How can Accretionary Prisms Elucidate Seismogenesis in Subduction Zones?

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Abstract

Earthquakes occur along the plate-boundary thrusts underlying and out-of-sequence thrusts that cut through accretionary prisms. Thermal models suggest that the earthquakes on the plate-boundary thrusts occur in a temperature range of 125°C to about 350°C. Because syndeformational diagenetic and metamorphic alterations recorded in accretionary prisms have specific temperature ranges, the alterations and the associated deformation can be correlated to the temperature range that accretionary prisms are seismogenic. Comparison of accreted rocks deformed above, within, and below the seismogenic zone suggests characteristics of rocks at seismogenic depths that may make them earthquake-prone.

During passage through temperatures from 50-150°C accretionary prism sediments become rocks, undergoing diagenetic reactions including of the transformation of smectite to illite, albitization of detrital feldspar, dehydration of opal, and the generation of hydrocarbons. Although the smectite to illite transition does not change the frictional properties of the prism so that it becomes seismogenic, water and cations (calcium, magnesium, iron) released during this transition and the albitization process foster cementation.

Cementation and veining by carbonates becomes common by 125°C, perhaps due to the above-mentioned release of cations. Pressure solution fabrics begin to be apparent at about 150°C, with well-developed cleavages and quartz veining common by 200°C. Pressure solution may be facilitated by the diagenetic formation of illite. Quartz veining and cementation in the 150 to 300°C range facilitates the change from a velocity-strengthening, clay dominated, to a velocity-weakening, quartz influenced, earthquake-prone rheology. Cementation by quartz and carbonates increases cohesion and may also make the rocks more earthquake-prone.

In accretionary prisms, brittle fabrics are progressively replaced by ductile fabrics through a temperature range of about 150 to 325°C. Although rocks in the seismogenic zone have lost most of their intergranular fluid through consolidation, vein geometries and fluid inclusions suggest high fluid pressures, approaching lithostatic. Strain localization in the form of discrete shear surfaces occurs across the lower aseismic to seismic transition. Strain localization is observed both at outcrop and map scale. At map scale, the seaward-most occurrence of out-of-sequence thrusts define the leading edge of the rigidified accretionary prism that is capable of storing elastic energy.

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Introduction

Accretionary prisms comprise materials that have been transferred from the oceanic plate to the overriding plate in subduction zones. At all but the shallowest levels, near the front of the prism, these sediments and rocks have been underthrust with the lower plate and passed through the subduction megathrust as they were transferred to the upper plate (Fig. 1). Thus, accretionary prisms constructed by this "underplating" process include faults that were for a period time subduction thrusts. In addition to the faults active during the initial emplacement of their rocks, accretionary prisms are cut by later faults, or out-of-sequence thrusts. In combination, the basal subduction thrusts and the later faults encompass faults active in the great subduction earthquakes (Plafker, 1972), the largest known seismic events (Lay and Bilek, this volume). The history of deformation through the earthquake cycle is recorded in the rocks of accretionary prisms. To the degree we can decipher this history we can learn much about the inception and evolution of the deformational processes associated with earthquakes.

Investigation of old rocks from the seismogenic realm provides windows on processes that cannot be observed short of deep drilling. Terranes of old rocks allow direct investigation of three-dimensional variations, which will be useful in interpreting any results from more physically limited boreholes. However, investigations of old rocks are constrained in that offer an interpretable record of past activity but do not allow direct observation of active processes.

Recognizing Faults Rocks From the Seismogenic Zone

Progressive addition or underplating of material at the base of accretionary prisms results in their uplift. Therefore the oldest rocks, exhumed from the deepest level, are the structurally highest, and commonly innermost parts of the continually accreted prism, with less deeply buried rocks progressively exposed in a seaward direction (Brandon and Vance, 1992; Plafker et al., 1994; Taira et al., 1988). Typically packages of rocks with similar sedimentary, deformational and metamorphic history are separated by prominent out-of-sequence thrust faults. The best-exposed packages of ancient accreted rocks occur where subduction was characterized by a generally high input of sediment, and consequent creation and uplift of a volumetrically significant accretionary prism, for example prisms in California, Washington, Alaska, and Japan. Even though these accretionary prisms are dominated by clastic rocks of the high sediment input intervals, selected sections include units formed during periods of low sediment supply, in which the subduction zone was more sediment-starved. Therefore, studies of these ancient rocks can provide information on seismogenesis in both sediment-dominated and sediment-deficient systems.

Given exhumed prism rocks of a range of ages, metamorphic grades, and structural styles, how can we recognize rocks that have deformed in the seismogenic level? Pseudotachylytes, or rocks formed by frictional melting on fault zones are most

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explicit evidence of past seismogenic behavior (Cowan, 1999; Sibson, 1975). However, pseudotachylytes are rare in accretionary prisms (Ikesawa et al., 2003) and there is much disagreement on what structural features may actually form during a seismic event (e.g. Cowan, 1999). A more inclusive approach to understanding rocks that have behaved seismogenically is to simply investigate faults in any volume of rock that has deformed through the P-T conditions where modern earthquakes occur. We can reasonably infer that these rocks have in part deformed seismogenically and that this deformation occurred along brittle structural features. Comparison of these rocks to those that behaved aseismically at shallower and greater depths provides insights on the rock fabrics and material properties that control seismogenic behavior.

During the last decade thermal models (Currie et al., 2002; Hyndman et al., 1997; Oleskevich et al., 1999; Wang, 1995) have defined the temperature range at which modern interplate earthquakes occur at seismogenic zones; earthquake depths are known from careful relocation programs (Bilek and Lay, 1999, 2000). The temperature range of large interplate thrust earthquakes is from 100-150^{o} C to about 350^{o} C, with the depth limits varying depending on the thermal gradient of the associated subduction zone (Hyndman 1997). Although there are undoubtedly significant errors in the thermal models, the consistency of temperature ranges for interplate thrust earthquakes at many modern subduction zones provides some confidence that the above-mentioned temperature limits for seismogenesis can be used to investigate the realm of seismogenic activity in ancient rocks (Fig. 2).

Pinpointing fault rock features forming in the seismogenic temperature range requires identification of syndeformational metamorphic minerals (Ernst, 1990), or the use of fluid inclusion P-T estimates derived from syndeformational minerals (Vrolijk et al., 1988) that formed under seismogenic P-T conditions (Fig. 3). Finally, the rock fabrics have to be interpreted in terms of formation during ductile (interseismic) or brittle (perhaps coseismic) deformational intervals.

What Progressive Changes Occur in Mineralogy and Fault Rock Fabrics Into and Through the Seismogenic Zone?

Our discussion is based on cataloging and organizing the mineralogy and microscopic to outcrop-scale deformational features observed in accretionary prism rocks that have been deformed at P-T conditions above, within, and below the seismogenic zone (Table 1). Although related, evidence for fluids, fluid pressure, and strain localization are discussed separately.

Deformational phenomena (Fig. 4) are subdivided into: 1) brittle deformation, associated with loss of cohesion along fractures and faults, and 2) ductile deformation, associated the coherent nonrecoverable deformation without fracturing at scale of crystal grains or larger (Twiss and Moores, 1992; van der Pluijm and Marshak, 1997, 2004). Following these authors we include cataclasis and granular flow in brittle deformation because cataclasis involves brittle fracture and they are both controlled by frictional rheology. Optical microscopic investigations clearly distinguish brittle and ductile phenomena, as defined above, and these observations can be extended to hand specimen and outcrop scales to distinguish brittle and ductile fabrics.

