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Supplementary Material

The thickness of subduction plate boundary faults from the seafloor into the seismogenic zone

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Details of compiled fault measurements

Above the seismogenic zone (<3-5 km or T<100-150°)

The shallowest portion of the subduction thrust interface is the only part directly investigated by ocean drilling. The insights from recovered core across active faults can be used to help calibrate the seismic reflection images from farther landward and deeper on the faults. Shallow diagenesis, dewatering and compaction causes the evolution of the thickness, strength and permeability of the subducting sediments as they are transported downdip. Compaction during deformation of the sediment in this shallow environment is thought to contribute to shear hardening, encouraging time-progressive thickening of the deformed zone (Moore & Byrne 1987).

Costa Rica – Sites 1040, 1043 and 1254

The subduction décollement in the Costa Rica Trench was penetrated at two sites by IODP Leg 170. Site 1040 is located 1.6 km landward of the deformation front and intersected the décollement, identified by biostratigraphic inversion, at 351 m below sea floor. At Site 1043, 400 m landward of the trench, the decollement was encountered 146 mbsf and was 9.07 m thick. There, the décollement was identified by incipient scaly foliation, biostratigraphic inversion and changes in paleomagnetic polarity (Shipboard Scientific Party, 1997). At Site 1254, penetrated on a subsequent drilling leg (Leg 205), the décollement had structural thickness of ~45 m. Discrete faults 3-8 cm thick are reported (Shipboard Scientific Party, 2003). The apparent discrepancy between the observations at two closely spaced holes (1040 and 1254) could probably be reconciled by comparison of the drilling/recovery damage of the cores that may have affected the recorded observations.

Barbados Prism – ODP Sites 948, 1044, 1045

Several DSDP and ODP Expeditions sampled the Barbados Prism near the toe and out to the deformation front where the décollement is weakly developed. Site 948 drilled during Leg 156 revealed a detailed section through the décollement, involving a zone of intensely scaly foliated parallel fault strands about 1-2 m thick over a total structural thickness of ~31 m. The lithologic décollement lies in about the center of this zone at 514 mbsf, indicating that plate motion is accommodated by deformation of both hanging wall and footwall sediments along the décollement surface. During Leg 171, the décollement was identified in structural measurements on core, as well as LWD logs and by correlation to the structural architecture described during Leg 156. Two measurements were made of the décollement, which consisted of a single strand in both holes (Shipboard Scientific Party, 1988; 1998).

Nankai Trough

Four measurements are available for décollement thickness in the Nankai Trough: at 422 m (IODP Exp. 316 C0007), 807 m (ODP Leg 190, Site 1174), 897 m (ODP Leg 196, Site 808, Hole 808C) and 945 m (Leg 131, Site 808, Hole 808 I). Coring at Site 808 (Leg 131) revealed a deformed zone 19.2 m thick with sharp boundaries, but it is not described in detail in the Proceedings. The same Site 808 was logged during Leg 196 revealing a thicker, more complicated décollement structure, consisting of three intensely sheared faults 5-7 m thick within a structural thickness of 68 m. The uppermost edge of the zone is a 1.5 m-thick breccia observed in the core. IODP Exp. 316 measured the frontal thrust (décollement near the trench) at 47.5 m thick but also recovered discrete slip surfaces ~2 mm thick which show an increase in vitrinite reflectance interpreted as evidence for shear and shear heating (Fulton and Harris, 2012; Sakaguchi et al., 2011).

Japan Trench Megathrust

The subduction thrust interface off northeast Japan was sampled during IODP Expedition 343, 14 months after the Tohoku-Oki earthquake and tsunami of March 11, 2011. The décollement was sampled at a depth of 821 m below the sea floor, where we estimate it had accumulated ~ 3.2 km of displacement (Chester et al., *submitted*). The intensively sheared fault itself was incompletely recovered, but has a maximum thickness of <4.86 m, and is localized within scaly clays of the subducting section (Chester et al., *submitted, Science Party Preliminary Report Exp. 343*). Discrete individual slip surfaces of < 1 mm thickness were described cutting the scaly clay fabric. The actual contact between the older wedge sediments of the hanging wall and the sheared pelagic clays of the footwall was not recovered, but must lie within a ≤ 1.5 m gap between recovered cores. For the purposes of this compilation, the single fault strand represents the entire deformed thickness of the décollement, so the measures of total fault thickness and fault strand are the same (≤ 4.87 m).

