Deformation and hydrofracture in a subduction thrust at seismogenic depths: the Rodeo Cove thrust zone, Marin Headlands, California.

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ABSTRACT

We have investigated the fabric and the deformational processes of an exhumed subduction zone thrust active at seismogenic depths. The Rodeo Cove thrust zone, outcropping north of the Golden Gate Bridge of San Francisco, imbricates two basalt-chert-sandstone-sequences belonging to the Marin Headlands terrane (Franciscan Complex). The thrust outcrop is a 200 m thick complex zone, displaying a range of stratal disruption from incipient deformation to a broken formation in the central part of the outcrop, dominated by basaltic lithologies, where zones of concentration of deformation have been mapped. Disruption is made by variably dense discrete fault systems synthetic to the main thrust (R and P fractures). These faults are marked by cataclasites with a shaly matrix showing a scaly foliation defined by chlorite and pumpellyte, which also constrain the depth of faulting (8-10 Km, T = 200-250 °C) within the seismogenic zone.

The central part of the fault also features the densest system of carbonate-filled veins. Veins occur in the broken formation matrix and fragments, in both cases paralleling the foliation. The veins are either folded, truncated or pressure solved along the cleavage. Cementation and hardening of shear surfaces of the fault core may have caused the distribution, as opposed to localization, of subsequent slip events. The fault core may have developed in basaltic rocks because of their inherently high permeability and propensity to transmit overpressured from deeper levels of the subduction zone.

The analysis has shown that accretionary deformation is strongly controlled by injection of overpressured fluids occurring through systems of multiple dilatant fractures grossly parallel to the décollement zone. The crosscutting relationships between veining and foliation suggest that fluid injection is cyclic and, consequently, that large transient variations in permeability and cohesion may occur. The repeated injection of veins parallel to the fault zone may be explained by cyclic changes of the stress, or by difference in tensional strength parallel to and perpendicular to the foliation, both requiring extremely high fluid pressure.

We interpret the features of the Rodeo Cove thrust zone with the seismic cycle, hypothesizing a compressional stress field in the interseismic phase and an extensional stress field in the immediately post-seismic phase.

Keywords: Franciscan Complex, accretionary prisms, seismogenic zone, hydrofracture, cataclasis, cyclic processes.
Subduction fault zones produce the planet’s largest earthquakes. We can remotely
sense their behavior through reflection seismology (Bangs et al., 2004), from earthquake
seismology (Bilek and Lay, 1999) and geodetic information (Rogers and Dragert, 2003).
Direct sampling of representative rock samples at the outcrop scale allows high-resolution
investigation of subduction-related processes inferred from the above “remote sensing”
techniques. Because deep drilling into subduction zones is not expected until near the end of
this decade, exhumed outcrops of subduction thrusts provide valuable understanding of
subduction zone seismogenesis.

Accretionary prisms grow by transfer of underthrust sediments and rocks from the
down-going plate to the overthrusting plate through the plate-boundary thrust (e.g., Moore
and Sample, 1986; Sample and Fisher, 1986; Hashimoto and Kimura, 1999; Bangs et al.,
2004). Thus, the plate-boundary thrust is incrementally and repeatedly preserved along the
boundaries of each package that is transferred to the accretionary prism. By investigating
thrust faults bounding rock packages accreted under the PT conditions of subduction zone
earthquakes we can examine processes associated with seismogenic deformation (e.g. Moore
et al., 2006).

Direct examination of subduction thrusts can potentially address a number of
questions regarding deformation and earthquakes in seismogenic zones. Since locking of the
fault is required to allow strain accumulation, consequent earthquakes and stress drops (ca. 30
bars, Kanamori and Anderson, 1975), the fundamental question is what controls the onset of
locking in the subduction thrust system? What types of incremental processes of lithification,
phase transformations or fluid pressure changes lead to the locking and onset of earthquakes with depth along subduction thrusts?

Seismogenic slip occurs by increasing of differential stress so that it exceeds the yield strength of the rock (Scholtz, 2002). The onset of unstable slip, or seismic behavior, in fault zones has been attributed to many factors, including changes in mineral phases with underthrusting in subduction zones (Vrolijk, 1990; Moore and Saffer, 2001), increases in fluid pressure or fault-valving (Sibson, 1990), the breakdown of cohesion (Muhuri et al., 2003), and to compaction and consequent overpressuring (Sleep and Blanpied, 1992). Stick-slip models for earthquake generation have outlined the effect of mineral precipitation on earthquake potential of faults (e.g. Brace and Byerlee, 1966; Hill, 1977; Dieterich, 1978; Sibson, 1987; 1989; 1990; 1992; Scholz, 2002). A number of these mechanisms include changes in the time-dependent frictional behavior of the fault material with depth (Marone, 1998).

In summary there are both mineralogical and physical criteria to distinguish faults that may have formed by creep or accelerating slip (velocity weakening vs. velocity strengthening behaviour). Thus, although there is continuing debate in the structural geologic community about what structures really record an earthquake, short of pseudotachylyte (Cowan, 1999), the investigation of ancient thrust outcrops can focus on whether they are developing any of the features that are inferred to cause the onset of seismic behavior. This evaluation requires attention to fault fabric, to the development of mineral phases during faulting, to evidence for solution and cementation in the fault, and to evidence for overpressures and fluid flux through the fault.