Observations

Diagenesis to Low Grade Metamorphism: Our discussion of metamorphic mineral transitions occurring in subducted rocks (e.g. Ernst, 1990) only focuses on a few alterations that apparently strongly influence the structural evolution of the rocks. Of these, the formation of metamorphic albite releases calcium from more calcic-rich detrital plagioclase (Boles, 1982). The transition from smectite to illite releases water, calcium, iron and magnesium (Boles and Franks, 1979). Sediments incoming to the subduction zone may include biogenic opal (diatoms or radiolarians) or opal in volcanic glass. Both transform to quartz below 100°C, causing a decrease in solid volume and water production (Behl and Garrison, 1994; Isaacs et al., 1983). Hydrocarbon production begins near the surface peaks around 100°C, and declines with the production of methane to above 200^{o}C (Hunt, 1996). Hydrocarbon production not only provides fluid by various carbon species that can influence mineral precipitation.

Cements and Veins: We focus on veins and cements that can be observed petrographically, excluding subtle clay cements that may be easily obscured by mechanical deformation. Observations from ODP/DSDP cores and the few exposures of shallowly buried accretionary prisms indicate that they are generally uncemented and sparsely veined below 125°C, excluding carbonates formed surface seepage (Kulm and Suess, 1990) and are not involved in seismogenesis. Above these temperatures calcite is locally abundant to the 150-250°C range. Quartz veining is not common until about 200°C. In prism rocks exposed on land, veins and cements occur both distributed through the rocks, (Fig. 5) and in locally high concentrations in a fault zones (Fig. 6). The distributed veins are most common in extensional fractures in boudins, and less obviously, they coat shear surfaces of boudins. The extensional veins inside the boudins are protected from the destructive slip processes occurring along shear surfaces coating boudins, perhaps accounting for their abundance.

Brittle Deformation: Brittle deformation includes fabrics associated with faulting in subduction zones: scaly fabric (mudstone), stratal disruption, and the associated development of complex cataclastic shear bands as well as macroscopically discrete shear surfaces (Moore, 1986). In subduction zones cataclastic phenomena are commonly localized into mm-wide shear bands (Aydin, 1978) of complex three-dimensional geometry, or “web structure” (Byrne, 1984). Apparently the shear bands achieve their complex three-dimensional structure because of the on-going rotational deformation and high strain that ultimately results in stratal disruption. Granular flow and distributed cataclastic flow occur at the earliest phases of development of subduction shear zones (Lucas and Moore, 1986). Pseudotachylyte is known from one locality and developed in rocks with background temperatures of 230 to 270°C (Ikesawa et al., 2003).

Ductile Deformation: Pressure solution is the initial ductile deformation mechanism in accretionary prisms. At temperatures less than 140-150°C pressure solution is subtle, characterized by local indentation and suturing of grains. At higher temperatures solution processes begin to produce cleavages of increasing intensity. Pressure solution is the most dominant ductile deformation mechanism in accretionary prisms (Feehan and Brandon, 1999; Fisher and Byrne, 1992; Fisher and Brantley, 1993; Ring and Brandon, 1999; Schwartz and Stockhert, 1996). Because pressure solution is commonly superimposed on previously stratally disrupted units, strong planar cleavages are not always obvious. Pressure solution apparently remains the dominant ductile deformation mechanism to temperatures exceeding 350°C. Intracrystalline deformation along dislocations is relatively rare (Schwartz and Stockhert, 1996) but the rocks undergo syntectonic recrystallization during growth of new phases, for example (Jayko et al., 1986).

Discussion

Smectite-Illite Transition and Albitization: The smectite to illite transition which is virtually complete at 150°C was proposed as a possible cause of the upper aseismic to seismic transition in subduction zones (Hyndman, 1997; Vrolijk, 1990) because this phase transition causes an increase in coefficient of friction (or strengthening of fault surfaces). However, recent experimental work on the rate dependent frictional properties of illite shows that it is velocity strengthening (Saffer and Marone, 2003), which is not consistent with acceleratiang away slip behavior associated with an earthquake (Scholz, 2002).

Although the smectite to illite transition may not have a direct physical effect on seismogenesis, the chemistry of the phase change may be significant. The smectite to illite transition produces calcium, iron and magnesium, which are expelled into porewaters. The albitization of plagioclase also produces calcium over about the same temperature range as the smectite to illite transition. The influx of these cations is thought to cause carbonate cementation during burial of sedimentary rocks (Boles and Franks, 1979) and also in accretionary prisms (Sample, 1990).

Carbonate Cementation: Carbonate cementation/veining occurs in significant amounts starting at about 100-150°C, which may reflect in influx of calcium, iron and magnesium causing the concentrations of these cations in porewaters to exceed the solubility of the various carbonate minerals. CO_3^{-2} in the carbonates is probably ultimately derived from oxidized hydrocarbons. The presence of carbonate can add to the cohesion of the rock and perhaps change its response to deformation (Muhuri et al., 2003). It is not clear whether carbonate is velocity weakening or velocity strengthening (Lockner and Byerlee, 1986), and therefore its significance in modifying the frictional response of fault zones is underdetermined.

Pressure Solution and Quartz Cementation: Pressure solution is normally considered as a component of diffusive mass transfer (solution, diffusion, and precipitation). Because fluid both advection and diffusion are important in transport of solutes in accretionary prisms, we focus our discussion on the solution and re-precipitation of materials. The onset of pressure solution appears approximately when the smectite to illite transition is complete. Research by sedimentary petrologists indicates that solution is strongly is facilitated by the presence of an illite-muscovite phase under very low stresses (Bjorkum, 1996). Therefore, the combination of increasing temperature, increasing effective stress, and the increase in abundance of illite from the smectite-illite transition may cause the onset of pressure solution observed at about 150°C in accretionary prisms. This interpretation suggests additional importance of the smectite-illite transition as a chemical if not a physical phenomena in inducing seismogenesis.

Byrn has suggested diffusive mass transfer processes homogenized rock fabric therefore allowed generation of recordable earthquakes (Byrne, 1998). Rowe and Moore (2003) further pointed out that the common quartz veining and cements occurring in areas of pressure solution change the frictional properties of the rock, leading to a velocity weakening slip behavior. Apparently silica is being mobilized by solution and re-deposited at the temperatures > 150°C while quartz demonstrates velocity weakening behavior at temperatures from about 100 to 300°C (Fig. 7). Rowe and Moore hypothesize that the overlap in these temperature ranges may be critical in controlling the seismogenic zone.

Schwartz and Stockhert (1996) argued the abundance of pressure solution and paucity of intracrystalline deformation is due to the low stresses in accretionary prisms, relative to continental deformation. Because accretionary prisms are thrust systems, higher mean stresses might be expected for a given depth. However, the ubiquitous presence of fluids in accretionary prisms may mediate the stress levels (see fluid pressures below).

In subduction zones, brittle deformation dominates to 150-200°C. Brittle structures in accretionary prisms begin to be overprinted by ductile structures at about 150 to 200°C. Rowe and Moore (2003), Meneghini (2003), and Onishi and Kimura (1995) studied rocks deformed in the 200-300°C range, where ductile deformation acting as pressure solution is repeatedly overprinted by brittle failure. Microscopically this alternation is seen a pressure solution fabric and as syntectonic growth of quartz fibers and other minerals that are cross cut by brittle fractures. Subsequently the brittle fracture phenomena are redeformed by pressure solution fabrics or encased by continuing mineral growth. In rocks deformed at 300°C and above there is little evidence for brittle deformation.

How Does Fluid Pressure Vary Above and Into the Seismogenic Zone?