Sestola-Vidiciatico Unit

The Sestola-Vidiciatico Unit is a shallow frontal thrust preserved in the Northern Apennines, Italy, estimated to have been active at < 5 km depth and 100-150°C during the early to mid-Miocene *(Reutter et al., 1983; Thompson et al. 2010; Vannucchi et al., 2008; Zattin et al. 2002)*. The total shear strain is accommodated by several geologically contemporaneously active anastomosing high-strain strands separated by largely undeformed tectonic slices which preserve preexisting deformation structures (Remitti et al., 2007; Vannucchi et al. 2008; 2012). The total fault thickness is 200-500 m, within which individual high-strain strands are up to a few meters thick but usually < 10 cm. Sharp brittle faults < 3 cm thick are abundant and veined with calcite slickenfibers.

Upper seismogenic zone

A large number of preserved plate boundary thrusts from accretionary complexes can be shown to have underplated at ~ 250°C, corresponding to probable depths of 10-20 km, where mafic rocks are characterized by prehnite-pumpellyite facies metamorphism, and clastic sediments show evidence of diagenesis of clays and organic matter and albitization of feldspars (c.f. Moore and Saffer, 2001). Cataclasis and solution creep are the dominant deformation mechanisms in this zone, as most of the constituent minerals are yet too cold for appreciable crystal plastic creep. The apparent frequency of underplating at this depth may correlate directly to a transition in rheological behavior of subducting sediments (e.g. compaction or cementation hardening) or the oceanic plate that results in downstepping of the plate boundary thrust to a lower stratigraphic level (beneath the sediments or into the upper oceanic crust; Kimura and Ludden, 1995; Kimura et al. 2010). We review four examples from three accretionary complexes. Three are major paleo-decollements and one (Rodeo Cove) is an intra-terrane imbricate thrust which probably accommodated less total displacement than the others, but is mature enough to show a similar structural pattern.

Mugi Mélange

The Mugi Mélange in Japan's Shimanto Belt is composed of at least two fault-bounded units, each <200 m thick. The upper unit contains older detrital zircons (66-73 Ma) and vitrinite reflectance suggests temperatures of 170-200°C, while the lower contains younger detrital zircons (58-64 Ma) and vitrinite reflectance suggests temperatures of 130-150°C (Ikesawa et al. 2005; Kitamura et al 2005). Fluid inclusion thermobarometry suggests temperatures of 150-200°C at depths of 4-6 km during mélange formation, assuming fluid pressure was lithostatic (Matsumura et al. 2003). Ikesawa et al. (2005) and subsequent papers appear to have reinterpreted the fluid inclusion pressure measurements from Matsumura et al. (2003) to imply a depth of 6-7 km (hydrostatic fluid pressure). As in the case of the Rodeo Cove thrust, structural repetition of fault-bound slices of the uppermost oceanic crust are evidence for sequential building of the Mugi Mélange during episodic down-stepping of the décollement, creating a cumulative duplex structure (Kimura et al., 2012). The individual fault strands, such as the boundary between the two sections of the mélange, are ~1 - 30 m thick (Ikesawa et al., 2005). Discrete surfaces of highly localized shearing are represented by ultracataclasites 2-20 cm thick, pseudotachylytes less than a few mm-thick, and veined fault surfaces (< 1 cm thick; Ikesawa et al., 2005; Kimura et al. 2012).

Okitsu Mélange

The Okitsu Mélange outcrops along strike from the Mugi Mélange in the Shimanto Belt on Shikoku Island (Ikesawa et al., 2003; Sakaguchi et al., 2003). The roof thrust of the mélange is 3-5 m thick and contains pseudotachylytes less than a few mm thick (Ujiie et al., 2007b). Individual mélange terranes are ~100-200 m thick, imbricated below the roof thrust forming large-scale duplex structure (Sakaguchi et al., 2003, Kimura et al. 2012). The depth of activity of this fault has not been specifically reported. Sakaguchi et al. (2003) argued for a transiently high geotherm of ~90°C/km caused by a ridge subduction event, and placed peak temperature at 190-270°C. If these numbers are correct, the depth of fault activity was 2-3 km, similar to the estimates from methane fluid inclusions (~1.5-4 km; Sakaguchi 1996). However, kinematic studies have suggested that the Okitsu Mélange was formed under the same thermal conditions as the Mugi Mélange, at great depths down the subduction thrust (e.g. Onishi and Kimura, 1995). If this is the case, the depth might actually be as much as 7-9 km, but as the majority of recent literature favors the shallower depth, and the distinction does not change any of our conclusions. It is also possible that the measured vitrinite reflectance within the Okitsu Mélange was elevated by mechanical effects of shear, compounding the thermal effects and resulting in an artificially elevated estimated temperature (Fulton & Harris, 2012; Mastalerz et al. 1993). This example is somewhat distinct from the others in that as a roof thrust of a duplex structure, it may have been active for only a brief proportion of the time of subduction, so in that way may more closely resemble an immature faults.