Changes in subduction thrusts that cause seismogenic behavior will be most apparent with the comparison of a number of examples that have been deformed above, within, and below the occurrence interval of thrust earthquakes. We report here on the structural study of
a thrust, the “Rodeo Cove thrust”, bounding an accreted package of oceanic basalt and
sedimentary rock. This fault occurs within an accreted terrane made up of thrust packages of
oceanic rocks that are bounded by thrusts similar to the Rodeo Cove thrust. This thrust is
good example of a paleo-décollement active at PT conditions typical of the upper seismogenic
zone of subduction thrust earthquakes (see below).

In order for an exhumed subduction thrust to preserve its emplacement history in the
seismogenic zone that deformation must be isolated from previous and subsequent events:
subsequent deformation must be mild, or at least clearly overprinting earlier deformation.
Moreover, deformation may or may not be acquired during underthrusting of the oceanic
package, prior to emplacement in the seismogenic zone. This deformation must be separable
from the faulting associated with emplacement. Fortunately, the synchrony of metamorphic
climax and main deformation in the Rodeo Cove thrust suggests that this event represents the
underplating of the terrane to the accretionary prism (see discussion of Van Gool and
Cawood, 1994). Therefore it is likely that each bounding thrust represents a once active
portion of the décollement or plate boundary thrust. Later deformation is very weak and
always clearly distinguished from the main deformation event.

At Rodeo Cove, an extraordinary exposure of the thrust, created by wave erosion, has
allowed a detailed analysis, at the centimeter scale, of a structural profile approximately
normal to the thrust dip (Figs. 3 and DR1). Field study accompanied by a careful microscopic
to ultramicroscopic scale analysis has focused on contrasts among hangingwall, footwall and
the shear zone deformational features.

GEOLOGIC SETTING OF THE RODEO COVE THRUST AND ASSOCIATED
FRANCISCAN COMPLEX
The Franciscan Complex crops out in central California, on the eastern side of the San Andreas Fault, associated with three geological sub-parallel domains (Sierra Nevada Batholith, Great Valley Sequence, Coast Range Ophiolite), interpreted as different components of a subduction complex related to underthrusting of Pacific Plate under the western North American plate margin (Blake et al., 1984; Wakabayashi, 1992). The Franciscan Complex (Fig. 1) is interpreted as the accretionary wedge built by offscraping and underplating of numerous fault-bounded units, from approximately 150 Ma until the onset of a transform tectonic regime about 30 Ma. (Wahrhaftig, 1989; Wakabayashi, 1992).

The Franciscan terranes' typical stratigraphic succession comprises ophiolitic sequences capped by deep sea fan and trench deposits. These sequences crop out as coherent units surrounded by highly disrupted units, mostly reduced to tectonic mélanges, defined by exotic blocks embedded in a sheared scaly matrix (Cloos, 1982; Blake et al., 1984; Wakabayashi, 1992; Jeanbourquin, 2000). Mélanges up to 1500 m thick mark the thrust zones bounding coherent units, and thinner stratally disrupted units, resulting from contemporaneous internal imbrication, have been interpreted by as analogues of plate boundary fault zones (Wakabayashi 1992; 1999); similar structures are documented in the Alaskan Kodiak Complex (e.g. Fisher and Byrne, 1987; Sample and Moore, 1987; Kusky et al., 1997) and in the Shimanto Complex of SW Japan (e.g. Kimura and Mukai, 1991; Hashimoto and Kimura, 1999).

Depending on the depth of accretion the units have experienced a subduction-related metamorphism ranging from zeolite to eclogitic facies (Ernst, 1984).

The Bay Area of San Francisco (Blake et al., 2000) shows well preserved products of subduction and accretion (Fig. 1) in the form of coherent units bounded by mélange units interpreted as analogues of thick plate-boundary zones (Wakabayashi, 1992). Except for some pervasive strong deformation near the San Andreas Fault, the Franciscan Complex
outcropping in the Bay area is the least affected by Neogene deformation, providing the best field area to examine the Franciscan structural evolution (Wakabayashi, 1992). The Marin Headlands is one of the best known Franciscan terranes from a stratigraphic and structural perspective.

**The Marin Headlands Terrane**

The thrust that we have studied is part of the Marin Headlands terrane, outcropping just north of Golden Gate Bridge (Figs. 1 and 2). The terrane comprises a complex array of SSE dipping, ENE-WSW striking coherent tectonic slices 300-500 m in thickness characterized by a low-grade metamorphism of prehnite-pumpellyite facies (Wahrhaftig, 1984, Wakabayashi, 1999). Although the main structural trend for Franciscan terranes strikes NW and dips NE (Fig.1), the Marin Headlands Terrane strata and internal shear zones dip S to SSE, due to a 90° to 130° clockwise rotation of the Marin Headlands block (Blake et al., 1984; Curry et al. 1984; Wakabayashi, 1999).

