramylonite, mylonite, protomylonite, and paragneissic Alpine Schist (Norris and Cooper, 2007; Sibson et al., 1981; Wellman, 1955). The zone of intense fracturing (i.e., damage zone) associated with the Alpine fault is typically on the order of 100 m in width on the Pacific plate (e.g., Cooper and Norris, 1994; Norris and Cooper, 1997; Wright, 1998). These rocks are especially prone to near-surface faulting and slope failure (Korup, 2004).

The Alpine fault outcrops at the foot of the steep western range front of the Southern Alps. Some of the highest peaks (~3000 m) along the main divide of the Southern Alps occur adjacent to the high-uplift region around Franz Josef; these are found at a distance of ~15 km southeast of the surface trace of the Alpine fault. Fast-flowing mountain rivers in steep-walled...
glaciated river valleys exit the Southern Alps and cross the Alpine fault at elevations of ~100 m onto wide and active river floodplains lined with widespread glacial moraine deposits attributed to as many as five major middle to late Pleistocene glacial advances (Barrell, 2011). The most recent widespread glacial advance dates to the early or mid–Last Glacial Maximum (LGM), ca. 27,000–20,000 yr B.P., which covered most of the range front of the Southern Alps in ice (Barrell, 2011; Cox and Barrell, 2007; Suggett, 1990). A high annual precipitation of 5000 mm allows a dense temperate rain forest to flourish west of the main divide.

**METHODS**

LiDAR data used in this study were collected by NZ Aerial Mapping Limited using an Optech ALTM3100EA instrument flown from ~1200 m altitude. Data were collected in six overlapping swaths, ~780 m wide (for a total width of

---

**Figure 2.** (A) Extent of the onshore trace of the Alpine fault (arrows) visible from topography. Notice the straightness of the Alpine fault at this scale (<10⁶–10⁴ m). All images in this figure utilize a hillshade derived from the Land Information New Zealand 100 m digital elevation model. Illumination is from the northwest. (B) Major serially partitioned (oblique-) thrust and strike-slip faults mapped from field, aerial photographic, and light detection and ranging (LiDAR) data (refined after Norris and Cooper, 1995). Serially partitioned segments are of the order of 10⁴–10³ m in length. The strike-slip faults occur at the scale of the major river valleys and can be thought of as passive linkage structures necessitated by tears in the basal fault plane in the near surface. (C) All fault traces identified in this study (n = 268) mapped at 10³–10⁰ m scale from LiDAR data, field checking, and previous work. Local Australian-Pacific plate-motion vector is from NUVEL-1A (DeMets et al., 1994). Towns of Franz Josef and Whataroa are denoted in capital letters. Location names are those referred to in Figure 4.
on 30 September 2019

 Fault Traces

In total, 268 fault traces were identified within the LiDAR coverage area in a 200–800-m-wide zone along the range front (Fig. 2C) for a total fault trace length of 68.9 km. We compared our results to a compilation of Alpine fault traces mapped by researchers at the University of Otago's Department of Geology (publicly available through their Web site). We found 12.4 km of the total fault length in this study had been previously identified as "accurate" (±50 m) and that, by length, 82% of the LiDAR-mapped traces are new. Only 4.2 km (6%) of the fault traces southeast of the range front were previously identified.

Mean trace length is 260 m, with a few traces longer than 1 km. Many ends of fault traces are covered or have been removed by slope failure or creek erosion and aggradation, suggesting the fault traces would have been longer and more continuous at the time they ruptured. Some fault traces extend off the LiDAR-mapped area, suggesting there are places where extending the coverage farther southeast may reveal more fault traces. However, in most places, the LiDAR imagery covers the full width of surficial structures we infer to be part of the Alpine fault surface damage zone. We observe no fault traces within the interfluves northwest of the range front and see that fault traces tend to occur at low elevations north or west of the steepest portion of the range-front step. Fault mapping across the whole width of the central Southern Alps by Cox et al. (2012) also showed a relative absence of faults 5–10 km southeast of the study area. Field investigations west of the Whataroa River have allowed us to confirm that LiDAR-mapped fault traces are indeed faults, and they have also allowed us to identify 1–2-m-wide linear troughs in Riedel shear orientations below the resolution of the LiDAR data. In addition, trenching of a north-striking fault trace at Gaunt Creek confirmed the existence of a multi-event thrust fault (De Pascale and Langridge, 2012).