Background: Because pore pressure is one of the most critical controls on rock deformation, a principal goal of the proposed deep drilling into seismogenic zones is to measure pore pressure (Kimura et al., 2003). Shallow direct measurements of fluid pressures at the frontal part of accretionary prisms have yielded modest overpressuring (Becker et al., 1997; Screaton et al., 1995) and modeling suggests development of higher pressures at somewhat greater depths (Bekins and Dreiss, 1992; Saffer and Bekins, 1998). Moreover, both frontal thrusts (Le Pichon et al., 1987; Moore et al., 1990) and out-of-sequence thrusts (Shipboard Scientific Party, 1994c) are known to seep fluid at the surface, thus indicating they are conduits of active fluid flow. The onset of high fluid pressures at depths less than 3-4 km is due to the rapid consolidation of sediments at shallow depths. Also mineral phase transitions including smectite to illite and opal to quartz transformations may contribute to overpressuring. The wide distribution of high fluid pressures suggested by the models coupled with the low state of consolidation and lithification of the sediments may explain the lack of seismicity at the depths of less than 4 km in sediment-dominated accretionary prisms. The disappearance of the decollement as a clear reflector at seismogenic depths in the Nankai accretionary prism has been attributed to dewatering and presumably depressurization of the sediment underthrust below the decollement (Bangs et al., 2004).

Observations from Subaerially Exposed Accretionary Prisms: Uplifted accretionary prism rocks provide evidence of fluid pressures preserved in both the fluid inclusions and geometry of veins and cements. Studies of fluid inclusions in extensional veins of accretionary prisms show high and variable fluid pressures that are interpreted to be near lithostatic (Lewis and Byrne, 2003; Vrolijk, 1987). Vrolijk (1987) suggested that the quartz vein growth was associated with a phase of major fluid movement along the decollement of the accretionary prism, and that it initiated at the high range of observed fluid pressures and cyclically decreased through time. (Lewis et al., 2000) believe that the observed veins represent a small amount of fluid trickling through a previously emplaced accretionary prism, albeit at fluid pressures 75% of lithostatic or higher.

Extensive veining paralleling a shallowly dipping latest Cretaceous accretionary thrust in the Marin Headlands of Northern California (Fig. 6) indicates that fluid pressures were sufficient to open cracks perpendicular to the minimum principal stress plus any tensional strength of the rock (Meneghini, 2003). Because this was a shallowly dipping accretionary thrust and the veins parallel it, the veins would have required a fluid pressure at least equal to the overburden. The zone of extensional veining is about 40 m thick along the thrust surface (Fig. 6). The extraordinary quantity of veins in the fault zone suggests copious fluid flow. Cross cutting relationships suggest generations of veining and associated brittle fracture. Additionally, pressure solution cleavage is superimposed on the veins indicating periods of compression alternating with periods of dilation across the fault surface. This alternation of compression and dilation may represent fault-valve behavior and may be tied to the seismic cycle (Meneghini, 2003). Apparently the 40 m thick zone of veins developed cumulatively with only a portion being active at any time. Although a 40 m thickness of dilated fault might be seismically resolvable at this depth, if only a narrower zone was active at any given time, it would not be imaged. This fault zone may be a good analogue for the disappearing decollement of Bangs et al. (2004).

Overall fluid pressures appear to be high and broadly distributed at shallow depths due to the intergranular fluid sources, mineral phase changes, and hydrocarbon generation that produce fluids. At greater depths, the fluid pressures also apparently remain high, but the conduits of flow are more localized along faults due to the reduction of permeability resulting from the consolidation and low-grade metamorphism in the accretionary prism (Lewis and Byrne, 2003). As prism rocks are buried beyond about 5 km, porosity changes are small (Bray and Karig, 1985), hence fluids are probably derived from continuing mineral dehydration reactions.

Strain Localization

Experimental studies suggest that shear strain transitions from being distributed to being more localized on discrete shear surfaces with the transition from velocity strengthening to velocity weakening behavior (Fig. 8) (Marone, 1998). In accretionary prisms this correlation generally applies, with the early faults being characterized by broader zones of scaly mudstone and stratal disruption, shear bands, and minor faults (Shipboard Scientific Party, 1991). Older faults in uplifted prisms are more discrete than earlier primary accretionary structures (Fig. 9).

On a larger scale it appears that shear strain localization in the form of out-of-sequence thrusts approximately correlates with the seaward limit of modeled earthquake displacements and onset of recorded microearthquakes in the Nankai Trough (Fig. 10) (Obana et al., 2003; Park et al., 2000). This implies that the consolidation/lithification processes in the prism are allowing it to deform as discrete large-scale blocks with slip localized along the out-of-sequence thrusts. Out-of-sequence thrusts are clearly defined in ancient prisms and tend to partition them into packages with differing sedimentary, structural or metamorphic history (Fig. 11). The demonstrated activity of these out-of-sequence thrusts in past great earthquakes indicates a significant role in releasing seismic energy (Plafker, 1972). Moreover, modern activity of out-of-sequence thrusts suggests major activity near the frontal part of the accretionary prism and quiescence in a landward portion of the prism (Fig. 11).

Summary and Discussion

Drawing from the consensus of thermal models of modern seismicity in subduction zones, we define prism rocks that have passed through the seismogenic zone as those that have been subjected to temperatures of 125 to 350°C. Such rocks that have had the opportunity to deform seismogenically in subduction zones contrast to those deformed above and below in the following ways:

1) During passage through temperatures from 50-150°C accretionary prism sediments become rocks, undergoing diagenetic reactions including of the transformation of smectite to illite, the albitization of detrital feldspar, dehydration of opal, and hydrocarbon generation. Although the smectite to illite transition does increase the coefficient of friction or strength, illite's rate dependent friction is velocity strengthening and not subject to accelerating slip. However, the cations (calcium, magnesium, iron) released during the smectite to illite transition and the albitization process foster cementation.

2) Cementation and veining by carbonates becomes common above 125°C, perhaps due to the above-mentioned release of cations. Pressure solution fabrics begin to be apparent at about 150°C, with well-developed cleavages and quartz veining common by 200°C.

Pressure solution may be facilitated by the diagenetic formation of illite and its catalyzing effect on quartz and feldspar dissolution.
3) Quartz veining and cementation in the 150 to 300°C range facilitates the change from a velocity-strengthening to a velocity-weakening, earthquake-prone rheology.
4) Cementation by quartz and carbonates increases cohesion and may also make the rocks subject to unstable failure, producing and earthquake.
5) In accretionary prisms, brittle fabrics are progressively replaced by ductile fabrics through a temperature range of about 150 to 325°C.
6) Although rocks in the seismogenic zone have lost most of their intergranular fluid through consolidation, vein geometries and fluid inclusions suggest high fluid pressures, approaching lithostatic.
7) Strain localization in the formation of discrete faults occurs across the lower aseismic to seismic transition. Strain localization is observed both at microscopic, outcrop and map scale. Active out-of-sequence thrusts occur in the frontal portions of accretionary prisms.

The evolution of the accretionary prism from aseismic to seismic behavior involves the changes in material properties from fault zones dominated by clays to those in which quartz and carbonate are introduced by diffusion and fluid advection. Although both the quartz and carbonate increase cohesion, only quartz has a velocity weakening frictional response. The rate dependent frictional behavior of carbonate is not well defined.

Consolidation, cementation, and other diagenetic-metamorphic transitions of the accretionary prism lead to the development of an upper plate of the subduction zone with increasing rigidity. Development of this rigid upper plate is a prerequisite for seismicity because fault zone can only develop between if both sides are capable of storing elastic deformation. The seaward-most out-of-sequence thrusts define the seaward edge of this elastically rigid block.

