Fossil fluid reservoir beneath a duplex fault structure within the Central Range of Taiwan: implications for fluid leakage and lubrication during earthquake rupturing process

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ABSTRACT

In order to understand the kinematics which likely facilitated the speedy rupturing process of the 1999 Mw 7.6 Taiwan Chi-Chi earthquake, we examined exposed rocks in the Taiwan Slate belt, where the pressure and temperature conditions most resembled the hypocentre of the Chi-Chi earthquake, i.e. sub-greenschist facies. Field observations and composition analyses of the silicified vein-rich zones beneath the duplex structure suggest that impermeable slate layers may serve as cap rocks for confining deep-seated fluids. These fluids most likely come from the Taiwan metamorphic complex at deeper depths by the dehydration and decarbonation reactions (or partial melting). In addition, the gouge zone of a link fault above the detachment also indicates the presence of overpressured fluids during faulting. It is probable that episodic leakage of the confined fluid reservoirs may provide essential fluids for fault lubrication during earthquake ruptures.

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Introduction

The 1999 Mw 7.6 Taiwan Chi-Chi earthquake occurred at a shallow depth of around 10 km (Chung and Shin, 1999; Kao and Chen, 2000; Ma et al., 2000) within the fold and thrust belt of Taiwan (Fig. 1). The damaging earthquake ruptured the geologically well-defined Chelungpu fault and the faulting propagated more than 80 km in length from south to north (e.g. Shin and Teng, 2001). The whole rupturing process consisted of five major subevents propagating from south to north and the amazing speed of the earthquake rupturing was measured as 2.2–2.6 km s⁻¹ (Chen et al., 2001; Kao and Angelier, 2001). After rupturing the largest vertical displacement occurred along the Chelungpu thrust fault was measured to be approximately 9 m (e.g. Lee et al., 2002).

The unusual rupturing speed has led to a common postulation that fault lubrication occurred during the earthquake (Ma et al., 2003). Actually, many studies on exhumed fault rocks indicated that faulting at seismogenic depths (c. 5–20 km) occurred as fluid pressure exceeds hydrostatic (e.g. Kerrich, 1986; Parry and Bruhn, 1990; Cox, 1995; Robert et al., 1995; Nguyen et al., 1998; Crampin et al., 2002) or even lithostatic levels (e.g. Boullier and Robert, 1992; Cox, 1995; Nguyen et al., 1998) as well as the existence of overpressured fluids during overthrusting (Hubbert and Rubey, 1959). Accumulated geological evidence has shown that within the middle to upper crust, active fault zones can play a crucial role in controlling the architecture of crustal fluid migration (e.g. Kerrich, 1986; Sibson et al., 1988; Hickman et al., 1995; Yamamoto et al., 2004). Fluids migrating through faults also have a substantial influence on fault mechanics (e.g. Sibson, 1989, 1992, 1996; Rice, 1992). However, little research has been performed to understand possible fluid chambers and to evaluate the role of fluids contributing to large earthquakes in Taiwan, such as the recent Taiwan Chi-Chi earthquake.

Here we assume the sub-greenschist facies Taiwan slate belt closely resembles the geological conditions now occurring at the same depths in the Taiwan fold and thrust belt. This assumption may be justified by the observations that the accretion process of the Taiwan Mountain belt forward from east to west (Fig. 1). In addition, the exposed slates and meta-sandstones within the Central Range (the internal fold-and-thrust belt) consist of largely Eocene–Miocene, continental slope and rise sediments. These passive continental margin sediments do not differ greatly with the fold and thrust belt of the Taiwan foothills where the Chi-Chi earthquake had occurred.

In this study, we described and analysed outcrops from central Taiwan showing that slate belt can be effective for confining fluids from great depths and that the vein materials contain high-temperature minerals. We proposed that a leakage of fluids and subsequent volatilization of gases (mainly H₂O and CO₂) can readily facilitate and lubricate the movement of the faults above the reservoirs. This explanation is consistent with the outcrop observation that the fossil fluid reservoirs situated underneath a well-developed duplex fault structure and that overpressured gouge zones developed along link faults above detachment.

Outcrop description

An outcrop of highly silicified zone containing abundant quartz veins appears along the Central Cross Island highway among the Backbone Range slate belt of Taiwan (Fig. 1). We have checked several tens of outcrops and excluded the outcrops obviously suffered polyphase deformation during exhumational stage. The lithology of the outcrop consists mainly of meta-sandstone and slate interlayers.
These rocks have undergone the latest Plio-Pleistocene Taiwan orogeny and were later brought up to the surface. The major sub-horizontal silicified zone exhibits abundant quartz veining, fracturing and brecciation (Fig. 2). On the borders of the silicified zone, fault slickensides are commonly observed. The silicified zone was approximately 1 m thick and above the zone sits a well-organized duplex fault system indicating a top-to-the-northwest thrust faulting. In addition, the silicified zone is noticeably capped by layered slates which contain very few veining structures.

Sub-horizontal zones of possible fluid-filled veins are interconnected with vertical veins (Fig. 3a) suggesting interconnections of fluids in horizontal silicified zones through vertical cracks. A large, lenticular quartz mass is located within a dilatant zone (Fig. 3b) of the silicified zone. The quartz mass exhibits that the pressurized fluid is concentrated in lensoidal compartments rather than distributed over large domains (Bruhn et al., 1994). The quartz mass also suffered brittle deformation characterized by the intracrystalline fractures and cracking. The fractured quartz grains are commonly surrounded by matrix cataclasites.