We recognize eight 10^3–10^4-m-scale serially partitioned segments in the LiDAR coverage area. The mapped segments are largely concordant with the regional-scale serial-partitioned segments mapped by Norris and Cooper (1995), with the exception of a new well-defined 3.5-km-long strike-slip segment between Docherty Creek and Franz Josef Township (Fig. 2B). Our mapping also shows a clearer link between serial-partitioned segments and major river valleys than these authors were able to make previously; the southwestern ends of oblique-thrust segments correlate to the southwestern side of major river valleys (e.g., Docherty Creek, Waio River, Waitangi-tna River, and Whataroa River). The overall strikes of oblique-thrust segments are 030°–053° (048° average), and those of strike-slip segments are 068°–088° (082° average). Thrust segments tend to be longer, although the longest strike-slip segment south of Whataroa Township is ~5 km long.

A rose diagram of 10^3–10^4-m-scale fault traces weighted by fault length gives thrust and dextral-thrust maxima at 040°–045°, oblique maxima at 060°–065°, and dextral maxima at 070°–075° (Fig. 3); when combined with structural measurements, these maxima are interpreted as thrust/dextral-thrust, oblique, and dextral fault sets, respectively. Range-front dextral-thrust fault traces are typically curvilinear and are expressed as poorly preserved west- to northwest-facing, 20-m-high scarps. Dextral-normal fault traces within 100–1000 m of the range front are expressed as linear or curvilinear, 1–10-m-high, south- to southeast-facing scarps or 10-m-wide symmetrical troughs. These dextral-normal traces have not been identified in the data set collected before this study, but they are thought to be coincident with east-west–striking clay gouge–cored faults observed in Docherty Creek (e.g., Norris and Cooper, 1995), which dip 70°–90°S with groove lineations raking 20°–60° from the west, indicating dextral-normal slip.

Dextral stream channel offsets are typically ambiguous along the range-front dextral-thrust traces. Alluvial fans have a tendency to deflect streams to the southwest (apparently sinistrally) as the highest part of the fan is shifted to the northeast relative to the mouth of the valley. The more rangeward faults have identifiable dextral offsets of creeks, particularly in the area west of the Whataroa River and near Darnley Creek, in part due to the creeks having deeply
Characteristic Fault Geometries

Characteristic transpressional fault geometries observed in this study are highlighted in Figure 4. McCulloughs Creek and Darnley Creek (Figs. 4A and 4B) are both examples of parallel partitioning in which a 100–300-m-wide fault wedge is bounded by a basinward oblique thrust and a rangeward dextral-normal fault rooted on a southeast-dipping Alpine fault plane. At McCulloughs Creek, the terrace riser north of the creek is offset ~100 m dextrally and 10 m down-to-the-southeast along the dextral-normal fault. A complex array of normal faulting occurs in the southeastern half of the fault wedge, while the northwestern half is dominated by three en echelon anticlinal ridges, clearly defined from LiDAR-derived contour data, that comprise the axis of the anticlinal fault wedge. At Darnley Creek in the Waitangi-taona Valley, a curvilinear thrust trace and a linear 10–25 m down-to-the-southeast dextral-normal trace bound the fault wedge. To the north, the dextral-normal fault offsets two stream channels, whereas to the south, it devolves into 75-m-long en echelon dextral-normal traces. Anticlinal ridges are parallel to the trace of the main dextral-normal fault.

The region between Franz Josef Township and Tatara Stream (Fig. 4C) is characterized by en echelon strike-slip faults that curve into parallelism with the rear of the fault wedge such that the overall character is similar to parallel partitioning. The basinward side of the fault wedge is dominated by oblique-thrust faults, and the rangeward side is dominated by dextral-normal faults. The range-front thrust faults have small apparent dextral offsets where they cross two small drainages, which correspond to dextral faults. This behavior is comparable to that generated in sandbox experiments conducted by Norris and Cooper (1995) using a rigid indenter and ignoring the effects of topography. The dextral faults have increasing down-to-the-southeast displacement as the faults approach parallelism with the rear of the fault wedge.

At Arthur Creek, two major fault traces are observed dextrally offsetting stream channels on the longest strike-slip serially partitioned segment in the study area. Well-defined east-northeast–striking anticlinal ridges (compared to more northeasterly striking anticlinal ridges on thrust segments) accommodated limited shortening on the basinward side of fault traces. No thrust traces were identified here. Fault traces here record the most cumulative dextral displacement preserved from offset features anywhere in the LiDAR study area.

The Docherty Creek–Waiho River and Gaunt Creek–Matainui Creek regions (Figs. 4E and 4F) are on transitions between near-orthogonally striking thrust and strike-slip serially partitioned segments. From Docherty toward the Waiho River, northeast-striking thrust faults transition to east-northeast–striking dextral-thrust faults to east-striking dextral-normal faults. Thrust fault traces still bound the basinward side of the fault wedge on this strike-slip segment. From Gaunt Creek toward Matainui Creek, north-northeast–striking thrust faults transition to east-striking dextral faults along the range front. More rangeward dextral faults strike northeast, effectively “cutting the corner.” Note that the width of the fault wedge (and density of faults) is greatest at the serially partitioned transition.