Despite pervasive internal imbrication, the stratigraphic succession can be reconstructed for the Marin Headlands terrane, comprising coherent pillow lava bodies, thinly bedded Jurassic to Cretaceous radiolarian cherts and Albian to Cenomanian turbiditic sequences (Wahrhaftig, 1984). Biostratigraphy indicates that this stratigraphic succession is repeated many times by thrust faults (Murchey, 1984).

**THE RODEO COVE THRUST ZONE**

The Rodeo Cove thrust outcrops at Rodeo Beach for a structural thickness of around 200 m (Figs. 2 and 3). The outcrop lies at the southern end of the Rodeo Lagoon and, with the exception of a landslide in the southeastern part of the outcrop, is exceptionally well exposed
because the coastline runs at a high angle to the fault strike, making possible a detailed
mapping and analysis of the thrust zone. The thrust strike is approximately ENE-WSW, with
a north-northwest vergence, consistent with the mean attitude of the mélange zone bounding
the entire terrane. The Rodeo Cove thrust imbricates two tectonic slices belonging to the
Marin Headlands terrane, juxtaposing pillow basalts over a chaotic chert/sandstones sequence
(Figs. 2 and 3).

Despite a landslide, the eastern end of the thrust is defined by a gradual transition to
undeformed pillow basalts of the hanging wall (Fig. 3), while on the west the alluvial deposits
of Rodeo Lagoon and Beach cover the western side of the thrust outcrop. Accordingly, the
original thickness of the thrust might have been greater than what actually preserved.
Although it is not easy to establish the displacement along the shear zones, because of the
disrupted nature of the lithologies and the lack of offset features in the basalts, offset
fragments cannot be correlated across the faults for distances of more than 1 m along any
shear surface composing the thrust zone. However, the basalt-chert-sandstone stratigraphic
sequence, originally many 100’s of meters thick, was repeated along a low angle fault. This
implies a minimum of many 100’s of meters of total displacement for the entire fault zone.

Structural Zonation of the Rodeo Cove thrust

Figures 3 and DR1 show the structural section measured normal to the thrust dip
documenting all the major structural features recognized at the outcrop. The thrust outcrop is
dissected by a complex fracture network that created smaller units (Fig. 4a), characterized by
different lithologies and deformation features. Moving from the footwall up structure, the first
1/3 of the outcrop is occupied by a dense alternation of internally coherent units of sandstone
and chert. This sandstone and chert unit is structurally overlain by a highly disrupted basaltic
The fracture network includes brittle shear zones associated with the main thrust, suggesting the thrust has developed through localization of deformation into discrete surfaces (see next section). These faults are arranged in two systems intersecting at angles of 15°-25° (Fig. 4). Kinematic and structural analyses at the meso-scale (i.e. S-C brittle structures, asymmetry and sense of elongation of rigid clasts, striae) reveal a top-to-the-NW sense of shear for both shear planes. These data, together with thrust vergence and mean map-scale attitude, suggest that the shear surfaces are R and P planes of the Riedel shear model (e.g., Riedel, 1929; Tchalenko, 1968; Cowan and Brandon, 1994). Following the model, we refer to the NW-dipping planes as the R shear planes, and to the SE-dipping surfaces as the P shear planes (Fig. 4).

According to observations in upper crustal brittle faults (Chester and Logan, 1987; Chester et al., 1993; Caine et al., 1996; Chester and Chester, 1998; Caine and Forster, 1999), the localization of deformation allows the Rodeo Cove thrust internal structure to be described using the damage zone-fault core model (Caine et al., 1996; Caine and Forster, 1999). The fault core is defined as the interval displaying the highest concentration of deformation-related structures (e.g. fractures, minor shear zones, brecciation, mineral veins, etc.), and that accommodates most of the displacement. The damage zones are the peripheral intervals, grading to the undeformed protolith, that show less penetrative deformation. These fault zone components can be variably developed in a shear zone, giving rise to different architectures (Caine and Forster, 1999). The central part of the Rodeo Cove thrust outcrop is characterized by 30-40 m of a highly disrupted basaltic unit. The unit is locally a broken formation generated by progressive stratatal disruption, penetrative fracturing and cataclasis (Figs. 3, 4 and 5). The basalts are dissected by the densest observed system of discrete slip surfaces (next section). Here decimeter to meter-sized blocks show a variably spaced foliation and the highest density of vein development has been identified (Figs. DR1, 3 and 7). Similar
vein distributions have been observed in cores of mature fault components of the San Andreas Fault System (Chester et al., 1993), although the RCT displays a much higher vein concentration than those observed by Chester and co-workers. This central zone of concentrated deformation grades toward the eastern and western lateral sides of the outcrop, distinguished by a decrease in mesoscopic deformation, fractures, and vein density (Figs. 3 and DR1). These damage zones above and below the central core can be traced continuously over a structural thickness of 20-30 m before the outcrop is lost to alluvium on the W and to a landslide on the E. The damage zones are comprised of mappable chert, sandstone and basalts units, featuring brecciation, fracture and joint sets and web structures in the sandstones (complex arrays of shear bands, see Byrne, 1983), juxtaposed by the network of discrete slip surfaces.