Acknowledgements

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Table 1

Temperature and Pressure Range	**Observations and Source Localities**	**References**
< 100°C Unmetamorphosed	No veins and cements through nearly all cored rocks in ODP. Minor carbonates in Barbados drill cores. Extremely rare quartz, carbonate and sulfides in Nankai trough. Accreted terrigenous deposits on Barbados Island lack any carbonate/quartz veins or cements. Faulting and stratal disruption includes cataclasis of sand sized particles widespread development of scaly fabric in mudstones.	(Byrne et al., 1993; Labaume et al., 1997; Maltman et al., 1993; Maltman et al., 1997; Speed, 1990; Vrolijk and Sheppard, 1991)
100-150°C; 5 km Typically Zeolite Facies	Evidence for cementation and veining variable. Locally significant carbonate cementation along fault zones. Quartz cementation/veins rare and minor. Cataclasis of sand sized particles widespread. Development of scaly fabric in mudstones. Incipient pressure solution cleavage.	(Geddes, 1993; Moore, 1980; Moore and Allwardt, 1980; Orange et al., 1993; Orange and Underwood, 1995; Rowe et al., 2002)
150–300°C; 5-15 km Typically Prehnite-Pumpellyite Facies	Quartz and carbonate veining common. Cataclasis in sands and veined materials temporally alternates with pressure solution. Cleavages common, and especially visible in more coherent units. Quartz veins/cements common in the 200-300°C range. Rare pseudotachylyte.	(Byrne, 1984; DiTullio and Byrne, 1990; DiTullio et al., 1993; Fisher, 1996; Hibbard et al., 1993; Ikesawa et al., 2003; Kimura and Mukai, 1990; Onishi and Kimura, 1995; Sample and Moore, 1987; Sample, 1990; Vrolijk et al., 1988).
150-350°C; 15 to 27 km Classic HP-LT (e.g. Franciscan Blueschists of eastern belt)	Often coherent layering with multiple fold generations, local stratal disruption predating metamorphism. Pressure solution common.	(Jayko et al., 1986; Ring and Brandon, 1999)
> 300°C, 8-27 km Prehnite-Actinolite, and Blueschist-Greenschist Facies	Widespread foliation development, pressure solution, microscopically apparent recrystallization during development of metamorphic assemblages. Many terranes surprising	(Helper, 1986; Norris and Bishop, 1990; Ring and Brandon, 1999; Roeske, 1986; Schwartz and Stockhert, 1996)

	coherent with multiple phases of folding. Brittle deformation during peak metamorphism not obvious, but a previous history is suggested by the stratal disruption in some areas.	

Table 1: Observed cements, veins and relevant structural fabrics in various temperature and metamorphic facies ranges. Temperature ranges are associated with typical metamorphic facies with actual temperature conditions determined from metamorphic minerals, fluid inclusions, and vitrinite reflectance. The pressure and temperature range encompass those of the cited examples with the associated metamorphic facies being identified. The P-T ranges do not include the maximum range of the particular metamorphic facies. Surface and near surface carbonate precipitates associated with cold seeps not included as their formation is too shallow to be involved in seismicity.

Figures:

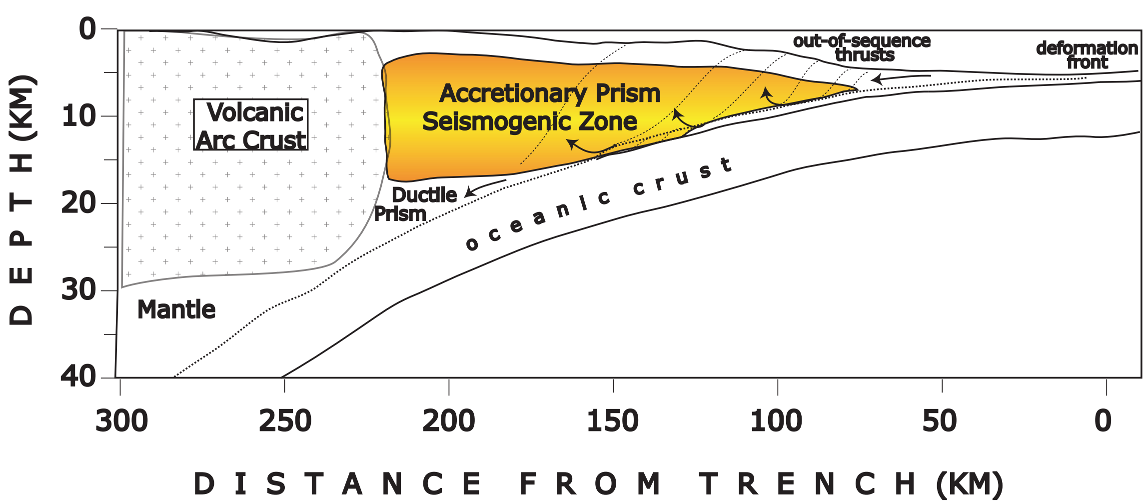

Figure 1. Cross section showing transport paths of rocks through the accretionary prism. Note that out-of-sequence thrusts begin at about seaward limit of prism seismogenic zone. Seismogenic zone defined by temperature limits of 125 to 350 ^{o}C; limits would shift with variations in geothermal gradient. Arrows show material transport paths in prism.

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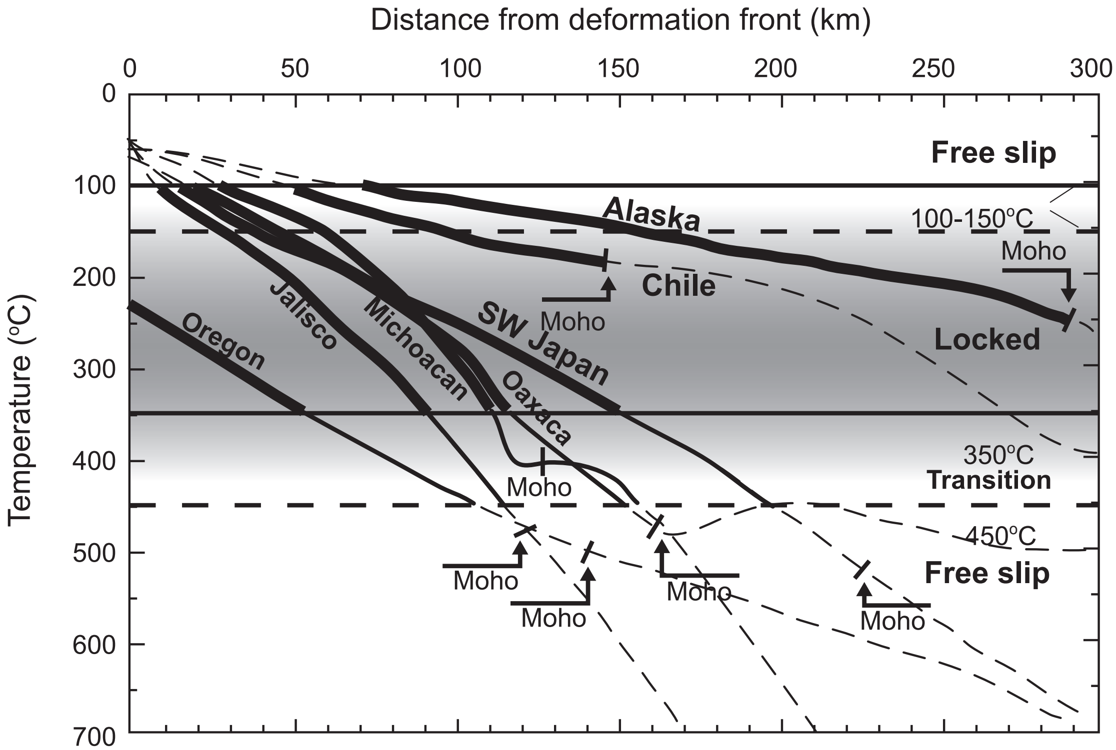

Figure 2. Compilation of modeled temperatures of subduction thrust interfaces verses distance landward of deformation front. Temperatures estimated from 2-dimensional thermal models with upper and lower bounds of seismogenic zone estimated from aftershocks or geodetically and/or tsunami-based of fault plane slip distribution (Currie et al., 2002; Hyndman, 1997).