Lineaments

In addition to fault traces, 175 lineaments were identified (Fig. 5). Most of these are more rangeward than the fault traces and cut topography steeply, frequently as strikingly linear drainages. We found that lineaments (100–500 m long) revealed in the LiDAR imagery within 1 km of the Alpine fault have similar orientations and abundances to large-scale regional lineaments within 7.5 km east of the Alpine fault near Franz Josef and Fox Glacier compiled from aerial photographs by Hanson et al. (1990). Hanson et al. (1990) identified three orientation sets of lineaments: a 025°-trending set parallel to the strike of the foliation in the Alpine Schist, a minor set trending 130°, possibly related to extension fractures, and an east-west–trending set of dextral faults with late normal displacement. The structures in both studies are similar in orientation despite the fact that the bulk of the area examined by Hanson et al. was in the Alpine Schist, which is the protolith of the Alpine fault mylonites that underlie most of the study area described herein. We find that structures parallel to the Alpine fault and mylonitic foliation are more dominant in our data set than in this previous study (Fig. 4). The dominant strike (035°) is slightly more parallel to the Alpine fault than was observed by Hanson et al. (1990), likely indicating a clockwise rotation toward parallelism with the Alpine fault with decreasing distance from the fault. This is consistent with dextral shear having been accommodated in the ductile shear zone at depth with concurrent foliation development. For shear strains >5 as measured by Norris and Cooper (2003), the angle between foliation and the shear zone should be <10°.

Anticlinal Ridges

Anticlinal ridges associated with near-surface Alpine fault deformation have not been previously identified within the study area. We mapped 100 anticlinal ridges with characteristic strikes 0°–15° counterclockwise to the nearest fault trace strike (Fig. 6). The resolution of the
LiDAR reveals that anticlinal ridges are composed of smaller-scale en echelon anticlines, which could indicate development in a stepwise manner (e.g., Fig. 4A). The majority of anticlinal ridges cluster around a strike of 055° (the average strike of the Alpine fault), with a minority approaching a strike of 085°, i.e., close to the average strike of strike-slip fault traces in this study. In the field, we observed one of these anticlinal ridges near Arthur Creek, west of the Whataroa River (Fig. 4D). It consists of Whataroa-derived bedded river terrace deposits folded into an asymmetric anticline with a moderately dipping northwest limb and shallowly dipping southeast limb. A comparable recently uplifted asymmetric anticlinal structure associated with hanging-wall near-surface Alpine fault deformation has been identified near Paringa, ~60 km south of the study area (Simpson et al., 1994; Adams, 1979; Suggate, 1968).

Fault Kinematic Analysis

We used the field data to predict dips for the lineaments identified as fault traces. The hanging-wall sequence of fault rock, consisting of mylonites and cataclasites developed during ductile and then brittle shear at depth on the Alpine fault, is exposed in stream sections to the southeast of the most recent trace (e.g., Norris and Cooper, 2007; Toy et al., 2008). Uncemented clay gouge zones outcrop throughout this exhumed sequence (Reed, 1964; Sibson et al., 1979), including at the contact of hanging-wall cataclasite on footwall gravel. We assume the gouge zones developed during near-surface fault slip since they have not been affected by hydrothermal cementation. Their mean orientation (Fig. 7) is 030°/40°SE, but dips ranging from 30° to 50° are common. Additionally, the mylonitic foliation in the hanging wall, which has an average orientation of 055°/50°SE (Norris and Cooper, 2007), presents a strong mechanical anisotropy, and brittle faults should therefore parallel it. The dominant orientation of the brittle part of the fault at depth (below near-surface complexities) can be explained in this way.

However, in the ~10 well-exposed thrust segments of the fault, the boundary between hanging-wall cataclasite and footwall gravel commonly dips more shallowly (~30°) than the mylonites that overlie it. This may be due in part to near-surface stress control, as this shallower orientation has a dip similar to that predicted for thrust faults in the near surface, where a principal stress is likely to be vertical (Anderson, 1951). It may also be related to collapse of the overthrust material toward the free surface. By the same principle, we expect strike-slip faults to be near vertical. Reassuringly, steeply S-dipping, E-W–striking clay gouge zones with (sub)-horizontal striae have been observed in a number of places in the hanging-wall sequence (Fig. 6A; Gaunt Creek—Toy, 2007; Darnley Creek—Easterbrook, 2010; Docherty Creek and Waikukupa River—Norris and Cooper, 1995, 1997). These vertical features are easily eroded in creek sections and do not outcrop as commonly as thrusts, and so they are underrepresented in the compilation of gouge zone orientations (Fig. 7A).

