Depth of oceanic-crust underplating in a subduction zone:
Inferences from fluid-inclusion analyses of crack-seal veins

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ABSTRACT
Fluid inclusions in crack-seal veins are analyzed in accreted mélangé now on land. The vein I inclusions are observed in the necked parts of sandstone blocks in mélangé, and the vein II inclusions developed in shales below the thrust fault, which cuts the mélangés. The pressure and temperature estimations from the inclusions within vein I show that the cracks were sealed at ~125–195 °C under ~92–144 MPa of fluid pressure. Vein II formed in cracks that might have opened in a damaged zone caused by the thrust fault as it broke through oceanic crust and into the mélangé; these veins contain fluid inclusions trapped at ~135–245 °C under ~107–149 MPa of fluid pressure. The depth (~4–6 km below the seafloor) and temperature estimates are consistent with the conditions where an aseismic décollement within sedimentary rocks steps down into the oceanic basement, so that a thin section of oceanic crust underplates in the hanging wall. Such a step-down site is the updip limit of the seismogenic zone in the modern Nankai Trough.

Keywords: mélangé, underplating, seismogenic zone, fluid inclusions, Shimanto belt.

INTRODUCTION
Accretion of oceanic crust to the continent is a characteristic phenomenon in subduction zones and might take place not at the toe of accretionary prisms, but in a deep part of the subduction zone by means of underplating (e.g., Moore and Silver, 1987; Kimura and Ludden, 1995). Determining where and how the oceanic crust is initially underplated to the hanging wall is important to understanding material transfer that results in continental growth over the long term (Kimura and Ludden, 1995) and a seismogenic event due to collapse of the related topographically high asperity over the short term (Cloos and Shreve, 1996).

Recently acquired seismic profiles from the Nankai Trough, southwest Japan, suggest that a décollement within the sediments in the shallow part of subduction zone steps down at the depth of ~5 or 6 km below seafloor and converges with the boundary between the underthrust sedimentary rocks and the basement of oceanic crust (Moore et al., 1990; Park et al., 2002). The step-down site is almost coincident with the updip limit of the seismogenic zone estimated from the trenchward limit of the aftershocks of 1944 (Tonankai) and 1946 (Nankaido) earthquakes (Kanamori, 1972), the rupture area estimated from tsunami inversion analysis and geodetic data (Ando, 1975), inversion of tsunami waveforms (Tanioka and Satake, 2001), and a cluster of microseismicity (Obana et al., 2001). The modern example of the Nankai Trough suggests a breakage and underplating of oceanic crust, but does not allow the direct examination of evidence.

The Late Cretaceous Shimanto belt is exposed on Shikoku Island near the Nankai Trough. Underthrust and underplated tectonic mélangé, including a few tens of meters thickness of oceanic crust, was metamorphosed at the zeolite to prehnite-pumpellyite facies (Onishi and Kimura, 1995; Kimura and Ludden, 1995). Many crack-seal veins and shear-zone–filling mineral veins are developed in the mélangé. We analyzed the pressure vs. temperature (P-T) conditions of the mélangé during underthrusting and underplating by using the water + methane fluid inclusions trapped in the veins. As a result, the depth of underplating was estimated as ~4–6 km below the seafloor, which is almost the same depth as where the décollement steps down in the modern Nankai Trough. This coincidence gives a hypothesis that the peeling of oceanic slab may be the process that would be observed by drilling into the modern subduction interface around the seismic front in the future Integrated Ocean Drilling Program (IODP) operation.

GEOLOGIC SETTING
The Shimanto accretionary complex on Shikoku Island, southwest Japan, is divided...
into two units, the Cretaceous and Tertiary (Taira et al., 1980). The Mugi mélange of Late Cretaceous age occurs in thrust sheets and is composed of a matrix of black scaly shales that enclose disrupted pillow basalts, pelagic to hemipelagic red shales, and sandstone lenses. Each thrust sheet preserves the original ocean-floor stratigraphy at the trench; in total they make an imbricated package of thrust sheets (Fig. 1). The repetition of ocean-floor stratigraphies (Onishi and Kimura, 1995) suggests that the Mugi mélange is an underplated accretionary complex. The mélange has a systematic fabric of deformation and is interpreted to have a tectonic origin relating to underthrusting (Onishi and Kimura, 1995). Foliations of the Mugi mélange strike east-northeast and dip steeply north or south (Figs. 1 and 2).

The age difference between the Coniacian to Maastrichtian shale matrix and the Cenomanian–Turonian pelagic red shale in the mélange (<30 m.y.) indicates subduction of a young oceanic plate in Late Cretaceous time (Taira et al., 1988). Thermal analysis by using vitrinite reflectance revealed that the Mugi mélange was heated to a maximum of 200 ± 20 °C. These geologic characteristics of the Mugi mélange—systematic deformation fabrics, lithologic associations, and thermal conditions—are similar to those of other underthrusting-related tectonic mélanges in the Shimanto belt (Kimura and Mukai, 1991; Ujiie, 1997; Hashimoto and Kimura, 1999; Onishi et al., 2001).

