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The role of silica redistribution in the evolution of slip instabilities along subduction interfaces: Constraints from the Kodiak accretionary complex, Alaska

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A B S T R A C T

Quartz veins from a subhorizontal shear zone in the Kodiak accretionary complex in southwest Alaska record cycles of cracking and sealing contemporaneous with simple shear, and analysis of the vein array in the context of silica dissolution, diffusion, and precipitation leads to the conclusion that the time needed to seal after a fracture event overlaps with the time scales associated with the recurrence of slip instabilities along active megathrusts. The central belt of the Kodiak accretionary complex is interpreted as a shear zone developed adjacent to a paleo-decollement that was active in the Late Cretaceous based on large strain magnitudes, recumbent isoclinal folds, and regional cleavage patterns that depict rotation of the steep cleavage that characterizes most of the Kodiak Formation into the horizontal fabrics of the central belt. Within this regional shear zone, crack-seal veins composed of quartz with phyllosilicate inclusion bands are spaced at less than a cm but *en echelon* vein arrays are spaced at 500 cm. These arrays indicate top-to-the southeast shear on southeast dipping brittle-ductile shear zones. Vein textures indicate cracking and sealing of thin veins in the matrix, but thicker veins in *en echelon* sets record initial cracking and sealing followed by periodic collapse of fracture porosity at a frequency that is lower than the frequency of crack-seal cycles. Silica depletion zones in the wall rock adjacent to veins indicate local transport of silica by diffusion. By combining the maximum time in which diffusion could dominate over advection with the time needed to precipitate the quartz associated with one crack-seal band, we show that a reasonable range of ΔP, or pressure difference between matrix and crack, can produce crack seal bands in less than 10 days. This time frame is less than the recurrence of earthquakes, and similar to the duration of some slow earthquakes in nature. Therefore, silica redistribution could play a role in modulating the frequency of plate boundary slip instabilities along convergent plate boundaries.

1. Introduction

Seismicity and GPS-based velocity fields from convergent plate boundaries record temporal and spatial deformation patterns consistent with significant downdip variations in slip behavior (Scholz, 1998). These variations are attributed to changes in the frictional properties of the megathrust interface—properties that control the cycles in differential stress associated with slip instabilities related to earthquakes. Slip instabilities require velocity weakening (Scholz, 2002), and much of the fault behavior observed along subduction zones such as downdip transition from creep to stick slip can be characterized by friction experiments and the rate-state frictional characteristics of fault materials (Marone, 1998). However, the recent recognition of a wider range of slip behavior such as earthquakes that slip at slow velocities (e.g., Gomberg et al., 2010) indicates that a new paradigm is needed that accounts for the full range of fault behavior and allows for both the generation of slip instabilities and, in the case of slow earthquakes, a mechanism for stabilizing them (Rubin, 2008).

Any paradigm for subduction zone plate boundary behavior should include thermally activated processes such as dissolution, diffusive transport, and precipitation–processes that vary in predictable ways in response to thermal structure and subduction inputs. Variations in fluid pressure can also be evaluated because the downdip variation in effective stress and fluid pressure is a function of the locations of fluid sources (e.g., dehydration

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reactions) and the permeability distribution (e.g., Saffer and Tobin, 2011). Regions of high fluid pressure are likely sites for hydrofracturing, a process that produces local chemical potential gradients that drive silica redistribution and sealing/healing (Fisher and Brantley, 1992). The importance of pressure solution is also suggested by experimental investigations of frictional properties on the subduction interface as a function of temperature (den Hartog et al., 2012).

One of the best opportunities we have to study the processes that occur in fault zones due to stress cycling, healing, and evolution of slip instabilities lies in the observation of fault rocks exposed in ancient accretionary complexes. Accretionary complexes are built by a combination of offscraping of shallow trench fill to form the outermost wedge of unmetamorphosed sediments (Aoki et al., 1982; McCarthy and Scholl, 1985) and underplating of subducted material that bypasses the frontal wedge and is transferred across the plate boundary by collapse of the footwall sediments to form duplexes or megalenses (Sample and Fisher, 1986) (Fig. 1). Because the process of underplating can occur at a variety of depths and inherently involves deactivating and incorporating a decollement zone into the overriding forearc (Fig. 1), the accreted paleodecollements associated with underplated rocks document a range of downdip slip behavior (Rowe et al., 2013).

The stress cycling in the forearc can impact fluid pressures and plumbing (Sibson, 2013). Considering shallow sources of water in pores and in clays combined with deeper sources of metamorphic fluids, Saffer and Tobin (2011) argued for the ratio of fluid pressure to lithospheric pressure along the plate boundary to be elevated i) at shallow levels due to undrained loading of underthrusting sediments and ii) at deeper levels from dehydration reactions in materials of low permeability/porosity (Fig. 1). Such a model allows for low effective stresses at the updip and downdip ends of the seismogenic zone and at depths consistent with slow earthquakes. If permeability is tied to the earthquake stress cycle through fault valve behavior (Sibson, 1990, 1992) or variation in the orientations of principal stress, then fluid pressure around the plate boundary should fluctuate with the same frequency as cycles in differential stress (e.g. Sibson, 2013).