By combining fault strikes from LiDAR with corresponding field observations of characteristic fault dips and striae on faults, we hypothesize a set of likely orientations and slip vectors for the major groups of faults identified in the LiDAR data (Table 1). If faults of these orientations bound semirigid crustal blocks, their intersections must approximately parallel the fault slip vectors in order to maintain geometrical continuity. For a slip vector parallel to the NUVEL-1A plate-motion vector trending 071° (DeMets et al., 1994), some fault orientations are thus further constrained so a single slip vector orientation (15°→071°) can lie within them, as indicated in Table 1 and Figure 7B. From Figure 7B, it is also apparent that it is difficult for such geometrical continuity to be maintained during coeval slip on reverse faults and faults of any other type. This may induce
the fault to partition into the other orientations as it approaches the free surface. We present a three-dimensional model for the geometry of interlinked fault segments with these orientations in the Discussion section.

An alternate model for likely fault orientations can be constructed based on the idea of a characteristic Riedel shear geometry. In natural situations, the elastic stress field generated in the material surrounding a slipping fault, particularly within a relatively unconsolidated (structurally weak) sequence above a basement fault, results in formation of a system of linked faults with characteristic geometry (Cloos, 1928; Riedel, 1929). Using this characteristic fault geometry, for a main fault orientation of 055°/45°SE (Norris and Cooper, 2007) and a slip vector parallel to the DeMets et al. (1994) Pacific-Australian plate-motion vector, Figure 7C shows a predicted fault system geometry. Most of the subsidiary fault orientations in this case strike parallel to fault traces identified in the LiDAR data set (e.g., P-shear at 038°/52°SE is similar to the group of faults with strikes 040°–045°; R-shear at 075°/42°SE is similar to the group of faults with strikes 070°–075°). Therefore, many of the faults identified in the LiDAR data could have initiated as part of a Riedel shear system arising independently of topographic and river incision effects. However, this system of faults cannot intersect parallel to the slip vector, so it is geometrically destabilized by ongoing slip. Internal deformation of Riedel shear–bounded blocks by folding could allow shear to continue on these structures. In either case, it is important to realize that displacement within the near-surface fault zone is controlled by slip/creep on the deep fault zone, and so the surface structures are constrained to an average strike similar to the deep regional structure and are required to accommodate oblique motion.

Fault Stability and Slip Tendency Analysis

We now consider the relative slip tendency of faults with the orientations indicated in Table 1. The orientation of the modern stress field around the Alpine fault has been estimated by a variety of methods (e.g., geodetics—Pearson, 1994; inversion of postglacial fractures—Norris and Cooper, 1986), most of which give $S_{max}$ (maximum horizontal compressive stress) trending 115° to 125°. The only three-dimensional solutions come from inversions of earthquake focal mechanisms (Boese et al., 2012; Leitner et al., 2001, their fig. 2.5), who derived a stress tensor for the central section of the Alpine fault between approximately Hari Hari and Haast where $\sigma_1$ (maximum principal compressive stress) trends ~10°–118° and $\sigma_3$ (minimum principal compressive stress) trends toward 220°. We take this as representative of the large-scale stress field, noting that it is likely to be significantly perturbed near the surface due to topography.

We evaluated the tendency of any particular fault orientation to slip by calculating the relationship between the static coefficient of friction ($\mu$) and the ratio of maximum and minimum principal stresses ($R = \sigma_1/\sigma_3$) at which slip will occur. This is accomplished by resolving the components of shear stress ($\tau$) and normal stress ($\sigma_n$) on the fault plane for various $R$, and then applying the limiting condition for failure, $\tau/\sigma_n > \mu$ (Collettini and Trippetta, 2007), for a range of $\mu$. This calculation was performed iteratively for increasing values of $R$ until this limiting condition was met, using a simple MATLAB script. Note that we assume that $\sigma_2 = \frac{1}{2}(\sigma_1 + \sigma_3)$ but obtain similar results if $\sigma_2 \approx \sigma_3$.

The results (Fig. 8) indicate that steeply dipping (i.e., strike-slip) faults have a greater tendency to slip than other orientations indicated in Table 1. This is apparent from the fact that, for a comparable ratio of principal stresses, a strike-slip fault will slip even if its frictional strength ($\mu$) is over twice that of any of the predicted thrust or oblique-thrust fault orientations. On the other hand, there is little difference in the strength of the various thrust and oblique-thrust fault orientations indicated by the LiDAR analysis when expressed in this way.