**OCCURRENCE OF MÉLANGE**

A well-exposed, complete section of an ~95-m-thick thrust sheet crops out along the rocky beach facing the Pacific Ocean, in Mugi Town, Shikoku, southwest Japan (Fig. 1). The bottom of the sheet is bounded by a cataclastic shear zone. Below the shear zone is mélange composed of sandstone blocks circled by a matrix of black shale. A primarily basaltic unit ~20 m thick in the basal part of the thrust sheet above the shear zone includes pillow basalt, hyaloclastite, pillow breccia, and pelagic limestone (Fig. 1). Mélange overlies the basalt. The lower part of the mélange is composed dominantly of shale surrounding a few sandstone and basaltic blocks; this part can be categorized as type II mélange (Cowan, 1985; Kimura and Mukai, 1991). Acidic tuff layers are also found in this horizon (Fig. 2). The upper part of the mélange is categorized as type I, which is defined as sandstone-block-dominated, block-in-matrix, chaotic rocks (Cowan, 1985). The matrix of this part of the mélange is also black shale. A sequential lithologic change in the mélange—basalts in the base, distal terrigenous shale with fine acidic tuffs, and proximal turbidites, in ascending order—indicates a preserved ocean-floor stratigraphy (Byrne and Fisher, 1990; Matsuda and Isozaki, 1991) in the trench. A systematic sinistral-reverse sense of shear represented by asymmetric P-Y-R fabrics (Logan et al., 1979; Rutter et al., 1986) and folds suggests that the origin of the mélange is tectonic and related to the underthrusting and underplating (Onishi and Kimura, 1995).

**OCCURRENCES OF CRACK-SEAL VEINS**

Two kinds of crack-seal and shear-zone-filling veins are recognized from the outcrops. The same occurrences were reported from other mélanges (Hashimoto et al., 2002). Vein I fills extension cracks developed in the pinched part or margins of the blocks of mélange (Fig. 2). The cracks are almost perpendicular or highly oblique to both maximum and intermediate axes of ellipsoidal sandstone blocks in the mélange, and are cut by enclosing black shale matrix. Vein II is quartz that cuts straight across the mélange fabrics and is well developed and has heterogeneous orientations in the shale-dominated part (Fig. 2). Extension-fracture-filling veins are especially developed in the shale below the cataclastic fault along the sole of the thrust sheet (Fig. 2). The crack-seal veins below the fault increase in abundance as the fault is approached. A cumulative spacing vs. distance fits the second-order
The heating and cooling experiments conducted on primary fluid inclusions in quartz veins. The primary inclusions are the isolated, negative-crystal type (Roedder et al., 1984). On the basis of laser Raman analysis, two kinds of inclusions were identified: one is water rich, and the other is methane rich. Coexistence of water-rich and methane-rich inclusions suggests that the water was saturated with methane at the time of vein formation. To estimate the fluid-trapping $P$-$T$ conditions, we used heating and cooling experiments according to conventional methods. The heating experiment was conducted on the water-rich inclusions. The temperature of homogenization during a heating experiment provides a direct estimation of the trapping temperature because it coincides with the temperature of methane saturation of water when the fluid was trapped. The modal value of the temperature of homogenization is taken as the trapping temperature. The cooling experiment was performed on methane-rich inclusions. Methane bubbles appeared below $-83$ °C in this study. No solid carbon dioxide was observed during the experiments. This fact suggests that carbon dioxide contents are <10% (Burruss, 1981). On reheating the inclusions, the methane bubbles disappeared. Methane density was obtained from the homogenized temperature of the cooling experiments. The modal value of the temperature of homogenization during the cooling experiments was taken as the trapping condition. An isochore line was chosen from the methane density based on the methane pressure-volume-temperature function (Angus et al., 1976). The <10% carbon dioxide content has a negligible effect on determining the isochore of methane density. The fluid pressure was obtained from combining the trapping temperature determined from the heating experiments and the isochore line in $P$-$T$ space.

Five samples of vein I (from below and in the upper third of the thrust sheet) and three samples of vein II (from below the thrust sheet) were analyzed. In each sample, we took the average of 10 temperatures of homogenization from the heating experiments and 5 temperatures of homogenization from the cooling experiment.