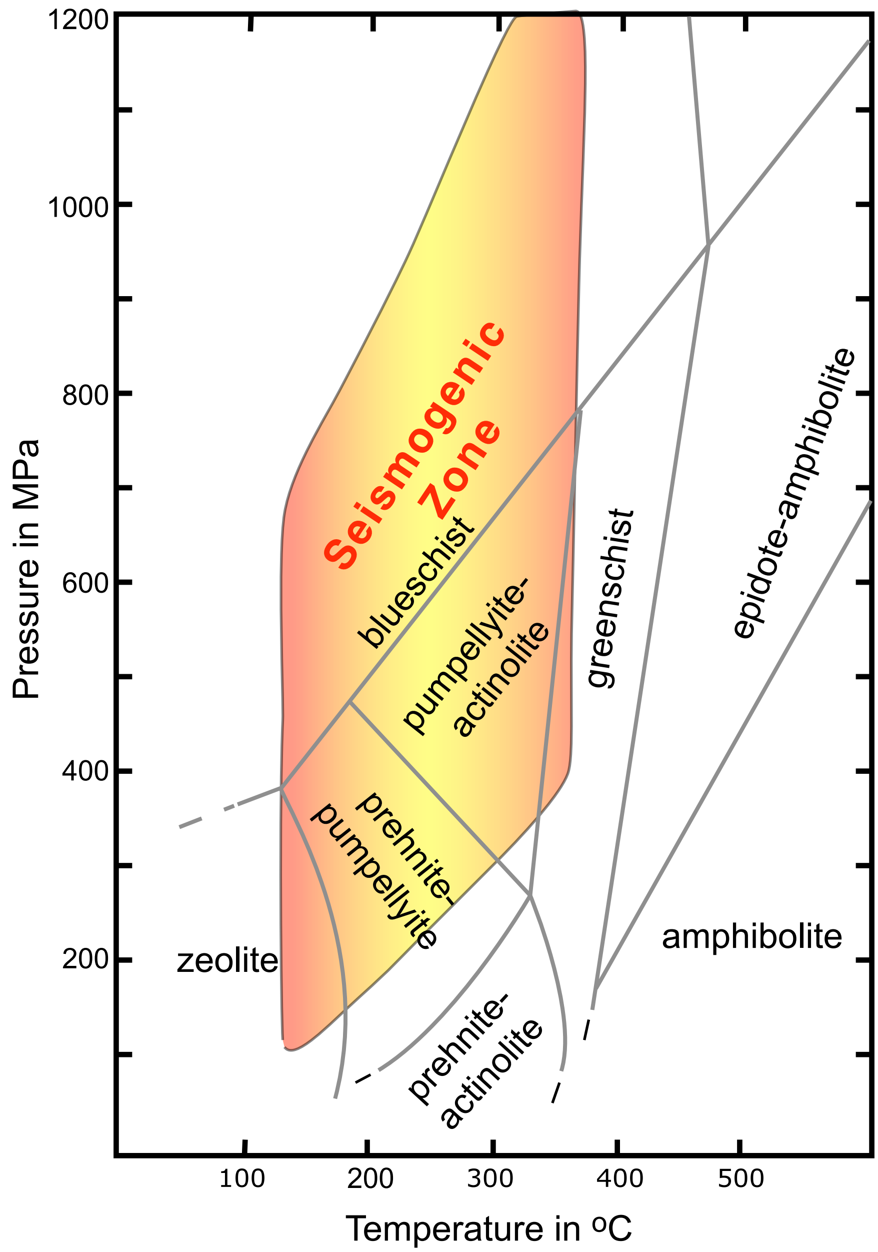

Fig. 2

Figure 3. P-T limits of seismogenic zone estimated from modeled temperature limits of modern systems (125-350°C) coupled thermal gradients from ancient prisms. Upper pressure limit constrained by extremely cold subduction systems such as ancient Franciscan Complex (Ernst, 1990) and and lower limits by very warm systems such as the Shimanto Complex of southwestern Japan (Lewis and Byrne, 2003). Limits of metamorphic mineral facies from Ernst (1990).

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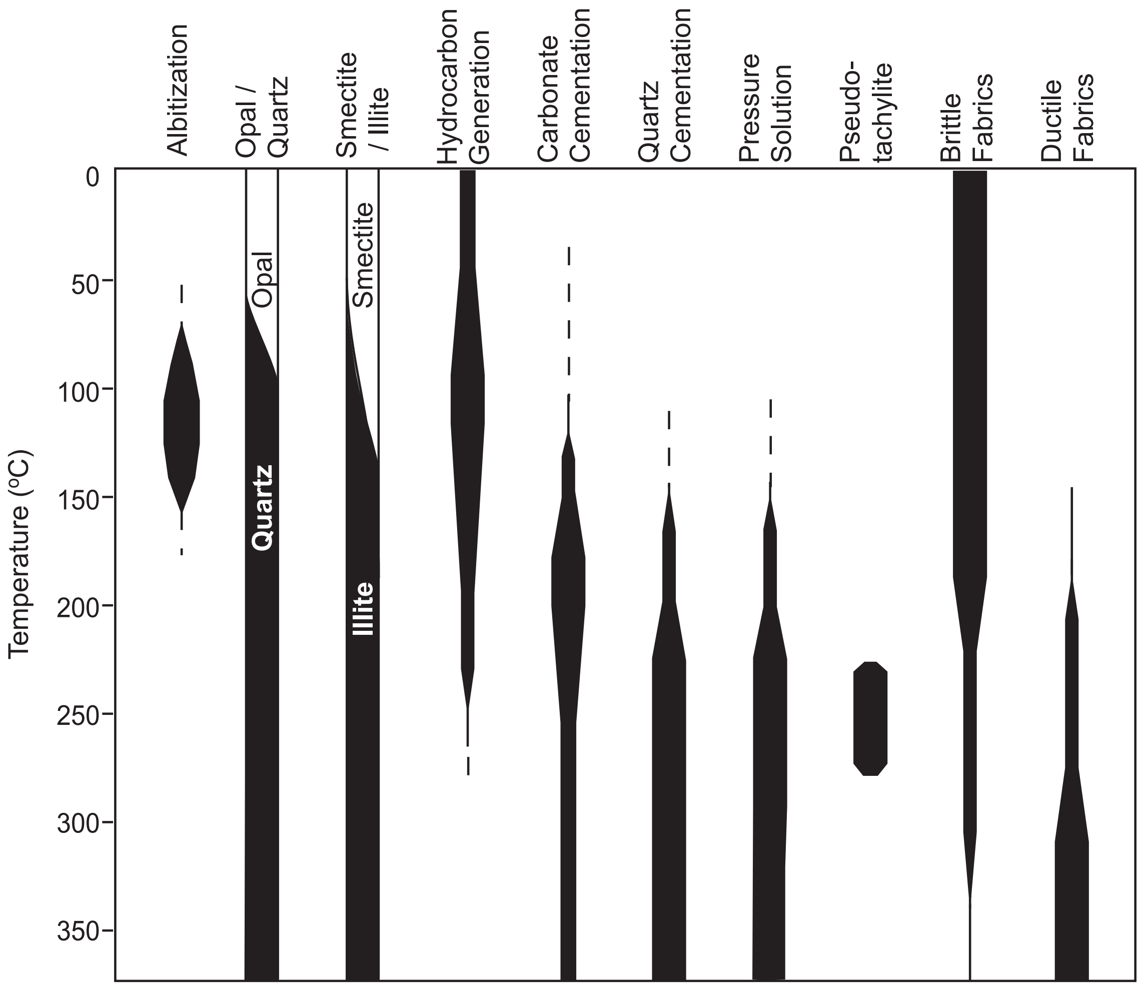

Figure 4. Mineralogical transitions and fabric changes in the 25 to about 375°C temperature range in accretionary prism. Abundance of minerals as well as intensity of processes metamorphic and structural shown schematically by width of bars. Temperature range of pseudotachylyte (frictional melt) is that of country rocks in which melting occurred. Information on this diagram is generalized from sources in Table 1 and references cited during discussion in text.