For comparison purposes only, we also evaluated a fault with the average strike of the Alpine fault overall, and dip parallel to the exhumed mylonitic foliation (055°/45°SE). This structure has even lower tendency to slip than any of the

---

**Figure 5.** Rose diagram (excludes fault traces). (A) Rose diagram (this study) showing azimuths of 175 lineaments with 5° binning. (B) Rose diagram redrawn from Hanson et al. (1990) showing the azimuths of 788 lineaments with 10° binning. Lineaments from Hanson et al. were traced from aerial photography of an area bounded by the Alpine fault, the Fox and Waiho Rivers, and ~7.5 km east of the Alpine fault.

**Figure 6.** Rose diagram of 100 anticlinal ridge axes with 5° binning.
structures we derived from the LiDAR analysis. This result suggests that new strike-slip faults will easily accommodate displacement within the hanging-wall wedge, and that thrust motion is most easily accommodated on faults oblique to the overall strike of the Alpine fault. The relative tendency of these fault orientations to slip is consistent with the formation of a partitioned fault system in the near-surface to accommodate oblique motion away from a nonideally oriented fault plane, and with our observations that fault traces in this study are reactivated during multiple earthquake rupture events.

As noted previously, it is unlikely that the local stress tensor around the faults is the same as that derived at depth by Boese et al. (2012) and Leitner et al. (2001), due to variations in topography and therefore in the orientation of the free surface. The anisotropic strength of the strongly foliated mylonites will also influence fault orientations and slip tendency. Furthermore, it is possible that the stress tensor is perturbed by the existing faults, so that a heterogeneous stress distribution allows slip on all fault orientations, despite their varying strengths. Essentially, kinematic constraints mean that slip has to occur on these faults, and stresses will locally rotate to allow this. Small-scale stress variations should be more thoroughly evaluated in the future by combining numerical models with in situ measurements derived from future borehole measurements.

DISCUSSION

First-Order Controls on the Alpine Fault

The Alpine fault is thought to have localized on an inherited Eocene (ca. 45 Ma) passive margin that separated continental and oceanic lithosphere (Sutherland et al., 2000). The Eocene rift boundary exploited Cretaceous oceanic transform faults and a major crustal discontinuity within the Zealandia continent that could be as old as Paleozoic (Sutherland et al., 2000).

The first-order structure (<10⁶–10⁴ m) of the central Alpine fault is thus simply imposed by the fact it experiences a component of rapid dip-slip motion throughout the continental upper crust of the South Island along a progressively weakening discontinuity. The fault zone only displays time-averaged dominantly brittle behavior in the upper ~8 km (Toy et al., 2010). Beneath this, viscous creep predominates within a ductile shear zone that continues to the base of the quartzofeldspathic crust at ~35 km (Little et al., 2005). Ductile shear...
results in development of a >1-km-thick zone of metamorphic tectonites with finer grain size than the protolith (i.e., mylonites; Sibson, 1977). Total simple shear strains range up to $\gamma = 180-220$, so a planar fabric is well developed parallel to the shear-zone boundaries (Norris and Cooper, 2003; Ramsay, 1980). Hot hanging-wall rock is uplifted relative to the footwall by shear displacement on the fault faster than diffusive cooling can occur, resulting in advection of hanging-wall isotherms across the ductile shear zone (Koons, 1987). This results in thermal weakening and localization of ductile shear, so that both dip-slip and strike-slip components of relative plate motions are focused on a single structure dipping 40°–60°SE (Norris and Cooper, 2007; Koons et al., 2003), a reasonably unfavorable orientation for slip according to an Andersonian view of fault mechanics (Anderson, 1951). Transient high stresses and high strain rates due to loading around a very narrow fault tip at the base of the seismogenic zone contribute to keeping the shear zone localized within the deforming lower crust (Ellis et al., 2006).

The ductilely sheared rocks are progressively exhumed up dip of the fault zone during successive earthquakes. At depths where viscous creep no longer predominates (<8 km), brittle shear remains localized within the exhumed shear-zone rocks, parallel to the boundaries of this zone at depth. This occurs because cohesion parallel to the well-developed shear-zone boundary-parallel foliation in the micaceous mylonites is lower than in any surrounding rocks. Consequently, brittle Mohr-Coulomb failure is most likely to occur parallel to the existing fabric (cf. Allen and Shaw, 2011). The end result is a fault zone that fails parallel to the inherited mylonitic foliation, which dips 50°–60°SE.

