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A Geologic Window Into a Subduction Megathrust

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Megathrust faults marking the subduction of oceanic plates are fundamental features of plate tectonics. In addition, these faults have significant societal relevance since friction along them can generate devastating earthquakes. One of the most important tasks in solid Earth sciences is to understand the mechanical and thermal processes that control the behavior of these fault zones. Geophysical studies of earthquakes address key issues of fault mechanics [*National Research Council*, 2003], and critical information can also be recovered from the geological record through structural and petrologic studies in areas where paleo-subduction megathrusts have been exposed at the surface.

Unfortunately, few such faults have been identified in the field, in contrast with several examples of major thrust faults formed during continental collision [*Moores and Twiss*, 1999]. Thus, we lack observational evidence of the actual physical conditions along subduction zone faults. Is there water along the faults? How large are stresses, and how do they vary? Is shear heating important? Is melt present? A rare example in the geologic record is the Salinas shear zone in the Coast Ranges of central California, a late Cretaceous subduction zone thrust fault (Figure 1). The exposed fault is an expression of the shallow subduction of the Farallon plate beneath the southwestern United States, which is widely documented in the geologic record through the latest Mesozoic (76 million years ago) eastward migration of deformation and magmatism known as the Laramide orogeny [*Saleeby*, 2003].

Salinas Shear Zone

The Salinas shear zone separates an upper plate consisting of North American intrusive arc rocks (the Salinian arc) from a lower plate comprising a sequence of metamorphosed sediments deposited in a subduction trench (the schist of Sierra de Salinas). The two units were originally located some 150 kilometers apart across the plate margin. In the earliest stage of the Laramide orogeny, the sediments became attached to the lower plate, in this case the subducting Farallon plate, and were transported downward before reattaching to the upper, North American plate by tectonic underplating.

During that process, the top of the sedimentary section became the subduction megathrust, which is currently exposed as the Salinas shear zone. Subsequently, the megathrust migrated downward, reuniting the underplated sediments with the upper plate and preserving the fossil shear zone. Extensional collapse and erosion of the upper plate resulted in more than 30 kilometers of exhumation in the latest Cretaceous, eventually bringing the deep arc rocks, the shear zone, and the schist to the surface. During the late Cenozoic, the entire package of rocks was transported to its present location in central California by more than 300 kilometers of right-lateral slip along the Cenozoic San Andreas fault system (Figure 1). However, none of the right-lateral slip faults within the Coast Ranges significantly affects the pre-Cenozoic tectonic assembly addressed here.

The schist of Sierra de Salinas is correlative to similar schists in southern California, which represent subduction trench deposits underthrust beneath the California continental arc during the Laramide event [*Grove et al.*, 2003]. The schists were deposited, subducted to depths of approximately 35 kilometers at plate tectonic speeds (> 5 centimeters per year), and then quickly exhumed. Geochronologic data from the schist of Sierra de Salinas indicate that these events occurred between 77 and 71 million years ago. This interval in time corresponds with the termination of Salinian arc magmatism at approximately 81 million years ago and the appearance of deep arc related rocks at the surface at about 68–69 million years ago [*Kidder et al.*, 2003]. Similarities in age and isotopic composition indicate that prior to underplating of the schist, the Salinian arc was part of a continuous volcanic system that included the Sierra Nevada and Peninsular Ranges arcs.

The Salinas shear zone represents the original contact between the Salinian arc and the underplated schist of Sierra de Salinas. High-temperature fabrics are developed both in upper plate rocks and the schist. Constraints on metamorphic equilibria from the upper plate, the lower plate, and the shear zone itself [*Kidder and Ducea*, 2006] indicate that shearing initiated in the upper plate at depths of 30–40 kilometers and a

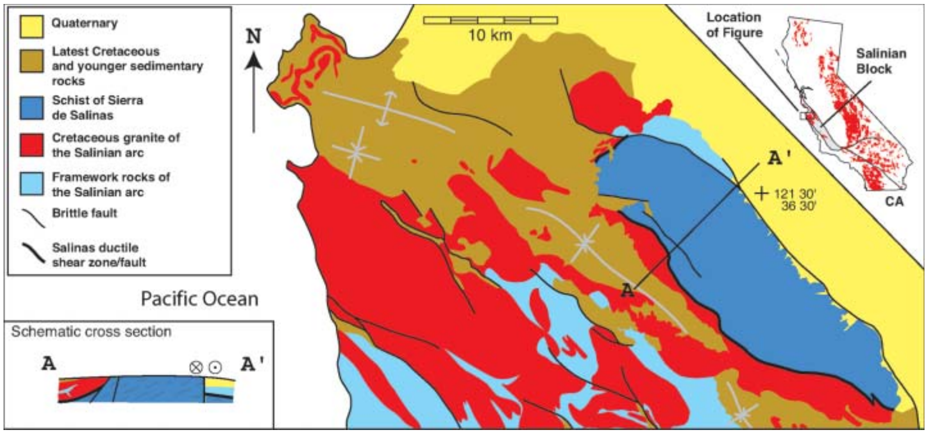

Fig. 1. Simplified geologic map of coastal central California showing the basement and cover units of the Salinian arc, the schist of the Sierra de Salinas, and recent sedimentary cover. (top right) Map showing the distribution of arc-related rocks in California. (bottom left) Cross section A–A' depicts the structural relationships between the upper plate Salinian arc and the underlying schist.