Discrete slip surfaces

The deformation and the displacement in the Rodeo Cove thrust occurred by development at all scales of discrete slip surfaces, arranged as R and P Riedel shear planes and ranging in thickness from the millimeter to the decimeter scale (Figs. 4 and 5). They cut all lithologies increasing in density toward the center of the outcrop, or fault core, where clusters of concentrated deformation occur.

The discrete slip surfaces are sites of concentrated deformation isolating less deformed competent blocks that usually preserve their primary textures (Fig. 5a). The discrete slip surfaces are marked by cataclasites composed of millimeter- to decimeter-sized elongate fragments enclosed in a greenish or reddish fine mixture of very fine siltstone and shale (Figs. 5 and 6). The fragments show lenticular shapes and various dimensions (Figs. 5a, 6b and 6c), and display pervasive brecciation, with variably spaced networks of intragranular and transgranular fractures. The matrix shows a penetrative foliation whose aspect and intensity
are closely dependent on clasts size and frequency. In general, the foliation is scaly (Figs. 5c and 6a), i.e. a system of anastomosing polished or striated shear surfaces pervasive on a scale of millimeters (Lundberg and Moore, 1986; Labaume et al., 1997a; Vannucchi et al., 2003). The scaly foliation is associated with other less abundant shear fabrics such as polished and striated fragment surfaces and brittle S-C structures (Figs. 5b and 6). C-type planes mean attitude approximates a plane striking N20°E-N35°E, consistent with the average strike of both R and P planes. The S-type foliation is approximately parallel to a spaced cleavage observed in the competent, basalt blocks (Fig. 4b). The shear sense of all these structures is always top-to-NW, consistent with that inferred for the main thrust.

Microscopically, the discrete slip surfaces show well preserved to strongly weathered competent cores of variable size, dispersed in a finer matrix (Figs. 6b and 6c). Fabric is mainly cataclastic, being characterized by extreme grain size reduction, large range in grain size, sharp and angular fragment boundaries and fine scaly matrix surrounding competent clasts (Figs. 6b-6c). The fine foliated matrix of the slip surfaces is composed of a mixture of chlorite and clay minerals (Fig. 6; see also Fig. 8). These minerals, whose strong concentration in the discrete shear surfaces compared to the fragments, their very-fine grain size and their intergrowth, suggest they are syn-tectonic, are preferentially oriented along cleavage lamellae arranged in an anastomosing web around the competent fragments (Figs. 6a-6c). Thin layers of hydroxides and opaque residual mineral bound the fragments concentrating along the edge of the clasts that frequently show sutured contacts; apparently pressure solution accompanied cataclasis (Figs. 6b and 8d). Fragmentation and re-orientation of clasts (B of fig. 6c) and pre-existing minerals occur parallel to the scaly foliation.

Chlorite re-crystallization records the opening and development of fractures through shear, as demonstrated by chlorite grown in S-C brittle structures (Figs. 6a, 6d and 8c). Acicular pumpellyite is often intimately associated with chlorite in these structures (Fig. 6d),
demonstrating that this mineral phase formed during thrust deformation, during subduction, and not during oceanic hydrothermal alteration. More importantly, the association of pumpellyite and chlorite in the cleavage lamellae (Fig. 6d), and the occurrence of laumontite across the terrane (Schlocker, 1974; Swanson and Shiffman, 1979), constrain the P-T conditions of deformation to about 2.5 kbar and 200-300 °C (Fig. 6e).

Mineralization and veins distribution

Veins occur in the damage zones and increase in frequency toward the center of the outcrop, where they locally make up ca. 80% of the outcrop area (Figs. DR1, 3 and 7). Thus, the fluid circulation and related fluid-rock interactions were localized where the discrete shear surface network is densest.

The veins are found both in competent blocks and in the fine scaly matrix of the discrete slip surfaces (Fig. 7, see also Fig. 4). Two vein textures are generally recognizable, depending primarily on vein thickness. The two types of veins have grossly the same geometries, are calcite and rarely quartz filled, but show different distributions. The thickest veins are generally 1 cm thick and occur generally in the sandstone and basalt blocks (Fig. 7). They show variable thickness along their strike, with sharp, pinched terminations and boudinage. Lateral continuity ranges from less than 5 cm up to about 50 cm. The thinner veins never reach 1 cm in thickness, being generally less than 5-6 mm thick. They develop along the discrete slip surfaces, or in association with finer lithologies, although locally they can be found in the highly disrupted basalt blocks. The thin veins show more continuous lateral extension compared to the thick set, being generally 50-60 cm long and occur as repeated sets of parallel veins (Fig. 7a).
Both types of veins show, sharp boundaries and “clear” vein fillings, with very low percentage of wall rock particles and record extensional strain (Fig. 8a). Locally some calcite crystal shows Type I and II twins of Burkhard (1993), suggesting twinning at 150-300 °C. The thickest veins always display mosaic, blocky textures defined by irregular arrangement of clear anhedral calcite crystals, locally intergrown with less abundant quartz crystals (Fig. 8b). A well-developed fibrous texture is locally visible in some of the thinner veins, where antitaxial straight, calcite fibers (Fig. 8d) occur, together with scattered, irregular, dark median lines.