**Second-Order Controls on the Central Alpine Fault**

At a second order (10$^3$–10$^4$ m), the central section of the Alpine fault (where uplift rates are high) is partitioned along strike into sequenced (i.e., serial) oblique-thrust and strike-slip segments. These arise in the upper <1–2 km when stress perturbations from hanging-wall topographic variations (a steep range front with deeply glaciated valleys and high peaks) on a dipping oblique-slip structure exceed the strength contrast imposed by the anisotropic tectonite fabric (Norris and Cooper, 1995, 1997). Our mapping illustrates a clear link between serial-partitioned segments and major river valleys, with the southwestern ends of oblique-thrust segments correlating to the southwestern side of major river valleys, such as at Doherty Creek, Waiko River, Waitangi-taona River, and Whataroa River. At these same transitions, active strike-slip traces do not extend past the oblique-thrust segments into the hanging wall, indicating that strike-slip movement is limited to the section between the offset oblique thrusts. This clearly supports the concept of strike-slip segments as linkage structures between (and only between) tears in the basal fault plane. The LiDAR data therefore provide strong support for the basic idea of serial partitioning proposed by Norris and Cooper (1995, 1997). Slip on the strike-slip segments should thus depend on (and be equal to) slip on the oblique-thrust segments in the manner oceanic transform faults are dependent on oceanic-ridge spreading. As such, the strikes of the strike-slip segments would be expected to be close to the azimuth of the plate-motion vector accommodated on the Alpine fault. The average strike-slip segment strike of 082° might locally indicate an 11° clockwise rotation of the slip vector from the 071° plate-motion vector, which would be consistent with observations of greater obliquity and higher uplift rates along the central Alpine fault. Oblique-thrust segments tend to be longer because they are continuous at depth with a 055°-striking dextral-reverse fault plane. The strike-slip segments are tears within this surface constrained to an average 082° strike. The amount of rotation of the oblique thrust adjacent to these tears, and hence the length of the strike-slip segment, is related to the amount of westward thrusting, which in turn is constrained by the spacing of major river valleys (~10–15 km) and by the 082° average strike of the tears.

Recent drill core recovered from the Deep Fault Drilling Project (DFDP-1) at Gaunt Creek has revealed that where the basal fault is thrust over gravels at 90 m depth, it dips 30° (DFDP-1A). Dip increases to >30° in another hole (DFDP-1B) 100 m away, where the hanging-wall Pacific plate fault rocks are juxtaposed against the footwall Australian plate fault rocks at a depth of ≤130 m (Sutherland et al., 2011). There may be similar dramatic changes in the dip of the fault plane over a short distance elsewhere where the fault changes from placing basement-on-basement to basement-on-sediment in the near surface. The fault dip should continue to shallow with progressive overthrusting into these unconsolidated sediments. Consequently, the thickness of footwall sediments will have a large control on the width of the fault wedge in the hanging wall at scales ≤10 m. This is observed for the Waikuku thrust of the Alpine fault, ~4 km southwest of the study area, where exposures document decreases in basal thrust dip from 30° at low elevations to horizontal at the highest terminus (Norris and Cooper, 1997). Detailed field mapping by Norris and Cooper (1995) at Doherty Creek has shown that from south to north, the oblique-thrust segment bends from a northeast-striking, moderately dipping orientation to a north-northeast-striking, slowly dipping orientation while becoming more dip-slip in nature to the north. In addition to topographic controls, we propose that this greater amount of thrusting over footwall sediments on the northern end of the oblique-thrust segments might also significantly influence fault dip. With the decreasing dip of the basal thrust as it progressively overthrusts footwall sediments, it becomes harder to accommodate oblique motion and likely encourages a rotation in fault strike or parallel partitioning. The geometry from DFDP-1 and our observations suggest that the serial partitioning described by Norris and Cooper (1995) may be rooted considerably shallower than the 4 km maximum depth they calculated as the limit of stress field perturbation due to surface topography.

**Third-Order Geometry of the Central Alpine Fault from the LiDAR Study Area**

Our LiDAR-interpreted fault traces allow us to reliably document a surface-rupture zone on the central Alpine fault for the first time. By combining fault traces revealed in the LiDAR imagery with field observations, we can identify a smaller scale of parallel partitioning superimposed on the second-order serial partitioning. Although Norris and Cooper (1997) defined serial and parallel partitioning, they proposed them as alternative geometries for the accommodation of near-surface oblique motion. Here, we demonstrate that they coexist at different scales along the same fault zone.

We confirm that active faults within the Western Province (Australian plate) are rare in the central Alpine fault zone. As the Alpine fault dips shallowly to moderately southeast with depth, fault traces south and east of the Alpine fault are rooted within the base of the Pacific plate (the main Alpine fault plane). Thus, the main trace of the Alpine fault tends to correspond to the most basinward (basal) fault trace, which still accommodates the most slip at the surface, with partitioning occurring only in the hanging wall.