### TABLE 1. RESULTS OF FLUID-INCLUSION ANALYSIS

<table>
<thead>
<tr>
<th>Sample no.</th>
<th>Heating $(n)$</th>
<th>Cooling $(n)$</th>
<th>Trap temperature ($°C$)</th>
<th>Cooling temperature ($°C$)</th>
<th>Pressure (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vein I</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MVE-5</td>
<td>2</td>
<td>10</td>
<td>195(+0/-0)</td>
<td>-87.5</td>
<td>92.0(+0/-0)</td>
</tr>
<tr>
<td>MVE-6</td>
<td>2</td>
<td>10</td>
<td>125(+0/-10)</td>
<td>-97.5</td>
<td>103.0(+0/-4.1)</td>
</tr>
<tr>
<td>MVE-46</td>
<td>13</td>
<td>11</td>
<td>165(+20/-0)</td>
<td>-102.5</td>
<td>135.1(+8.6/-0)</td>
</tr>
<tr>
<td>MVE-29</td>
<td>16</td>
<td>8</td>
<td>185(+10/-10)</td>
<td>-102.5</td>
<td>143.8(+4.2/-4.3)</td>
</tr>
<tr>
<td>MVE-28</td>
<td>20</td>
<td>2</td>
<td>175(+20/-20)</td>
<td>-97.5</td>
<td>122.9(+7.7/-7.9)</td>
</tr>
<tr>
<td>Vein II</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MVE-3</td>
<td>2</td>
<td>2</td>
<td>245(+0/-0)</td>
<td>-97.5</td>
<td>149.4(+0/-0)</td>
</tr>
<tr>
<td>MVE-7</td>
<td>10</td>
<td>3</td>
<td>135(+20/-10)</td>
<td>-97.5</td>
<td>107.0(+8.0/-4.1)</td>
</tr>
<tr>
<td>MVE-8</td>
<td>8</td>
<td>3</td>
<td>205(+50)</td>
<td>-92.0</td>
<td>115.8(+0/-17.2)</td>
</tr>
</tbody>
</table>

$\dagger$ Number of inclusions analyzed from heating experiment.

$\dagger$ Number of inclusions analyzed from cooling experiment.

$\dagger$ Homogenized temperature of cooling experiment.

**DISCUSSION**

The Mugi tectonic mélangé is believed to be an underplated complex (Onishi and Kimura, 1995). A study of vitrinite reflectance has revealed that the mélangé in the study area reached a maximum temperature of $\sim$200 °C. The result is almost consistent with that obtained from the fluid-inclusion analysis.

Such consistency in temperature results between vitrinite-reflectance and fluid-inclusion data suggests that fluid passed through cracks below the thrust and thermally equilibrated in the veins’ host rocks. Pressure information is indicative of a depth from underthrusting to underplating of sedimentary rocks and oceanic crust. If the obtained pressures were closer to the lithostatic condition, they would suggest a burial depth. We assume the density of sedimentary rocks as 2.5 g/cm$^3$, which is reported from the modern Nankai accretionary complex (Taira et al., 1992). The pressure range of $\sim$50 MPa indicates a difference in depth of a few kilometers, if lithostatic pressure is assumed. A relationship between the temperature and burial depth suggests a thermal gradient of 40–50 °C/km, which is consistent...
with the conclusion that the subducted plate was young, based on the age difference in the matrix and blocks in the mélangé (Onishi and Kimura, 1995).

The depth of the oceanic-crust underplating estimated for the studied rocks is comparable to the depth of the décollement step-down in the modern Nankai subduction zone. Figure 4B represents a simplified profile from Park et al. (2002). The décollement separating an offscraped accretionary prism from underthrust sedimentary rocks steps down and converges to the boundary between the upper accretionary package and the lower oceanic basement of the Philippine Sea plate at the depth of ~5 km below the seafloor. What takes place at the décollement step-down is not clear from the seismic reflection profile (Fig. 4B), but one possibility is that the décollement cuts into, peels off, and underplates the oceanic crust beneath the upper plate. Kimura and Ludden (1995) suggested that for a thickness of several tens of meters, the top of the oceanic crust is less porous than the part of the crust below owing to mineral precipitation from hydrothermal and cold-water circulation in the open ocean before subduction. Such an inverse hydrological profile of the oceanic crust would produce a weak region during subduction because the effective pressure would be reduced by the high pore-fluid pressure in the porous part; the weakness could lead to the faulting of the upper part of the oceanic crust (Kimura and Ludden, 1995).

In the Nankai Trough subduction zone, the place where the décollement steps down is very close to the updip limit of the seismic zone defined from tsunami inversion of the 1944 Tonankai earthquake (Tanioka and Satake, 2001) and the oceanward limit of the rupture zone of the same earthquake (Ando, 1975). The stepping down of the décollement and the oceanic-crust underplating seem to be related to the onset of the seismogenic zone. Combining this oceanic-crust break-off with the lithification hypothesis for the onset of the updip limit (Moore and Saffer, 2001), a new hypothesis is possible. Sedimentary rocks and the uppermost part of oceanic crust stick to each other, and a weak part of oceanic crust breaks seismically. This hypothesis should be tested by direct drilling into the plate-boundary fault in the future.

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