Large-scale pseudotachylytes and fluidized cataclasites from an ancient subduction thrust fault

Christen D. Rowe  Earth Science Department, University of California–Santa Cruz, 1156 High Street, Santa Cruz, California 95064, USA
J. Casey Moore  Dipartimento di Scienze della Terra, Università di Pisa, via S. Maria, 53, 56126 Pisa, Italy
Francesca Meneghini  Department of Geosciences, Pennsylvania State University, 320 Deike Building, University Park, Pennsylvania 16802, USA

ABSTRACT

In the Kodiak accretionary complex, Kodiak Island, Alaska, pseudotachylyte occurs in black, locally vitreous ultrafine-grained fault rock. Microscopic observations show that the pseudotachylytes are composed of glass, with vesicles, amygdules, microlites, and flow structures, indicating a frictional melt. The pseudotachylyte is gradational to cataclasite and shows outcrop-scale injection and ductile deformation structures. The cataclasite was ductily mobile (i.e., fluidized) simultaneous with the formation and emplacement of pseudotachylyte melt. The pseudotachylytic rocks postdate the strataf disrption fabric of associated shear-zone mélanges and show similar direction of thrust transport, and have undergone limited subsequent deformation. We interpret the strataf disrption as resulting from underthrusting of the subducting plate and pseudotachylyte development as the final activity of this thrust surface. The gradational contacts between pseudotachylyte and cataclasite demonstrate that the cataclasite also formed as a seismically and may represent paleoseismic rupture zones, possibly of very great earthquakes, and without accompanying pseudotachylytes. The pseudotachylytes are voluminous, and many are spatially disconnected from generation surfaces. This style is distinct from pseudotachylytes described in other environments, and this may explain the rarity of documented examples of subduction-thrust pseudotachylyte.

Keywords: pseudotachylyte, Kodiak accretionary complex, subduction thrust, paleoseismicity, fluidized gouge, cataclasite.

INTRODUCTION

Subduction thrust faults generate the world’s largest earthquakes and are the site of ~90% of global moment release (Pacheco et al., 1993). Studies of exhumed subduction complexes provide the only means of geologically observing the seismogenic zone. However, explicit geological evidence of paleoseismicity in subduction-zone rocks exhumed from seismogenic depths has been elusive. Fisher and Byrne (1987) recognized that mélanges zones preserved in accretionary prisms represent ancient subduction thrust faults. However, deformation in these systems is broadly distributed. Ikewawa et al. (2003), Austrheim and Andersen (2004), and Kitamura et al. (2005) discovered direct evidence of paleoseismicity as frictional melts or pseudotachylytes in ancient subduction thrust faults. These pseudotachylytes satisfy the strictest criteria for identifying paleoseismicity (Cowan, 1999). Pseudotachylyte-bearing faults are uniquely able to record dynamic rupture processes during earthquakes (Björnerud and Magloughlin, 2004; Lan-Bin et al., 1997). Given that the majority of modern subduction zones are seismogenic, direct evidence of paleoseismicity seems strangely absent in the rock record.

Pseudotachylytes

Many pseudotachylytes are associated with cataclasites, suggesting that ultracumminution is a stage in the development of pseudotachylyte, and possibly a necessary precursor (Björnerud and Magloughlin, 2004; Magloughlin, 1992; Spray, 1995). It is the general consensus that both ultracataclasism and frictional melting play a role in pseudotachylyte formation (Magloughlin, 1992), and that pseudotachylytes are formed exclusively during seismic slip (Sibson, 1975). Otsuki et al. (2003) documented association of cataclasite and pseudotachylyte horizons in the Nojima fault zone over millimeter scales, reinforcing the genetic relationship between cataclasis and melting.

GEOLoGIC SETTING

The Kodiak accretionary complex (Fig. 1) comprises a mid-Mesozoic to early Tertiary accretionary prism constructed of accreted, NW-dipping, thrust-bounded units. These rock units are progressively younger toward the southeast, with modern equivalents forming in the Aleutian Trench (Plafker et al., 1994). Décollement-system thrust faults are preserved in several accreted units, recording the history of the décollement during its activity at some discrete depth (Fisher and Byrne, 1987).