The dynamic landscape only records a fraction of the expected horizontal and vertical displacements expected on the Alpine fault in this area (~27 mm/yr and ~10 mm/yr, respectively). Glacial trimline and moraine crest elevations indicate extensive glaciation in this area during the Last Glacial Maximum (LGM). Because ice
faults in Figure 7B. We observe relatively few wedge above (which is highly fractured due to materials in the adjacent footwall and fault rock distributed into the lower rock mass strength (Koons et al., 2003). Thus, deformation becomes partitioned onto the fault traces at the rear of the plate motion is unable to be accommodated on 9C). In particular, a component of the strike-slip movement gradient on the basal plane and cause some shortening to be distributed as folding between the two faults planes bounding the fault wedge. The average fold axis trend is 055°–060°, i.e., slightly oblique to the overall fault wedge orientations of ~048°. A similar analog is observed on a large scale along the Hikurangi subduction zone on the east coast of the North Island, where regional folds and strike-slip faults within the accretionary prism trend parallel to the trench to indicate trench-perpendicular shortening despite the overall oblique displacement (e.g., Lamb and Vella, 1987). The antilines in our study are not produced by classic wrench tectonics, but by the kinematics of parallel-partitioned oblique thrust wedges.

While the wedge-bounding dextral-normal faults are kinematically stable over many earth-quake cycles, the oblique plate-boundary movement gradually transports them up the basal oblique-thrust plane. This causes the fault wedge to narrow until new dextral-normal faults form farther back. Whatever the mechanics, the basal fault is usually still oblique and accommodates the most slip (Norris and Cooper, 2007).

Additional Third-Order Controls on the Central Alpine Fault

It is expected for the near-surface structure of the Alpine fault to vary throughout glacial and interglacial periods. Removal of sediments due to glacial abrasion could act to reduce the width of the fault wedge, as a thinner sediment package would give less distance for the fault plane to rotate to a lower dip. The mass of extensive ice cover during a glaciation would serve to lessen the stress perturbations caused by the deep valleys cut into the hanging wall, potentially significantly enough to reduce the development of a serially partitioned fault zone. Extensive postglacial aggradation of river and glacial sediment would promote a wider near-surface fault zone as the fault shallowly overthrust a thicker sediment package in the footwall, and more sediment was available to be incorporated in a “bulldozed” fault wedge. Periods of degradation should focus the width of surface ruptures by rendering oblique-thrust wedges subcritical, as previously discussed by Norris and Cooper (1995, 1997).

At first glance, the predominance of range-ward facing dextral-normal scars on a transpressive plate boundary may seem counter-intuitive. Late-stage upthrust-facing normal fault scars are also ubiquitous in the Charwell region of the Hope fault in the northern South Island, despite the fact that the fault accommodates predominantly strike-slip transpressive motion (Eusden et al., 2005). Eusden et al. (2005) proposed a model in which a 1-km-wide fault wedge is extruded between thrust and normal faults, and then collapses to produce a secondary wedge comprising late normal faults in a 2-km-wide wedge in an unsupported hanging wall. In contrast to observations on the Hope fault, we find that no obvious crosscutting relationships exist between the observed fault traces to suggest the near-surface fault zone has evolved (i.e., partitioning has evolved with time). We suggest that normal-motion traces observed on the central Alpine fault arise purely geometrically to accommodate a more-or-less stable extruding fault wedge consisting of incohesive sediment and semicohesive fault rocks. These traces are thus coseismic and not postseismic collapse features as on the Hope fault. The predominantly strike-slip nature of...
Figure 9. Geometric models. (A) Oblique three-dimensional model based on geometry near Franz Josef (Fig. 4C). Topographic profile is derived from the light detection and ranging (LiDAR) digital elevation model. The relative sizes of the arrows show how slip is partitioned relative to a stationary Australian plate. Lines on fault planes show expected slip vectors from field data and calculations. Plan views show expected slip vector partitioning on the fault wedge boundaries (does not account for deformation within the fault wedge). (B) Fault-perpendicular cross section through front of model in A showing fault wedge structure. (C) Conceptual model showing relative strengths of materials. Note the significance of the depth to basement in the footwall for controlling the basal fault dip and the width of the fault damage zone for controlling the width of the fault wedge.
many of the apparently “normal” traces here also argues against a collapse mechanism. The fact that some of these fault scarps have faces greater than 10–15 m high, and a characteristic earthquake here generates <1.5 m throw, suggests that once established, reactivation of these faults is preferred over formation of new faults (as also demonstrated independently in our slip tendency analysis). This suggests that the fault configuration has been more-or-less stable since the LGM. We predict future earthquake surface ruptures will appear on or near known fault traces.