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Fig. 5

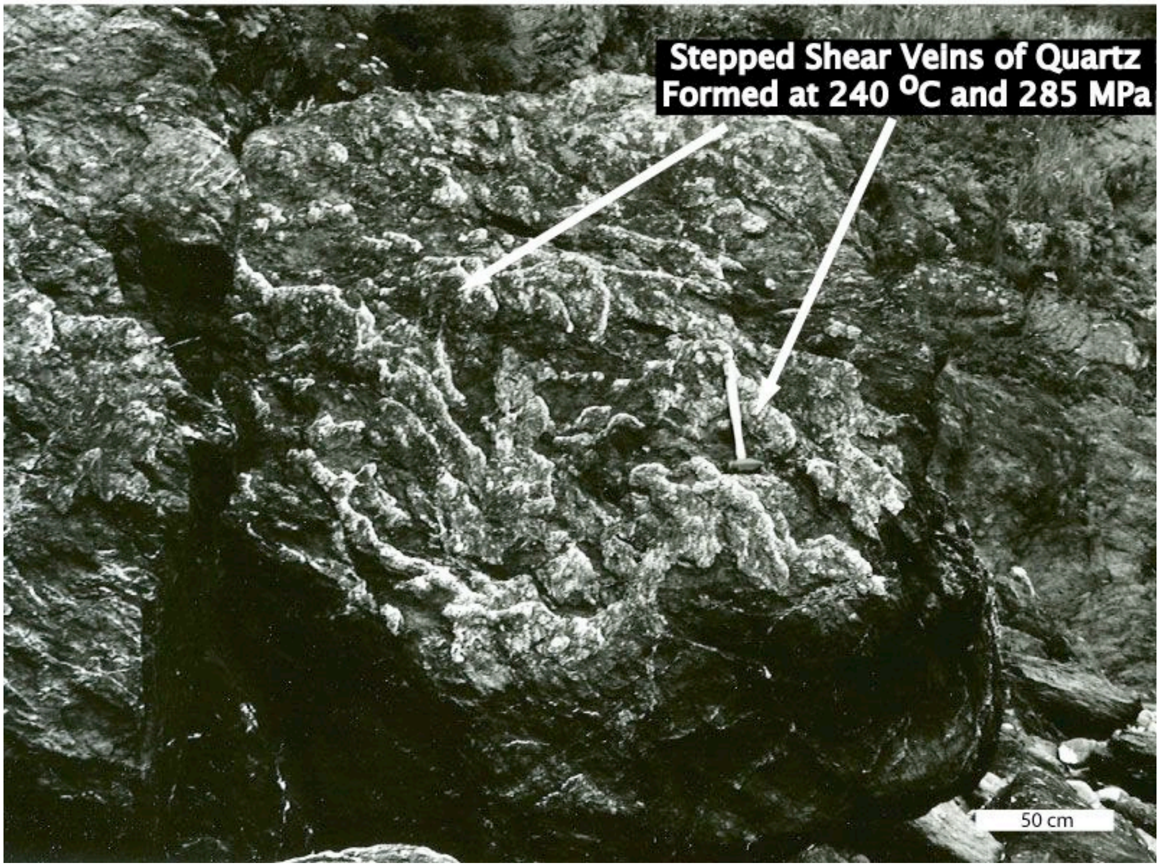

Figure 5. Photo of quartz veined block surface of stratally disrupted zone, Paleocene accretionary prism, Kodiak Islands, Alaska (Vrolijk et al., 1988). Shear veins coating surface of this block probably developed during interseismic phase of deformation, but would provide a quartz influenced rheology during seismic deformation.

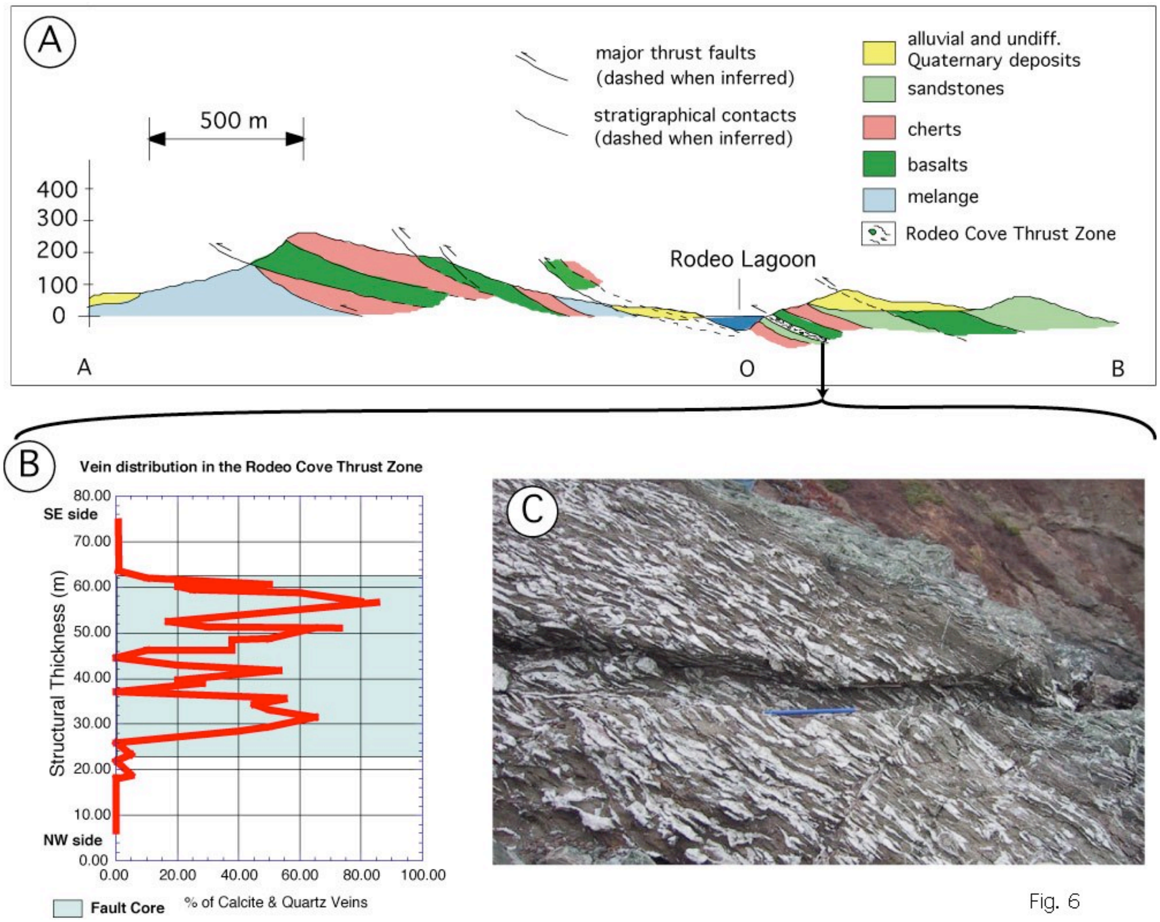

Figure 6. Evidence for localized fluid flow on a subduction thrust system. A) Northwesterly cross section through Rodeo Cove area, Marin Headlands (Meneghini, 2003; Blake et al., 2000). B) Concentration of carbonate and quartz veins in Rodeo Cove thrust zone (Meneghini, 2003). C) Outcrop of carbonate and quartz veins in Rodeo Cove thrust zone. Note parallelism to dip of fault zone in A. Veins are also parallel to pressure solution foliation in fault zone (Menegini, 2003)