Despite the slightly different distribution, thick and thin veins show similar arrangements with respect to foliation and slip planes, lying parallel to both the anastomosing spaced foliation of the competent blocks and the S-planes in the scaly foliation of the matrix (Figs. 7 and 8). Discontinuous films of opaque, residual minerals also parallel S-planes and veins (ps in Fig. 8d). This observation, together with frequent stylolites occurrence in the calcite filling, support the interpretation of pressure solution.

Crosscutting relationships between veins and foliation have been observed from meso- to micro-scale (Figs. 7 and 8). For example, veins, as well as S-planes and pressure solution seams, are often rotated and truncated by the C-planes of scaly foliation marked by fine-grained chlorite and opaque mineral seams (Figs. 7d, 8c and 8d). Vein deformation also occurs as close to isoclinal folds with acute hinges and tight limbs (Figs. 7d, 7e and 8b). The limbs parallel the discontinuous chlorite layers that define the anastomosing foliation, lying along two crosscutting fracture planes (Fig. 8b). Limbs are frequently thinned and stretched along the planes, so that most of these veins appear as isolated fragments (Fig. 7e).

**DISCUSSION AND INTERPRETATION**
**Structural development of the Rodeo Cove thrust**

The Rodeo Cove thrust imbricates two tectonic slices belonging to the Marin Headlands terrane. The thrust is parallel to the unit-bounding shear zones that make up the entire terrane, showing same vergence and attitude, same metamorphic conditions. The Rodeo Cove thrust does not deform or cut across other faults, so it can be considered as part of this thrust imbrication. Particularly, the entire Marin Headlands terrane can be interpreted as a series of underplated duplexes forming at the same P, T conditions.

The depth and temperature range of accretion inferred from the preserved metamorphic minerals along the Rodeo Cove thrust falls within the typical depth of seismogenic zones of subduction thrusts, suggesting the thrust acted at seismogenic depth or immediately below the aseismic to seismic transition. In fact, this transition along subduction margins has been estimated to occur at around 4 km depth, through relocation of recorded earthquakes (Bilek and Lay 1999), and along the ~125° isotherm, by using a thermal proxy (Hyndman et al., 1997; Oleskevich et al., 1999).

The Rodeo Cove thrust crops out as a variably deformed, copiously veined, 200 m-thick fault zone in which strain is accommodated primarily by discrete slip surfaces, occurring from mm to m scales and is typical of active accretionary thrusts (e.g Lundberg and Moore, 1986; Labaume et al., 1997a) and shallow faults and gouges (Chester et al., 1993; Caine et al., 1996; Chester and Chester, 1998, Labaume and Moretti, 2001).

Upper crust fault zones show complex architectures made by variably distributed components, such as a fault core and a damage zone (Caine et al., 1996; Caine and Forster, 1999). The evolution of fluid flow in these faults can vary greatly depending on the particular distribution of fault zone components (Caine and Forster, 1999). Following this model, and taking into account the lacking of part of exposure and of clear constraints on displacement vs. deformation, the Rodeo Cove thrust zone can be described as part of a thick Distributed
Deformation Zone (DDZ of Caine et al.; 1996 and Caine and Forster; 1999). As widely described, localization of deformation occurs from meso- to micro-scale, and throughout the entire exposure, by a variably distributed complex network of discrete shear surfaces. Concentration of deformation characterizes the central part of the outcrop, where an increase in number and density of shear surfaces and a major degree of disruption are documented. This zone only involves basalts, suggesting a possible lithologic control on localization of deformation during thrust activity. The discrete shear surfaces arrangement can also be compared to the Distributed-Localized Shear (DLS) deformation pattern defined by Jeanbourquin (2000) for the Franciscan mélange outcropping at Pacifica, south of San Francisco. The DLS is described as a complex anastomosing array of narrow shear surfaces concentrated in bands.

The main features observed in the discrete slip surfaces, i.e. the extreme grain size reduction, grain alignment and the scaly foliation, are interpreted as the result of shear-related compactional strain. The fabric observed in the slip surfaces suggests that cataclastic flow, as defined by Passchier and Trouw (1996), represented the main deformation mechanism. Shear-related compaction, cataclasis and disaggregation decrease the lithification state of some zones, allowing intragranular particulate flow to accompany cataclastic flow. The subsequent re-orientation of grain fragments parallel to the S-foliation caused porosity to collapse in the slip surfaces with respect to the host rocks. Parallel to S-foliation are seams of opaque minerals interpreted as the result of pressure solution around the competent clasts. These mechanisms contributed to the sealing of the fractures and are interpreted to have lowered both porosity and permeability.

