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Incrementally developed slickenfibers — Geological record of repeating low stress-drop seismic events?

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ABSTRACT

An accretionary mélange of Triassic age ocean floor sediments exposed in the Chrystalls Beach Complex, South Island, New Zealand, comprises competent sandstone and chert phacoids set in a cleaved mudstone matrix, deformed in a continuous–discontinuous style at subgreenschist conditions. Deformation structures include a pervasive anastomosing fault–fracture mesh of multiple shearing surfaces, subparallel to cleavage, coated with incrementally developed quartz–calcite slickenfibers. Microstructural observations reveal slickenfiber growth by 'crack-seal' shear slip increments of 10–100 μm, with incremental slip transfer of the same order accommodated by opening of extension fractures that link *en echelon* slip surfaces. Individual slip surfaces can be traced for meters to tens of meters so that the ratio of average slip, u, to potential rupture length, L, predominantly lies within the range, $10^{-6}<u/L<10^{-5}$, characteristic of microearthquakes obeying 'constant stress-drop' scaling with a low stress-drop $\Delta\tau \sim 30$ kPa, typical of low frequency earthquakes. The host-rock assemblage, metamorphic environment, inference of near-lithostatic fluid overpressures, low stress-drop and mixed continuous–discontinuous shearing, resemble conditions and characteristics of low frequency earthquakes as identified within the seismic signals recorded during episodic tremor and slow slip events, at the downdip end of the seismogenic subduction thrust interface and within accretionary prisms.

1. Introduction

Active deformation pervades crust adjacent to plate boundaries. In most well-studied subduction zones, and along the San Andreas fault, a proportion of relative plate motion is accommodated by episodic tremor and slow slip–transient creep events occurring with remarkable regularity and accompanied by distinct low frequency seismic signals or high levels of microseismic activity (e.g. Brown et al., 2009; Gomberg et al., 2010; Obara, 2002; Peng and Gomberg, 2010; Rogers and Dragert, 2003; Shelly, 2010; Wallace et al., 2009). Relics of repeating microseismic activity should therefore be widespread in ancient crust surrounding paleoseismic zones. Small-scale faults are widely distributed in ancient rock assemblages (e.g. de Ronde et al., 2001; Faulkner et al., 2010; Meneghini and Moore, 2007) but definitive evidence that slip on such structures was necessarily seismic is often lacking (Cowan, 1999). One approach is to look for evidence of transitory high levels of power dissipation (~10 MW/m^2 for every 10 MPa of shear resistance) anticipated for seismic slip (Sibson, 1980). This may take the form of pseudotachylyte derived from friction-melting or evidence of intense transient thermal anomalies localized around faults recorded, for example, by thermochronologic or vitrinite reflectance anomalies (Bustin, 1983; O'Hara, 2004). Fault-generated pseudotachylyte is, however, only likely to be easily recognizable for larger slip events ($M_w>3$) and in fact, records of fault-generated pseudotachylyte are sparse and generally restricted to crystalline rock assemblages that were comparatively intact and dry at the time of faulting (Sibson and Toy, 2006). Low frequency events have very low stress drops, suggested to indicate high fluid pressure on the fault plane (Ito and Obara, 2006). Inferred near-lithostatic fluid pressure in the region of episodic tremor has been suggested from several studies (Katsumata and Kamaya, 2003; Matsubara et al., 2009; Shelly et al., 2006), and implies shear resistance is too low to produce a distinct thermal anomaly during slip in these events. Thus, evidence for localized high temperatures is unlikely to characterize the geological record of microearthquake or tremor activity.

An alternative approach is to look for evidence of recurring incremental slip comparable to present-day seismic displacements on exhumed faults, as is routinely done for larger ruptures ($M_w>4$) in paleoseismic trenching investigations (McCalpin, 2009). At the microearthquake level, for example, high-resolution studies along the creeping segment of the San Andreas fault and at Parkfield have shown that a significant proportion of recorded microearthquakes are repeating 'characteristic' events (Nadeau and McEvilly, 1997; 2004); slip events of the same size

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and displacement that recur at the same location at fairly regular intervals. Repeating, episodic tectonic tremor signals also appear to contain numerous small earthquakes, and therefore also represent repeating incremental slip events (e.g. Brown et al., 2009; Ide et al., 2007; Shelly et al., 2007). Shear displacements for such microearthquakes are so small (sub-millimeter), that they will generally only be observable at the microscopic level. Although indefinitive, evidence of recurring slip increments on exhumed faults at this scale may be regarded as a probable indicator of former microearthquake or tremor activity.

2. The Chrystalls Beach Complex

The Chrystalls Beach Complex, exposed along the SE Otago coast on the South Island of New Zealand about 60 km southwest of the city of Dunedin, is largely made up of dismembered mid- to late-Triassic ocean floor sediments and has been interpreted as part of an accretionary mélange (Fagereng, 2011; Nelson, 1982). Principal constituents are sandstone and shale with minor proportions of radiolarian chert, tuffaceous sediment, and scattered pillow basalts. Competent lenses (phacoids) of sandstone, chert, and basalt fragments range in size from centimeters to around 200 m and are set in a cleaved pelitic matrix (Fig. 1A,B).

Rocks within the mélange have a complex history including 'soft-sediment' deformation as well as 'hard-rock' deformation in a sub-greenschist environment (Fagereng, 2011). The lowest grade exposures (in which the fault–fracture mesh described below is best preserved and least metamorphically and microstructurally overprinted) occur in the most southwesterly corner of the complex at Chrystalls Beach itself, where rocks are inferred to have experienced pumpellyite–chlorite facies metamorphic conditions with $P < 550$ MPa and $T \sim 300$ °C (Fagereng and Cooper, 2010).