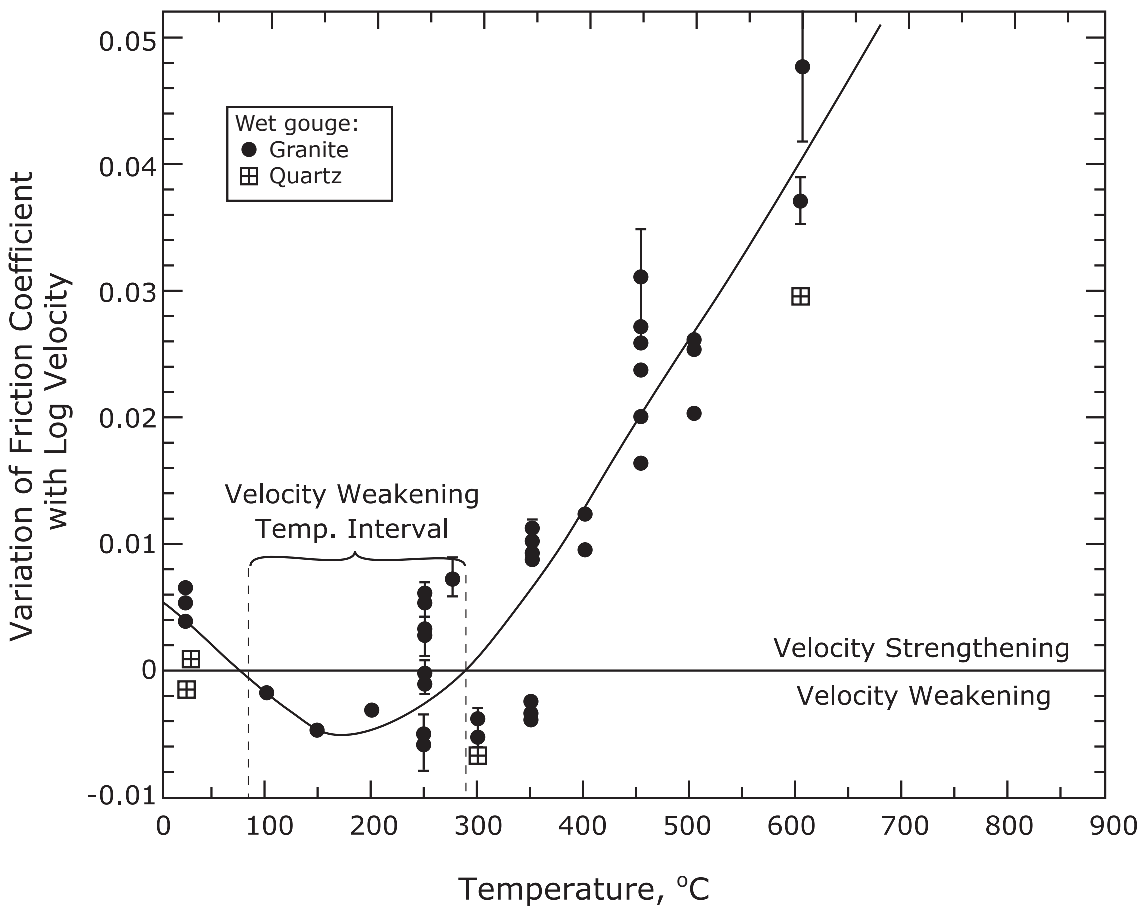

Figure 7. Velocity dependence of granite and quartz gouge samples (Blanpied et al., 1995). Note that velocity weakening occurs in a temperature range from about 100 to 250 to 300 degrees C, which coincides with the onset of major cementation and veining in accretionary prism fault zones.

Moore, J. C., Rowe, C. D., and Meneghini, F. (2007) How Accretionary Prisms Elucidate Seismogenesis in Subduction Thrust Faults. In: Dixon, T. and Moore, J. C., eds, The Seismogenic Zone of Subduction Thrust Faults. Columbia University Press, New York, NY, pp. 288-315.

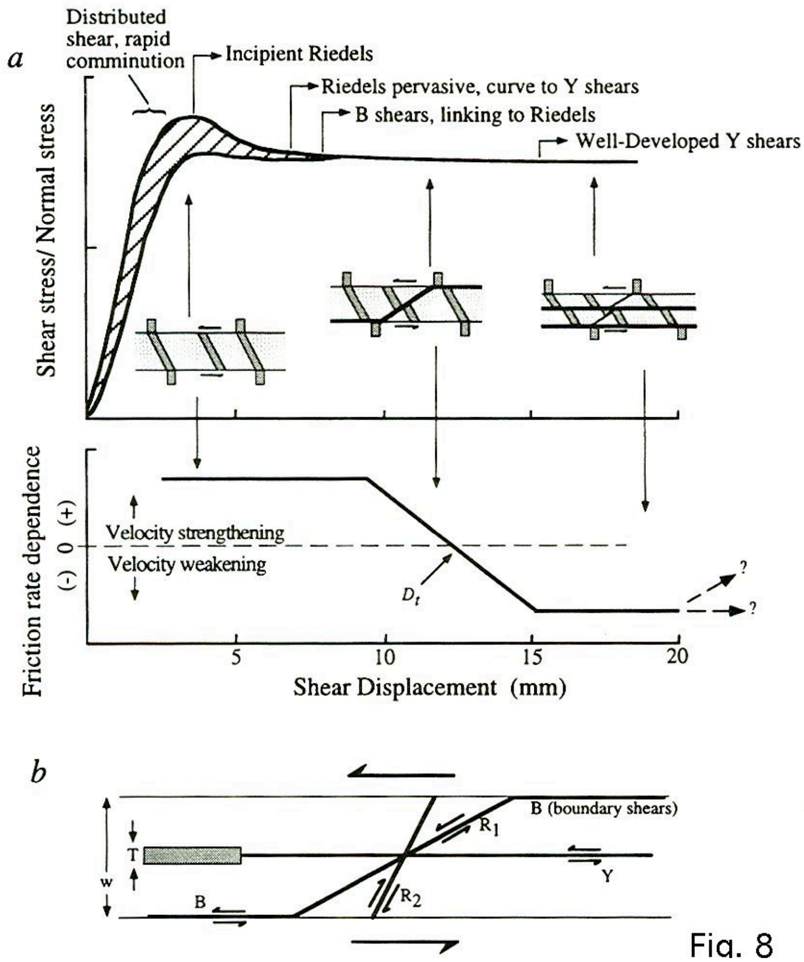

Fig. 8

Figure 8. Conceptualization of the experimental correlation of the transition from more distributed deformation to more localized deformation with the transition from velocity strengthening to velocity weakening (Marone, 1998).

Fig 9

Figure 9. Depth section with nearby microearthquakes projected on to it (Obana et al., 2003). Note that microearthquakes die-out just seaward of the initial development of out-of-sequence thrusts. Note also that the accretionary prism has a shallow even taper in its seaward extent but the surface slope begins to steepen and become more irregular landward of the development of the out-of-sequence thrusts and the onset of seismicity.

Moore, J. C., Rowe, C. D., and Meneghini, F. (2007) How Accretionary Prisms Elucidate Seismogenesis in Subduction Thrust Faults. In: Dixon, T. and Moore, J. C., eds, The Seismogenic Zone of Subduction Thrust Faults. Columbia University Press, New York, NY, pp. 288-315.