Vein Development and State of Stress in the Rodeo Cove Thrust Fault
The high concentration of veins in the Rodeo Cove thrust indicates flow of fluid along the thrust zone. The veins represent Mode I fractures, recording episodes of pore pressure build-up (e.g. crack-seal of Ramsay, 1980). Moreover, the meso- and micro-scale analyses of vein features indicate that vein growth was structurally-controlled by fractures, the hydrofractures opening along the pre-existing, relatively weak surfaces that define both scaly fabric and disjunctive foliation. The tabular geometry of veins and their macroscopic and microscopic regularity seem to confirm this hypothesis. The straight, sharp vein boundaries also suggest structurally-controlled vein growth, although this feature can be partly correlated to the high competence of the host basalt. Higher competency of the basalts not only implies it is stronger than the sediments but also more brittle and consequently can facilitate extensional strain localization. This observation may also explain the concentration of veining in basaltic lithotypes.

Alternatively, the veins could have formed at a steeper angle, in the extensional direction of a simple shear couple and have undergone rotation into the fault surface. The pressure solution surfaces would have been forming simultaneously in the plane of maximum flattening of the shear couple. Although we do see folded veins, we do not see examples of progressive rotation of veins nor development of veins with large angular differences from the foliation and shear surfaces. Thus, we do not favor this interpretation.

Crosscutting relationships between the thick and thin types of veins and their similar arrangement with respect to the structural elements, suggest that they probably formed simultaneously, and are then referable to the same deformation phase. Lithification-dependent dilatancy may also justify the different textures and distributions of the observed veins. Thick veins develop into the preserved basalt blocks because they are more brittle than the matrix, so they dilate more easily. In fact they develop an intense disjunctive cleavage. On the contrary, the matrix is dominated by sets of millimeters-thick veins, apparently because
dilatancy is minimized in this relatively low strength material. Therefore, in the matrix, the episodes of high pore pressure caused the opening of smaller fractures that were easily filled by fluids. This is supported by the fibrous texture, which characterizes only the thinner veins; the mosaic texture of the thick veins may indicate that growth rate was unable to keep pace with fracture opening.

The occurrence of dilatant structures (hydrofractures and veins) along compactional structures (scaly foliation surfaces) has been observed also at shallower levels in modern accretionary margins (Labaume et al., 1997b) and interpreted as due to cyclic variations of the stress controlled by variations of pore pressure. Crosscutting relationships between foliation development, pressure solution and vein formation in the Rodeo Cove thrust (Figs. 8b-8d) support the above-cited model, suggesting that a sequence of fracturing, vein formation, and development of anastomosing to scaly foliation through shear and solution, repeated cyclically. In each cycle scaly foliation formation occurred during low fluid pressure episodes, as a result of shear-related compactional strain. Similarly, the pressure solution surfaces formed perpendicular to the maximum principal stress (Fletcher and Pollard, 1981), implying a local stress field as that indicated in upper part of Fig.9. Conversely, high fluid pressure episodes and hydraulic opening of pre-existing fractures imply extension, perpendicular to the minimum principal stress, with no large component of shear (Fig. 9a). Then, the parallelism of the carbonate veins and the pressure solution surfaces (Fig.8d) suggest that the minimum and maximum principal stresses may have switched of approximately 90 degrees between the periods of formation of these features. Alternatively, a significant difference in tensional strength parallel to and perpendicular to the foliation may explain vein formation parallel to the S-planes and the pressure solution seams, without requiring rotation of the principal stresses (Fig 9b). In order for a hydrofracture to occur, the fluid pressure must overcome the tensile strength of the material (Secor, 1965). If a significant
difference exists in tensile strength parallel and perpendicular to the foliation, an increasing in fluid pressure may result in a shifting of the Mohr circle past the origin of the Mohr diagram, so that both Sigma 1 and Sigma 3 become tensile stresses. If the pressure rises such that Sigma 1 becomes tangent to the failure envelope parallel to foliation, but the Sigma 3 has not yet reached the failure envelope perpendicular to foliation, then an extension fracture parallel to the foliation and perpendicular to Sigma 1 can occur. This requires the differential stress to be less than difference in tensile strength parallel to and perpendicular to the foliation. Both of these interpretations require cyclical episodes of high fluid pressure.

Fault Evolution and the Seismic Cycle

Although the only clear, universally accepted fossil evidence of seismic slip are pseudotachylites (Cowan, 1999), we know since the 70’s the importance of fluid migration and mineralization in faults and fractures in triggering small earthquakes, promoting a stick-slip behavior of faults (Hill, 1977; Sibson, 1987; 1989; 1990; 1992). Starting from the inferred Rodeo Cove thrust evolution, and considering a fault-valve behavior of the thrust (e.g. Sibson, 1990), we can tentatively correlate the above-described deformation and hydrogeological cycling to the seismic cycle.

We suggest the following sequence of fabric formation (Fig. 10). 1) During compaction, in interseismic intervals, the shear zones experience high shear stress and S-foliation and pressure solution fabric form almost perpendicular to high effective maximum principal stress. The fault behaves as an impermeable seal (Sibson, 1990; 1992). 2) Failure (possibly seismic?), stress relaxation and high fluid pressure allow fault zones to dilate along S-surfaces and pressure solution folia. The thrust forms a highly permeable channel for fluids that flow until the hydraulic gradient reverts to hydrostatic (Sibson, 1990; 1992). 3) The pressure drop accompanying discharge causes mineralization and relatively rapid
precipitation of carbonate occurs (Fyfe et al., 1978). 4) Further mineral precipitation and
lowered pore pressure would respectively increase cohesion and effective stress, allowing to
strengthening of fault (e.g. Sibson, 1990; Scholtz, 2002) and re-accumulation of stress. The
common occurrence of cataclasis and slickenlines may have developed during the relatively
rapid seismic failure, but could also occur during interseismic periods along surfaces subject
to shear failure.