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temperature of approximately 700°C. In thin section, hornblende grains from the upper plate are reduced in size and replaced by clinopyroxene in highly deformed bands (Figure 2). This metamorphic reaction is transitional between the amphibolite and granulite facies (referred to below as simply 'granulite facies') and indicates a hotter and dryer metamorphic state in the shear zone than what is recorded in adjacent rocks. The products of the reaction were melts or hydrous fluids, which escaped in part along fractures. A small percentage of melt remains as deformed veins, which cut across the shear zone [*Kidder and Ducea*, 2006]. These relationships indicate that shear heating was an important process in the shear zone.

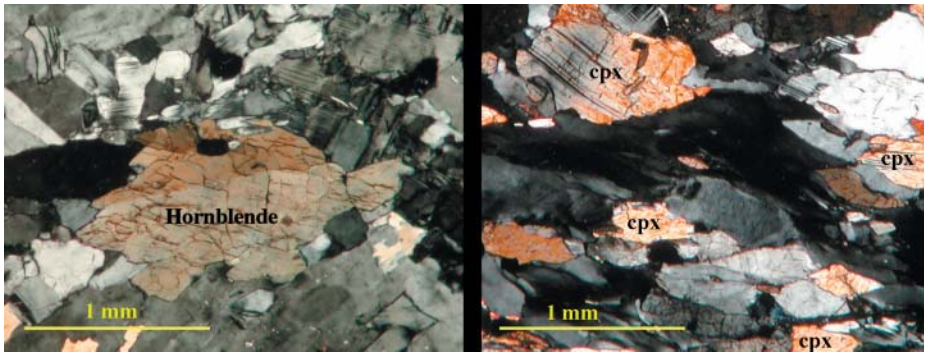

Fig. 2. Microphotographs from a single thin section (crossed polars) within the Salinas shear zone showing association of granulite facies metamorphism with deformation. (right) A highly deformed band from the shear zone. The yellow crystals are clinopyroxene (labeled 'cpx'). Deformation twins in large grain can be seen in the upper left. Dynamically recrystallized quartz dominates this part of the slide. (left) A less deformed band where hornblende is preserved.

The latest stages of deformation occurred at cooler temperatures and involved a local reduction of grain size in quartz to approximately 15 micrometers by plastic deformation processes. Shear stresses corresponding to this recrystallized grain size are of the order of 30 megapascals or higher [*Austin and Evans*, 2007]. Late deformation in quartz is spatially associated with deformation twinning in clinopyroxene (e.g., Figure 2), an indicator of large, seismic stress pulses of at least 140 megapascals and perhaps an order of magnitude higher [*Trepmann and Stöckhert*, 2001]. The observed plastic deformation of quartz requires a much longer time to form than does an earthquake; thus, offset during late stages of the shear zone was accommodated by alternating seismogenic and plastic processes.

Granulites and Slow Earthquakes

The geologic observations and models presented above have implications for understanding the evolution of subduction zones. An important consequence of the local development of granulite metamorphism along this subduction shear zone is dehydration. If the shear zone acted as a sealant for fluids, granulite facies meta morphism would not have developed at depths of 30–35 kilometers. Within the past few years, geophysicists have identified episodic tremor and slip along shallow subduction zones worldwide at depths similar to the paleo-exposure levels of the Salinas shear zone [e.g., *Melbourne and Webb*, 2003]. Tremors common during 'slow earthquake' events are interpreted by some researchers to represent fluid bursts in or out of the fault zone. Tremors occurring today beneath the Cascadia subduction zone may represent dewatering during ductile slip along the megathrust at depths of some 30–50 kilometers and thus may signal the local formation of deformed metamorphic rocks similar to those exposed in the Salinas shear zone.

The early granulite facies fabric was overprinted by later seismogenic and plastic deformation, which localized along quartz-rich layers. The estimated shear stress which drove deformation of quartz is similar to stress drops involved in mega-earthquakes along modern subduction faults [*National Research Council*, 2003]. On the basis of evidence for extreme, localized stresses in the form of twinned and fractured clinopyroxenes, we interpret that large seismic events initiating in brittle portions of the Salinas shear zone propagated downdip into a predominantly plastic region. Stress perturbations of the order of 30 megapascals were created during earthquakes and were relaxed by postseismic plastic deformation in quartz. Postseismic creep is a major component of the earthquake cycle [*Montesi*, 2004], and we suggest that it may be appropriately modeled using a plastic quartzite rheology.

Further study of this shear zone, as well as the recognition of similar characteristics in other shear zones, should be a priority for Earth scientists interested in subduction processes. Structures like the Salinas shear zone can link many of the geophysical observations from modern settings to large-scale geologic processes, such as the development of granulite facies metamorphism, dewatering, and structural slip as reported here, and thus advance our understanding of physical processes along subduction faults.

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Author information

Mihai N. Ducea, Department of Geosciences, University of Arizona, Tucson; E-mail: ducea@email.arizona.edu; Steven Kidder, Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena; and John T. Chesley, Department of Geosciences, University of Arizona.