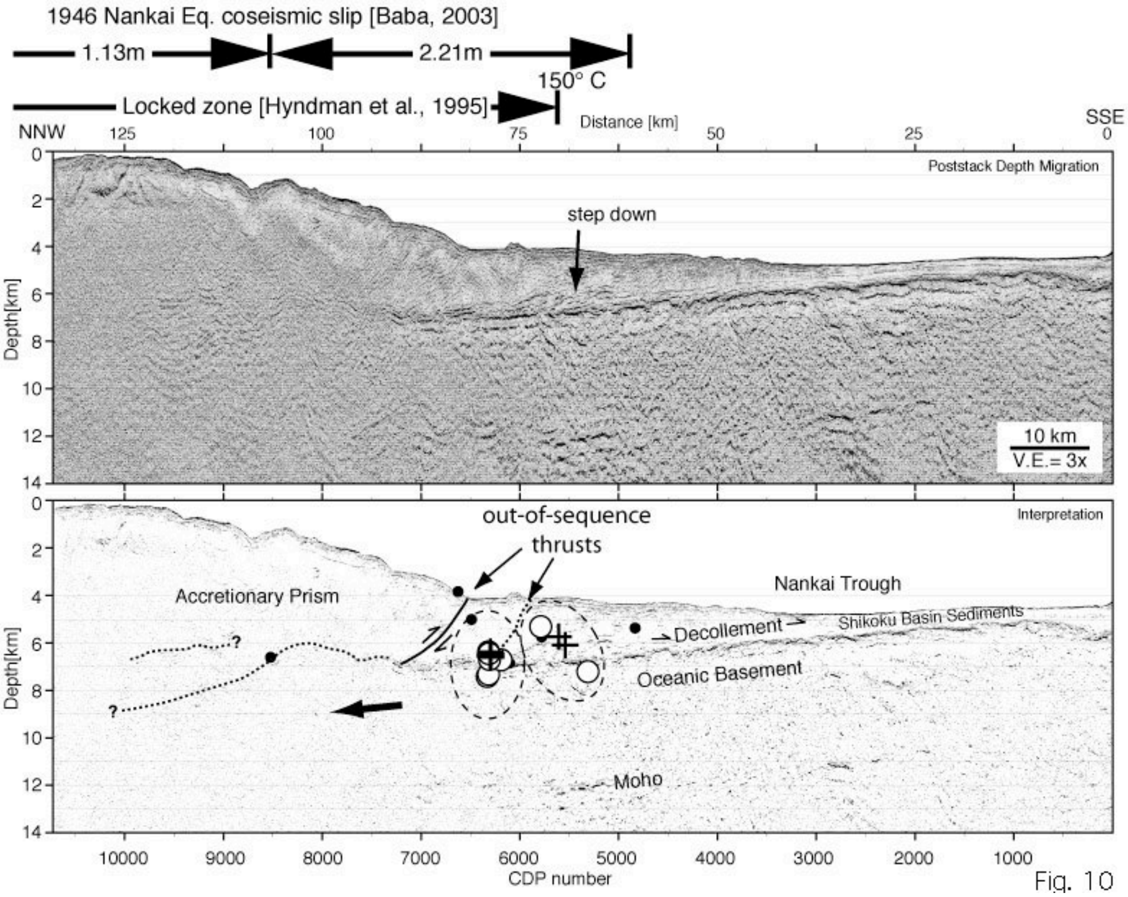

Figure 10: Outcrop examples of distributed faulting verses shear localization in accretionary prisms. A) Outcrop of a stratally disrupted fault zone, Eocene accretionary prism, Dominican Republic (Witschard and Dolan, 1990). Broad zone of deformation that continues at least 10 m right beyond the edge of the photo. Inclined fabric of disruption zone indicates stratified rocks, where Jim
Dolan is standing, are up relative to the disrupted rocks. B) Discrete out-of-sequence thrust fault cutting early steeply dipping stratally disrupted fabric, (beneath Peter Vrolijk's feet); note white quartz vein in fault being pointed to by Tim Byrne. Paleocene accretionary prism, Kodiak Islands Alaska.

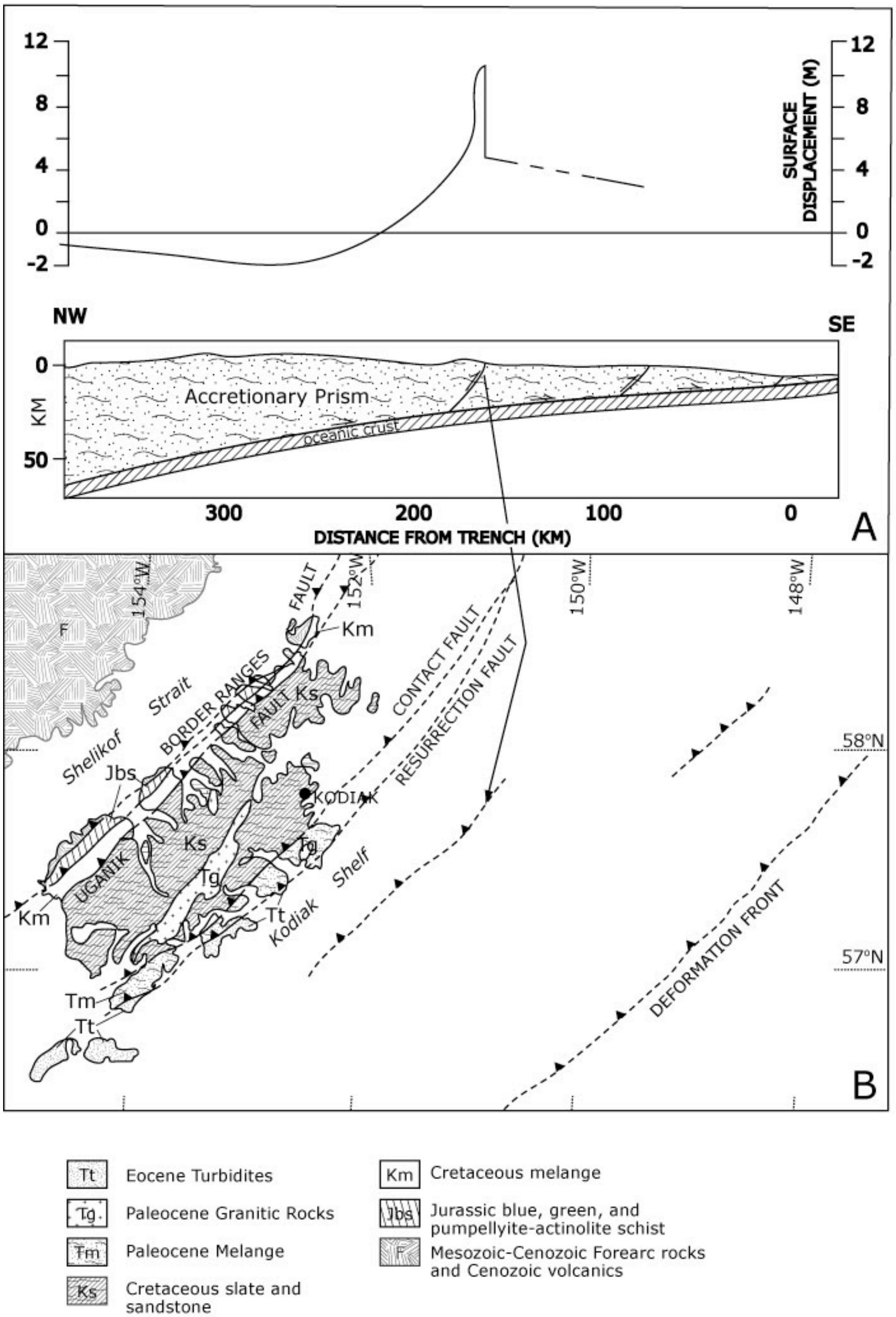

FIG. 11

Figure 11: A) Map showing thrust faults cutting accretionary prism (Moore et al., 1991; Plafker, 1972; Plafker et al., 1994). All but frontal thrust are out-of-sequence thrusts. B) Cross section from Prince William Sound, just north of A, showing correlation to fault

that was active during 1964 earthquake (Plafker, 1972) . Faults seaward of the correlated fault were inferred to be active during the 1964 earthquake. Seismic reflection data shows that these faults deform young sediments at the seafloor.

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