The Rodeo Cove thrust

The Rodeo Cove thrust separates tectonic slivers of basalt and sediments in the Marin Headlands Terrane of the Franciscan Complex of California (Meneghini and Moore 2007, Wakabayashi 1992). It is interpreted to represent an internal imbricate thrust within the duplex of the Marin Headlands Terrane, which is underthrusted only a few meters below by the Point Bonita Terrane, an underplated seamount with OIB geochemical affinity. Faulting was active at 8-10 km depth and 200-250°C. The total fault thickness is ~ 200 m, with a high strain fault strand thickness of 30-40 m. Within this zone, numerous discrete shears 0.1-20 cm thick are found in P and R orientations. Meneghini and Moore (2007) argue that the lack of development of a dominant fault core, and maintenance of numerous individual slip surfaces, can be explained by the abundant calcite veins and cements which re-strengthened rupture surfaces after each slip.

The Pasagshak Point thrust

The Pasagshak Point Thrust, exposed on Kodiak Island, Alaska, is an ancient subduction décollement active in the earliest Paleocene at a depth of 12-14 km and ~250°C (Rowe et al. 2011, Vrolijk et al., 1988). The preserved plate boundary consists of anastomosing strands of cataclastic fault rock 7-31 m thick, spaced over a total structural thickness of ~400 m. These fault strands crosscut the formation-scale Ghost Rocks mélange, which contains distributed small faults and zones of disrupted strata (1-2 km thick; Fisher & Byrne, 1987). The deformation fabrics in the Ghost Rocks mélange represent progressive flattening and shearing during subduction of the sediment pile. At the depth of underplating (12-14 km), only the anastomosing cataclastic fault strands were active. These strands contain pseudotachylyte-bearing faults 5-30 cm thick, and broken fragments of older pseudotachylytes, demonstrating that the thicker cataclastic zones were intermittently active between earthquakes (Rowe et al. 2011). As the pseudotachylyte-bearing black fault rocks are observed to collect and pool in the areas of greatest thickness, we estimate the co-seismic slip surfaces to be maximum 10-20 cm thick.

El Cerrito Quarry thrust / Hillside Mélange

The Franciscan Complex is home to several formation-scale (few km thick) mélange terranes, previously interpreted to represent subduction décollements (Wakabayashi 2011). Recent detailed structural, metamorphic, geochronologic and provenance studies have revealed internal structure in at least one of these which indicates that the thickness of tectonically sheared section is much thinner than the total mapped width of the mélange. Based on the pressure/temperature conditions of peak metamorphism of the footwall rocks, and by comparison to metamorphic studies of similar Franciscan sediments, Wakabayashi (2013) estimates the fault was active at 15 km and 250-350°C. The Hillside mélange (thickness ~ 100-200 m) has been interpreted by Wakabayashi (2013) as a subducted sedimentary mélange where only the uppermost 10-20 m have strong shear fabric and mixed hanging wall and footwall material (the El Cerrito Quarry thrust), are interpreted to have accommodated the majority of the total displacement of 100-300 km. Due to limited exposure in the landslide-dominated Coast Ranges of California, it is unknown whether the Hillside Mélange contains multiple fault strands below the El Cerrito Quarry thrust, so an effective total thickness of the décollement cannot be estimated but a maximum estimate is the total thickness of the Hillside mélange (100-200 m). Individual earthquake slip surfaces are recorded as sharp thin layers of black fault rock, and range from ~1 cm to 1 mm in thickness.

Caveats in compilation

Ocean drilling cores are susceptible to drilling damage, which may artificially increase the estimated thickness of fault-induced shear fabric, while outcrop measurements are not. For example, Site 808 in the Nankai Trough was studied on two ODP drilling legs (Leg 131 and Leg 196). Leg 131 reported a single ~19 m-thick strand. Leg 196 reported a multi-stranded fault with thin strands over a depth interval that would include the single fault reported by Leg 131 (Shipboard Science Party 1991; 2002). Within this uncertainty it is possible that some fault strands thicken with depth but our data do not reveal any trends.

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