The structurally lowest part of the Paleocene Ghost Rocks Formation of the accretionary complex is an argillaceous mélangé and Fisher and Byrne’s (1987) prime example of a décollement zone. We have studied this mélange at Pasagshak Point, where it primarily consists of variably disrupted turbiditic argillites with a few continuous massive sandstones (>10 m thick). Prehnite-pumpellylite facies greenstones occur locally (Fig. 1). Water and methane fluid inclusions in synmélangé quartz veins indicate mélangé formation at depths of 12–14 km and temperatures of 230–260 °C (Byrne, 1984; Rowe et al., 2002; Vrolijk et al., 1988). As the mélangé formation occurred before, during, and up to basal accretion of the unit (Byrne, 1984), this is taken as an estimate of minimum burial conditions.

SHEAR ZONES AND ULTRAFINE-GRAINED FAULT ROCKS: FIELD RELATIONS

The mélange of Pasagshak Point includes at least three 5–15-m-thick shear zones that are subparallel to local fabric (Figs. 1 and 2). The shear zones are characterized by argillite matrix with pervasive scaly fabric, containing rotated and rounded sandstone boudins, and strong down dip lineation on both matrix pha-roids and sandstone boudins (shear-zone fabric; Figs. 2A, 2B). Extensional veins exist within clasts and fabric-parallel veining is rare. Sandstone clasts vary from submillimeter to 10 cm along fabric strike, and up to 20 cm down fabric dip. These shear zones are in a sense “micromélange,” but are easily distinguished from background argillite-matrix mélange by a more pervasive fabric, and rounding, smaller scale, and rotation of sandstone clasts (Figs. 2A, 2B). One shear zone is exposed for 1 km along strike and can be correlated for a total of 3 km along strike. Its base grades into disrupted argillite with variable sandstone bed fragments and boudins. The upper surface of this most continuous shear zone follows the base of a massive sandstone layer. Dark gray to black, locally vitreous,
ultrafine-grained fault rocks crosscuts and intrudes the shear zones. The base of the ultrafine-grained layers is sharp and cuts shear-zone scaly fabric at a low (≤20°) angle (Figs. 2A–2C). Outcrops show intrusive sills, dikes, and flow structures, some of which resemble flute structures. These intrusive structures often deform the shear-zone fabric around them (Figs. 2B, 2C). Asymmetrical and sheath folds of the ultrafine-grained fault rock occur along contacts of, and within, the shear zones (Fig. 2C). The massive ultrafine-grained fault rock frequently shows blocky, layer-perpendicular jointing (Figs. 2A, 2C). The structurally highest and most continuous example occurs at the top of the most continuously mapped shear zone, just below a massive sandstone (Fig. 1). The ultrafine-grained fault rock layers sometimes occur singly (Fig. 2A), sometimes as a double horizon encasing variably organized fabric of mixed lithologic material, or are overlain by horizons that are transitional to a shear zone and characterized by flow-banding folds (Fig. 2C).

**Microscopic Observations and Classification of Ultrafine-Grained Fault Rocks**

Ultrafine-grained fault rocks contain predominantly quartz, feldspar, illite, and chlorite. Quartz and feldspar matrix grains are generally 300 μm or smaller in diameter. The fabric is characterized by unsorted grains of quartz and feldspar in a microphanitic matrix (microphanitic is used here as a nongeneric term for microscopically irresolvable fault rock). The matrix grades from very fine grained chlorite ± clays to completely microphanitic matrix (Fig. 3A). Where grains are discernable, the matrix varies from slightly foliated chlorite and/or clay to a random fabric mat of lathes.

**Overall Appearance**

The optical appearance of the microphanitic fault rocks varies. Some samples have fine, patchy birefringence textures due to very fine grained chlorite, clay, and quartz. Others are opaque, even in overly thin sections (sub–30 μm thickness). In some layers, the concentration of clastic material is so great and the matrix so opaque as to obscure the nature of the groundmass.

**Vesicles and Amygdules**

Rare vesicles and amygdules occur in the most fine-grained matrix (Fig. 3B). They are very small, isolated, and subspherical (aspect ratio > 1/3). Rarely, radiating cracks extend outward from the vesicle walls. Some are partially to totally infilled with quartz, calcite, pyrite, and/or apatite.

**Rounded Grains**

Rounded grains are plentiful within aphanitic horizons (Figs. 3A, 3C, 3D); the boundaries of dominantly aphanitic horizons are often gradational into cataclasite, where grain proportion increases over 1 mm or less from <10% to near 100% of the rock. In the microphanitic regions, rounded grain populations are entirely quartz, but where grain population increases, grains become more angular, and feldspar grains become more common.