3. Fault–fracture mesh

Displacement was accommodated in a fault–fracture mesh and by dissolution–precipitation creep in the phyllosilicate-rich matrix, so that the mélange as a whole deformed by mixed continuous–discontinuous deformation (Figs. 1A,B, 2A) (Fagereng and Sibson, 2010). Discontinuous shear occurred on innumerable shallowly dipping slip surfaces, subparallel to cleavage, and coated with quartz/calcite slickenfibers (Fig. 1A,B,C,E) (Fagereng et al., 2010). Individual slickenfiber shear surfaces extend from meters to many tens of meters with a total displacement commonly of some centimeters. The slickenfibers commonly curve or change growth direction abruptly, indicating that the mélange of competent phacoids enveloped within a mesh of anastomosing shear surfaces functioned as a 'dead-fish' shear zone. Multiple generations of slickenfiber shear surfaces were apparently active at different times. 'Sense-of-shear' is variable but top-to-the-north indicators predominate (Fig. 1C).

Extension veins commonly link adjacent shear veins in dilational step-overs (Figs. 1D, 2A), and are oriented at a high angle to shear veins (Fig. 1E). Such step-overs are present at all scales in the crust from kilometers to subcentimeters. This study focuses on slickenfiber shear veins resembling dilational step-overs at the centimeter scale (Fig. 2A). At this scale shear displacement is accommodated by cyclical opening of extension fractures between adjacent microscopic slip surfaces, termed 'micro

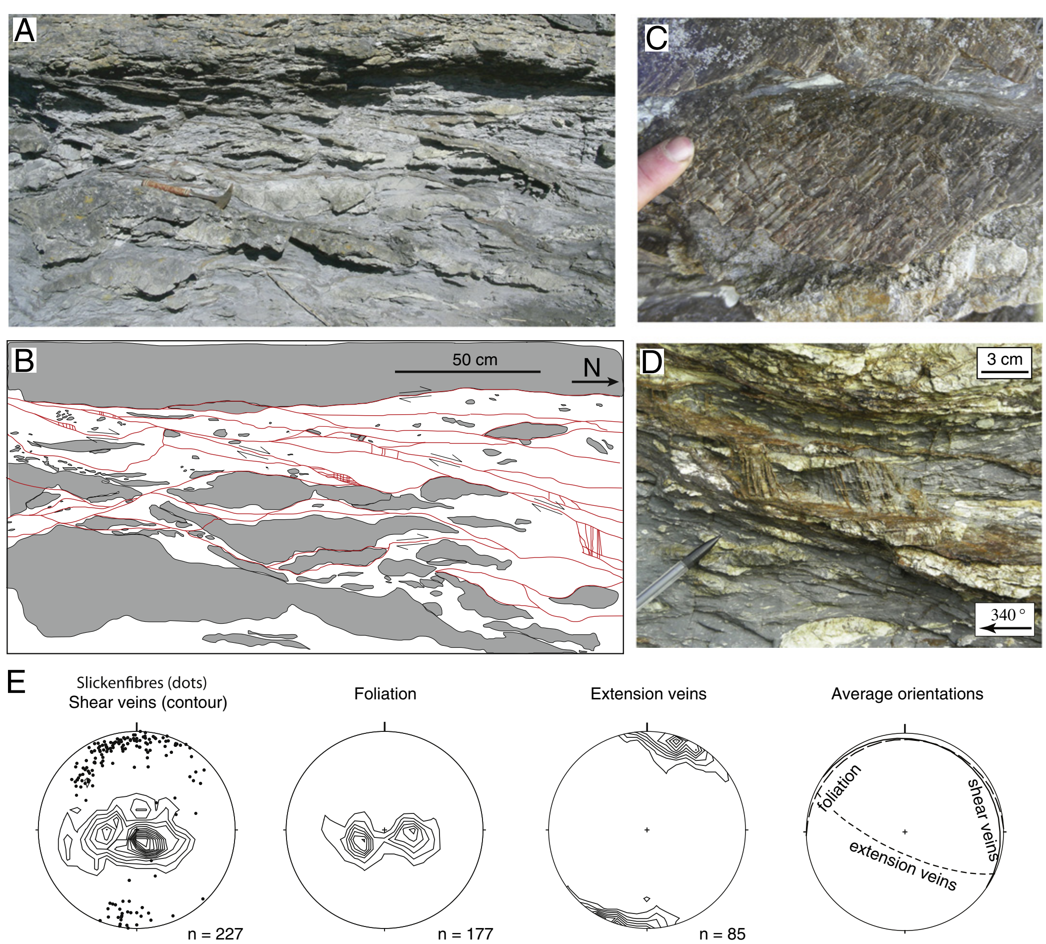

Fig. 1. Outcrop appearance of the Chrystalls Beach Complex mélange and fault–fracture mesh. A. Representative outcrop photograph, with outcrop map B showing competent sandstone and chert phacoids (gray) in a politic matrix (white) cut by a vein-filled fault–fracture mesh (red lines). C. Slickenfibers indicating top-to-the-north shear. D. Dilational step-over where extension veins link *en echelon* shear surfaces. E. Lower hemisphere, equal angle stereoplots showing orientations of slickenfiber shear veins, foliation, and extension veins within the Chrystalls Beach Complex.