Non-localized Slip and the Basaltic Composition Fault Core

The Rodeo Cove thrust shows several principal sliding surfaces (Figs.3 and 4) rather
than a narrow, well-defined fault core (e.g. Chester et al., 1993). We believe that this
distributed deformation is due to the sealing of discrete slip surfaces with calcite and quartz
veins, causing fault hardening and migration of slip elsewhere. Accordingly, only a limited
number of slip surfaces were active during any seismic cycle, with the current volume of vein
fillings being cumulative. Moreover, the significant slip expected from any large subduction
zone earthquake could be distributed over a number of shear surfaces. Such distributed
deformation has been reported from sedimentary mélanges interpreted as décollements
(Fisher and Byrne, 1987) and attributed to hardening by dewatering (Moore and Byrne, 1987).
Also, distributed deformation in a broad fault zone in granitic rocks is attributed to healing of
fault surfaces by mineral precipitation and solidification of pseudotachylytes (Di Toro and
Pennacchioni, 2005).

Why does the fault core occur in basaltic rocks? The sandstones and chert of the
flanking damage zone is of similar or lower strength than the basalts (Byerlee, 1978; Morrow
and Lockner, 2001). The concentration of veins in the basalt rather than the associated
sandstones and cherts suggests that fluid flow concentrated in the basaltic fault core,
presumably due to relatively higher permeability. The compactive deformation and diagenetic
transitions in the sandstones and cherts would have reduced their permeability, and perhaps prevented migration of fluids away from the basaltic fault core. Studies of oceanic crust have suggested that the upper several hundred meters of pillow lavas can be a zone of higher permeability than the overlying sediments (Fisher, 2005). In this scenario, the down-dip extension of the upper oceanic basement would allow it to tap into sources of high fluid pressure that would be transmitted updip through the basaltic aquifer favoring failure in this lithology (Kimura and Ludden, 1995).

CONCLUSIONS

The Rodeo Cove thrust provides the only high quality exposure of the classic basalt-chert-sandstone imbricates of the Marin Headlands. Syn-metamorphic chlorite and pumpellyite indicate that this thrust was active at temperatures of about 200-250°C, where seismogenic behavior typically occurs. Thus, the Rodeo Cove thrust, and by implication the imbricated basalt-chert-sandstone sequences of the Marin Headlands, are interpreted as a series of underplated duplexes in the seismogenic zone. The fault deformational history shows an alternation of brittle deformation, vein formation, and pressure solution. The central 30-40 m of the fault is massively, extensionally veined by carbonate and to a lesser degree quartz. The veins are oriented parallel to the mean pressure solution foliation. Thus, directions of extension during veining and directions of shortening during pressure solution are parallel. This enigma can be explained by either: 1) large-scale switching of principal stresses between the intervals of veining and pressure solution, or 2) veins forming parallel to fabric anisotropy due to the principal foliation, under small differences in principal stress magnitude. In either case very high fluid pressure is required. We interpret the veining as occurring immediately post-seismic as a result of fluid pressure (including P CO2) drop and consequent carbonate
precipitation, and the S-C structures and pressure solution as due to slow interseismic
deformation. The cataclastic fabrics may be interpreted as due to slow deformation (e.g.
Cowan 1999) or during fault movement at seismic slip velocities, which we favor. The
absence of a localized principal slip surface indicates the Rodeo Cove thrust fault failed along
a series of distributed shear surfaces. The healing and hardening of slip surfaces by mineral
precipitation discouraged their subsequent use, with additional slip events being
accommodated by different fault strands. The location of the core of the Rodeo Cove thrust in
a basaltic lithology may have been due to its ability to preferentially transmit high fluid
pressures from depth, creating a zone of weakness.

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Figure Captions

Figure 1 – Franciscan Complex of the San Francisco Bay area. A-B, C-D: traces of cross sections shown on bottom of figure. Map based on Blake et al., 1984; Wahrhaftig, 1984; 1989; Wakabayashi, 1992.

Figure 2 – (a) Geologic map of the Marin Headlands peninsula, N of San Francisco, after Blake et al., 2000 (location in Fig.1). The cross section, constructed after fieldwork, shows thin sandstone and chert units overthrust by basalts through the Rodeo Cove thrust (RCT). (b) Close up view of Rodeo Lagoon geology.

Figure 3 – Line-drawing from pictures of the Rodeo Cove thrust. RL: reference line for section truncation in figure.