**Oxide and Sulfide Crystals**

The aphanitic rocks are generally free of microlite crystals. The exceptions are skeletal pyrite grains, and tiny spherical grains or nodules of titanium oxide and zinc sulfide, which occur in scattered clusters or rows of subspherical grains within the aphanitic matrix (Fig. 3C). Rutile is extremely rare as a detrital mineral in the wall rock, and sphalerite has never been observed elsewhere in the rocks. Pyrite occurs in the host rock in detrital and authigenic fragments, but the grain size in the host argillite and shear zone is very small, while the skeletal and frambooidal grains found in the ultrafine-grained fault rocks are an order of magnitude larger (Fig. 3D).

**Interpretation and Identification of Pseudotachylyte**

Many of the features described here are consistent with previously reported observations of melt-derived pseudotachylyte, and hold some clues to the conditions under which melting occurred. The microphanitic fault rock material is interpreted to be pseudotachylyte glass, which is variably devitrified. The amygdules are identified as mineral-filled vesicles formed during cooling of pseudotachylyte glass immediately after formation (Madock et al., 1987). Amygdul mineral growth may or may not have been coeval with the development of veins in fine extensional joints, which also characterize the glassiest layers of the fault rock.

The rounded grains observed in the aphanitic groundmass are interpreted to be survivor grains. This interpretation is supported by the mineralogy (quartz is more refractory than micas and clays, which dominate source rock) and the smooth rounding of grains, distinct from the angular shape of detrital grains in the source rock and crushing-derived grains in the cataclasite. The pattern of rounded quartz grains within a microphanitic layer, grading to increasingly angular grains of less refractory minerals (feldspars, clasts of older pseudotachylyte), is consistent with the pattern observed by Otsuki et al. (2003) in variably
melted gouge from the Nojima fault zone. The gradational transition between glass-rich, to glass-matrix, to clast-dominated cataclasites (i.e., Fig. 3A) is similar to that described by Berlenbach and Roering (1992).

The oxide and sulfide mineral grains are distinct from any in the source rock, either by mineralogy (rutile, sphalerite) or by grain size and morphology (coarse skeletal pyrite). Therefore it is likely that these grains are endemic to the ultrafine-grained fault rocks, and that they originated by crystallization from a melt. Skeletal pyrite grains from pseudotachylites may be indicative of crystallization from a melt. The isotropic, aphanitic ultrafine-grained rocks, which display vesicles, rounded survivor grains, skeletal pyrite, and metallic microlites, are consistent with the identification of pseudotachylite.

**DISCUSSION**

Globally, the upper limit of seismicity in subduction zones varies in depth, but roughly correlates with the 100–150 °C isotherm in thermal models (Hyndman et al., 1997; Oleskevich et al., 1999). This locality, as well as the Japanese subduction thrust pseudotachylite locality (Ikesawa et al., 2003), likely formed in the middle to upper seismogenic zone, while the Corsican locality likely formed in the brittle-ductile transition zone (Austrheim and Andersen, 2004; Hyndman et al., 1997). It has been suggested that pseudotachylite formation is restricted to dry faults (Bjornenud and Magloughlin, 2004; Sibson, 1975), because the presence of water could lubricate the fault and/or act as a heat sink and prevent the heat buildup needed to cause frictional melting during earthquakes. In contrast, calculations by Dixon and Dixon (1989) demonstrated that the presence of vesicles in a melt requires entraining of available volatiles during pseudotachylite cooling, because there is insufficient time to nucleate bubbles by degassing, as previously suggested (Maddock et al., 1987). O’Hara and Sharp (2001) demonstrated that microlite isotopic compositions required melt-groundwater interaction during pseudotachylite formation.

The thickness of the Kodiak pseudotachy-
lytes (≤ ~10 cm) exceeds predications for the maximum melt thickness that could be produced on a single surface (~1 cm), as melt production is modeled as inherently self-limiting (McKenzie and Brune, 1972). Work by Di Toro et al. (2005) suggests that a thickness of 2–3 cm could be correlated to coseismic slip of ~10 m, so by that relation, a 10-cm-thick fault vein would require extraordinarily large slip. It is possible that this conflict could be resolved by considering at least three factors: (1) the thick pseudotachylyte veins that are dense with survivor grains contain less melt than a completely glass vein of the same dimension, (2) melting of phyllosilicate source rocks may require less energy consumption (lower heat capacity) than the models assumed, and (3) even pseudotachylyte fault veins that are semiplanar for tens or hundreds of meters could represent accumulated melt from a larger generation plane that has ponded locally. Despite these qualifications, the very thick pseudotachylytes from the Kodiak Islands may well be the products of great earthquakes, which would be expected in this environment.