Second- and third-order structures are dependent on the first-order controls of geometry, continuity, and plate-motion kinematics of the fault at depth. The third-order structure of a given area is strongly influenced by its position on a second-order serially partitioned segment because the orientation of the basal thrust or strike-slip segment will have an influence on the geometry of the near-surface fault wedge. Third-order transpressional flower structures are most obvious on oblique-thrust segments (e.g., McCulloughs Creek, Darnley Creek, and Franz Josef), while strike-slip segments host fault wedges bounded by parallel strike-slip faults (e.g., near Arthur Creek and upper Waitangi-taona River). In this sense, there is a hierarchy of influences on fault segmentation from continuous fault planes and shear zones at depth (<10^4–10^5 m length scales) to zones of partitioned faults in the near surface (10^4–10^5 m length scales).

The near-surface complexity in this region has formed despite paleoseismic evidence that the Alpine fault ruptures during one through-going M7–8 event every ~100–500 yr (Wells et al., 1999; Yetton, 1998; Yetton et al., 1998; Sutherland et al., 2007; Berryman et al., 2012a).

The complexity therefore illustrates that during these large to great oblique-motion fault ruptures rooted in basement, slip does not remain localized when the fault propagates through unconsolidated surficial sediment and fault-damaged rock under low confining pressures. Near-surface complexity in the upper 1 km of the crust here is insufficient to halt earthquake rupture propagation (as proposed at different scales by Sutherland et al., 2007; Norris and Cooper, 1995).

CONCLUSIONS

We used LiDAR data to contribute to a structural hierarchy of along-strike observations on the Alpine fault.

At the first order (<10^4–10^4 m), the Alpine fault is a kinematically driven system in which seismic loading and thermal weakening by advection and exhumation cause localization of oblique slip on a single, relatively planar, moderately to steeply southeast-dipping shear zone at depth (Ellis et al., 2006; Koons et al., 2003). This orientation is inherited above the brittle-ductile transition due to the anisotropic fabric developed at depth. Development of weak clay minerals and associated high fluid pressures contribute to a localized fault zone in the upper crust (Warr and Cox, 2001). Consequently, at first order, the structure has a remarkably straight and continuous surface expression with no step-overs greater than 1 km (Sutherland et al., 2007).

At the second order (10^3–10^4 m), the central section of the Alpine fault (where uplift rates are high) is partitioned along strike into sequenced (i.e., serial) oblique-thrust and strike-slip segments that arise due to stress perturbations from hanging-wall topographic variations in a transpressional regime on a dipping structure (Norris and Cooper, 1995, 1997). Imbricate thrusts at this scale form as a result of rapid river incision reducing the wedge taper below its critical value (Norris and Cooper, 1997) and/or decreasing dip of the basal thrust as it progressively overthrusts footwall sediments.

At the third order (10^3–10^5 m) asymmetric positive flower structures in the hanging wall are bounded by parallel-partitioned dextral-normal and thrust faults rooted at shallow depths (<600 m) on a planar, moderately southeast-dipping, dextral-reverse fault plane. These parallel-partitioned fault wedges form with characteristic widths of 200–600 m bounded by and containing kinematically stable fault traces. Likely influences on third-order structure include thickness of footwall sediments, width of the fault damage zone, increases in friction on the basal fault with increasing overthrusting (due to abrasion of fault rocks), a decrease in basal fault dip in the near surface, sea level, glacial cycles of sedimentation, abrasion, and ice cover, and changes in stress orientations toward a free surface.

A fault kinematic analysis can predict the orientations of fault traces observed and indicates that topography is not a significant factor at this scale. Most fault traces observed have large offsets, indicating they are the product of many surface-rupturing earthquakes. A slip tendency analysis confirms the fault trace orientations are stable and are expected to accommodate repeated slip. Despite the multiplicity of near-surface traces, most displacement still occurs on a basal slip surface that preserves the hanging-wall fault rock sequence. We predict future earthquake surface ruptures will appear on or near fault traces identified in this study.

ACKNOWLEDGMENTS

We acknowledge the New Zealand Natural Hazards Research Platform for funding this study. We wish to thank Will Ries at GNS Science for his work processing the light detection and ranging (LiDAR) data. We thank Rupert Sutherland for helpful comments. This manuscript was greatly improved by critical and constructive reviews by Mike Oskin and Kate Scharer, and editorial comments by Eric Kirby.

REFERENCES CITED


Chan, Y.C., Chen, Y.G., Shih, T.Y., and Huang, C., 2007, Characterizing the Hsincheng active fault in northern Taiwan using airborne LiDAR data: Detailed geomorphic features and their structural implications: Journal of Asian