Figure 4 – Typical features of fault broken formation. (a) P and R Riedel arrangement of discrete shear surfaces disrupting basalts of the fault core. Main shear zone is indicated with arrows. (b) Schematic section of typical geometrical arrangement of P and R discrete shear surfaces with respect to main shear zone. Although foliations are anastomosing surfaces, they are schematically represented as thin straight lines. Along S-foliations, in (b1) and (b3), also thin and thick veins (see Fig.8). (b1) S-foliation on basaltic blocks grossly parallels the scaly foliation of the matrix. Straight lines also represent pressure solution surfaces. (b2) Lower hemisphere poles projections of the two main systems of discrete shear surfaces. The great circle represents the mean, map-scale orientation of the RCT. (b3) Schematic close up of discrete shear surface showing scale invariant cataclastic aspect made up by clasts wrapped by a very fine matrix, showing scaly
fabric and S-C structures. S-foliation in P-planes makes a very-low angle with S-foliation outside the discrete shear surfaces.

Figure 5 – Typical discrete shear surfaces and broken formation of basalts in the highly-concentrated deformation zone. (a) Deformed pillows as fragments in the breccia. (b) S-C brittle structures in the matrix. C-planes parallel the general attitude of discrete shear surfaces. Sense of shear is top-to-the-NW. Grain size reduction and variability are visible. (c) Cataclastic, scaly matrix of the broken formation. Pencil mimics the general orientation of the fabric sub parallel to the discrete shear surfaces.

Figure 6 - Microscopic features of discrete shear surfaces. (a) Discrete shear surface cutting basalts defined by syn-tectonic very-fine chlorite, often arranged in S-C structure. PPL. (b) Extreme grain size reduction accompanied by pressure solution seams into discrete shear surfaces. PPL. (c) Anastomosing web of chlorite layers (L) surrounding competent clasts (B). XPL. (d) Mixed backscattered and secondary electron image of chlorite (chl) in discrete shear surfaces. Pumpellyite (pmp) is intimately associated with chlorite. (e) Inferred P/T conditions of Marin Headlands terrane (MHT) accretion based on metamorphic paragenesis in basalts (Peacock, 1993).

Figure 7 – Mineralization along the Rodeo Cove thrust. (a) Typical vein occurrence. Note the high % of veins per area. (b) Interconnected network of thick veins in basalt block. Veins follow and are truncated by anastomosing disjunctive cleavage. (c) Vein distribution across the thrust zone. (d) Mesoscopic regularity of veins parallel to foliation. Note frequent thinning, truncation and folding of veins (f). S-C relationships, with the C cutting off the veins at top and bottom of the block, are also visible. (e)
Crosscutting between veins and foliation causes brecciation of veins and isolated vein fold hinges (h).

Figure 8 – Microscopic views of veins (V). (a) PPL image of calcite vein. Note clear vein filling and strong parallelism with chlorite-marked, S-foliation in the wall rock. (b) Folded vein, XPL. The limbs (L) parallel the discontinuous chlorite bands (S) that define the S-foliation. Blocky texture of calcite filling is also visible. (c) Mixed backscattered and secondary electron image of S-C brittle structures. Chlorite marks the S-foliation, calcite veins (V) are also parallel to S and apparently have been locally sheared into parallelism with C-planes (C). Sense of shear is top-to-the-NW. (d) Plane light view of thin fibrous veins (V), with discontinuous median line (ML). Note that veins and pressure solution surfaces parallel to S-foliation and are in turn cut and deformed by left-inclined C-planes.

Figure 9 – Possible states of stress responsible for the observed parallelism of veins and foliation/pressure solution fabric. Stages 1 and 2 in both schemes refer to same stages in Figure 12. (a) The principal stress axes switch when stress is released at failure. Veins form immediately post-seismic leading to healing of the fault zone and stress re-accumulation. (b) The parallelism of veins and foliation/pressure solution fabric can also be explained with a fixed stress orientation and a significant difference in tensional strength parallel to and perpendicular to the foliation.

Figure 10 - Conceptual model of deformation-related fluid circulation in the RCT, with possible relation to seismic cycle. Not to scale. Stage 1) During compactional regime in interseismic intervals the shear zones experience high shear stress and S-foliation and
pressure solution fabric form almost perpendicular to high effective maximum principal stress. Stage 2) After (seismic?) failure, stress relaxation and high fluid pressure allow fault zones to dilate along S-surfaces and pressure solution foliation. Precipitation of carbonate occurs as PCO₂ is lowered and fluids exit through fracture permeability (Fyfe et al., 1978). Stage 3) Return to interseismic compactional regime.
1. S-foliation and pressure solution seams form normal to $\sigma_1$ along décollement zone.

2. High fluid pressure opens S-surfaces allowing to approximately 90° rotation of stress axes. Mineralization sub-normal to $\sigma_3$.

2. High fluid pressure translates the Mohr circle to the left so that $\sigma_{1\text{eff}}$ is more negative than the failure envelope // to foliation. Hydrofracture and mineralization occur normal to a tensile, foliation-normal $\sigma_{1\text{eff}}$. $\sigma_{3\text{eff}}$ is not more negative than the failure envelope normal to the foliation.
1. Compactional regime: high shear stress on shear zone. Scaly foliation, S-C structures. INTERSEISMIC