Dixon and Dixon (1989) showed that the residence time of thin tabular bodies of silicate melt is short (seconds to hours). Flow banding and intercalation with fluidized gouge and entainment of volatiles and clasts must have immediately followed melt generation and therefore occurred during or immediately after seismic rupture. This association requires that the transiently fluidized cataclasite is an earthquake product, formed in the same environment as, and adjacent to, the frictional melting that formed the pseudotachylyte. This determination does not require that all cataclasites have a seismic origin, but demonstrates the possibility that cataclasite could be a seismic signature in the rock record (Otsuki, 2003).

**CONCLUSIONS**

The Pasagshak Point locality hosts the thickest and most voluminous subduction thrust pseudotachylytes described to date. The flow-banded bodies indicate that considerable volumes of frictional melt and ultracataclastic material were rapidly created during seismic rupture. Pseudotachylyte was likely produced in a wet fault, suggesting that the contention that pseudotachylytes form in dry faults may have some exceptions. The pseudotachylyte crosscuts background scaly fabric of a shear zone at a low angle; therefore, it formed by a seismic event that postdated slower stratal disruption processes, which characterize the pre-existing mélangé and shear zones. The lack of significant overprint deformation suggests that the pseudotachylyte formation was followed by transfer to a lower strain-rate environment, probably the upper plate of the subduction thrust. The recognition of this pseudotachylyte occurrence style widens our understanding of the record of paleoseismicity in subduction zones. Such deformationally late, outcrop-scale fluidization structures may indicate paleoseismicity in accretionary prisms, even in the absence of pseudotachylyte.

**ACKNOWLEDGMENTS**

We thank Alan Rempel for discussions on the thermodynamics of frictional melting. We appreciate the helpful comments of Gaku Kimura, Yuzuru Yamamoto, and an anonymous reviewer that substantially improved this manuscript. The Institute of Geophysics and Planetary Physics at the University of California–Santa Cruz provided assistance for field logistics. This work was supported by the National Science Foundation grant OCE-0203664.

**REFERENCES CITED**

Austheim, H., and Andersen, T.B., 2004, Pseudo-

Berlebach, J.W., and Roering, C., 1992, Sheath-


Di Toro, G., Pennacchioni, G., and Teza, G., 2005, Can pseudotachylytes be used to infer earth-
quake source parameters? An example of limitations in the study of exhumed faults: Tectono-

Dixon, J.E., and Dixon, T.H., 1989, Vesicles, amygdules and similar structures in fault-


Hyndman, R.D., Yamano, M., and Oleskevich, D.A., 1997, The seismogenic zone of sub-


Kitamura, Y., Sato, K., Ikawa, E., Ikehara-

Lan-Sin, C., Chuan-Yong, L., Chen, X.-D., Xiao-
Ou, Z., and Mei-Xiang, B., 1997, Character-


Magloughlin, J.F., 1992, Microstructural and chem-


O’Hara, K., and Sharp, Z.D., 2001, Chemical and oxygen isotope composition of natural and arti-

Oleskevich, D.A., Hyndman, R.D., and Wang, K., 1999, The updip and downdip limits to great subduction earthquakes: Thermal and structur-
al models of Cascadia, south Alaska, SW Japan, and Chile: Journal of Geophysical Re-

Otsuki, K., Monzawa, N., and Nagase, T., 2003, Fluidization and melting of fault gouge during seismic slip: Identification in the Nojima fault zone and implications for focal earthquake mechanisms: Journal of Geophysical Re-


Rowe, C.D., Thompson, E., and Moore, J.C., 2002, Contrasts in faulting and veining across the aseismic to seismic transition, Kodiak accrete-

Silbey, R.H., 1975, Generation of pseudotachylyte by ancient seismic faulting: Royal Astronom-


Manuscript received 13 May 2005
Revised manuscript received 1 August 2005
Manuscript accepted 5 August 2005

Printed in USA