Evidence for cyclic variation in fluid pressure is well documented in ancient accretionary wedges in the form of crack-seal textures in calcite and quartz veins (e.g. Vannucchi et al., 2010; Fagareng et al., 2011) and these features have been suggested as recorders of the seismic cycle (Bouillier and Robert, 1992; Fisher and Brantley, 1992; Petit et al., 1999), although it has alternatively been argued that they arise due to crystallization pressure and variations in geochemistry at the vein wall (Wiltschko and Morse, 2001). A particularly dense array of crack-seal quartz veins is exposed within the Central Belt of the Late Cretaceous Kodiak Formation (Fisher and Byrne, 1990; Fisher et al., 1995; Fisher, 1996), a regional subhorizontal shear zone from the Kodiak accretionary complex in southwest Alaska (Fisher and Byrne, 1992). Here, the deformation conditions are characteristic of the lower end of the seismogenic zone or the inferred shallowest extent of slow earthquakes, with a temperature of ∼280 °C and with low effective stresses driven by high fluid pressures related to the onset of dehydration reactions in low permeability rocks (Brantley et al., 1997). Individual veins record hundreds of cyclic events of cracking and crack closure within a regime of simple shear.

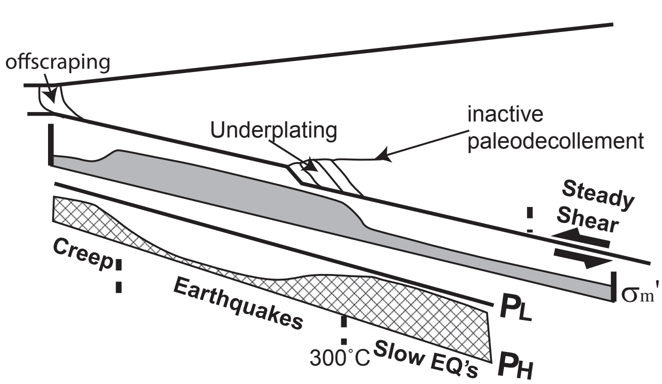

Fig. 1. Conceptual model for behavior of the seismogenic zone based on Liu and Rice, 2007. Downdip variations in effective mean stress (σ_m') and fluid pressure relative to hydrostatic (P_H) and lithostatic (P_L) pressure (from Saffer and Tobin, 2011). Duplex is shown consisting of thrust slices accreted by collapse of the footwall at a ramp in the decollement (e.g. Sample and Fisher (1986)), incorporating an inactive decollement into the accretionary wedge.

In this paper, we summarize our publications from the 1990s with respect to interpretations of the regional tectonic setting and physical conditions for deformation of the Kodiak Formation by placing the rocks in the context of the Late Cretaceous subduction zone. Then, we review the structural geology of the central belt of the Kodiak Formation and the arguments that this deformation occurred along or adjacent to a paleo-decollement. Given this framework, we characterize the distribution of veins and the implications of these spatial patterns for fracture networks and plumbing using the approach we advocated in Fisher and Brantley (1992). The microstructures in the veins are considered within the context of the inferred evolution of the system. Finally, we evaluate the time needed to precipitate the quartz associated with each cracking event to place a constraint on the periodicity of cracking and the potential cause of cycling in fluid pressure.

Unlike our original calculations (Fisher and Brantley, 1992), however, we note that the slates are likely more porous than we had assumed, and we note that analyses of oxygen isotopes and fluid inclusions have indicated higher temperatures and salinities, respectively (Brantley et al., 1997). With these new parameters, we show that the vein set exposed in the Kodiak accretionary complex records crack sealing and silica transport at rates that could influence the evolution of slip instabilities related to slow and fast earthquakes.

2. The Kodiak Formation: the interior of a Late Cretaceous forearc

The Kodiak Accretionary complex in southwest Alaska is an assemblage of oceanic lithologies that were accreted episodically along a convergent margin that has likely been active since the Jurassic (Fig. 2) (Byrne and Fisher, 1987). The complex consists of a series of northeast-striking accreted units that decrease in age and metamorphic grade toward the Aleutian Trench from Jurassic blueschists to Eocene low grade sedimentary rocks (Moore et al., 1983). The Eocene Sitkalidak Formation, which is exposed along the southeast side of the archipelago and forms the basement for the shelf offshore, is likely offscraped, as it displays low metamorphic grade, both landward and seaward vergence and is unconformably overlain by slope basin material (Moore and Allwardt, 1980). All the other accreted units are underplated, as indicated by higher metamorphic grades (Sample and Moore, 1987), seaward vergence for all folds (Sample and Moore, 1987, Fisher and Byrne, 1992), reset zircon fission tracks (Clendenen et al., 2003), and fluid inclusions that record temperatures that exceed 250 °C (Vrolijk, 1987; Brantley et al., 1997). The Kodiak Formation, for example, has oxygen isotope data and fluid inclusions from quartz veins that record temperatures of ∼270–280 °C and pressures of 260 ± 40 MPa (Brantley et al., 1997) in the thermally elevated convergent setting that preceded ridge subduction (e.g., Bradley