Minor thin quartz veins are recognized in the meta-sandstone layers alternating with the slate layers above the silicified zone. These veins are largely perpendicular to the sedimentary layers. One important observation is that V-shaped veins typically abutted the less permeable slate layers suggesting that fluids were trapped and contained mostly within the highly fractured meta-sandstone layers (Fig. 4). These minor thin quartz veins are interconnected with other fluid sources, especially, the silicified zone. The V-shaped vein features in the meta-sandstone beneath the slate layer, are recognized as ‘arrested hydrofractures’ in the layer beneath soft layer (Gudmundsson and Brenner, 2001; Brenner and Gudmundsson, 2004). The hydrofracture features depend on the local stresses controlled by abrupt changes in the rock’s Young’s moduli (Gudmundsson and Brenner, 2001).

Another outcrop examined is close to the Lishan lineament, a major tectonic boundary in Taiwan near the sampling site (Fig. 1). The Lishan lineament appears to be one of the most obvious geomorphic features in Taiwan. The lineament was interpreted as a tectonic fault, the Lishan fault, which separated the two domains of the Taiwan slate belt, the Hsuehshan Range and the Backbone Range, and is considered as the link thrust to the detachment (Lee et al., 1997; Ho, 1998). Although the Lishan fault remain largely covered by river terraces and sediments, a fault outcrop with unusual veining activities was discovered along a river along the Lishan fault.

Most veins at the outcrop are sub-vertical and concentrated within a zone where sandy slates dominate. The subvertical veining zone is also truncated by several sharp and thin faults. A gouge zone contains unusual fabrics: fractured quartz and carbonate grains floating within the clay matrix (Fig. 5). These fractured mineral grains possibly came from crush...
ing of the surrounding quartz/carbonate veins. These veins are strongly sheared and show wavy extinction suggesting the deformation did occur at great depths. There are no particular shear fabrics or foliation within the grain-filled gouge zone. The random arrangement of the crushed mineral grains within the clay gouge matrix suggests that gouge zone may have been once filled with high-pressure fluid leading to very low shear strength of the fault.

The veining zone of the Lishan fault outcrop also shows slickensides along its borders. The fault striations indicate variable sliding directions including down-dip, oblique and strike-slip. Away from the narrow veining zone, there is little occurrence of veins indicating that these veins are quite localized along the observed fault zone.

Petrochemical characteristics

In order to understand the fluids origin and interaction with the country rocks, petrochemical analyses (XRF scanning, SEM-EDS and EPMA observation) were performed on rock samples collected from the concentrated vein zone of the sampling site (Fig. 1) in the Backbone Range slate belt (Figs 1 and 2). A detailed description and the petrological significance are summarized as follows.

Veins have complex cross-cutting relationships but can be distinguished primarily as vertical and horizontal ones. Observation of polished slabs and thin sections revealed that veins can also be classified into two types in terms of mineralogy: a calcite vein and quartz vein. Calcite veins contain calcite minor apatite and sulphide minerals. Quartz veins consist of quartz, albite, apatite, calcite (Fig. 6), as well as minor rutile, K-feldspar and monazite. One observation shows that a quartz vein was cut by a calcite vein, which in turn was cut by a quartz-feldspar vein. This cross-cutting relationship suggests almost simultaneous and/or repeated vein formation of the observed vein structures.

Mineral group in the observed quartz veins indicates that the fluids came from a high-temperature source, likely higher than the metamorphic peak temperature of the outcrop because rutile is quite insoluble in an aqueous fluid at upper crustal conditions (e.g. Pearce and Cann, 1973). The metamorphic grade of the host rock is sub-greenschist to lower greenschist facies characterized by chlorite + K-feldspar mineral paragenesis without biotite. Thus, based on the observed mineral group in the veins, the source fluids of veins are not of in situ but of exotic origin from depths.

In order to better characterize the \( P, T \) conditions of the silicified zone, we also carried out a fluid inclusion analysis.
study of the sampled quartz veins. Table 1 lists the fluid inclusion data. To sum up, the total homogenization temperatures (Th) are in the range of 208–255 °C. Fluid pressure ($P_f$) is estimated to be higher than 228 MPa at temperatures above 250 °C. These data are consistent with the trapping of an $H_2O$–$CO_2$–$NaCl$ fluid in the single-phase region.

**Discussion**

For the development of fluid over-pressure in the sub-greenschist facies at depths, there must be low-permeability capping layers formed in either stratigraphic process (e.g. shale formation) or hydrothermal cementation (e.g. Bruhn et al., 1990; Hunt, 1990; Blanpied et al., 1992; Byerlee, 1993; Sibson, 2000). Our field observations suggest that the slate layer above the detachment plays a critical role as impermeable capping layer because the observed vein textures clearly indicate that hydrofractures become arrested and poorly interconnected upward, as explained by Gudmundsson and Brenner (2001) and by Brenner and Gudmundsson (2002, 2003).

Taiwan is a typical continent-arc collision zone, and continental slope and rise deposits were overthrust in the western half of the Taiwan upper crust. The stratigraphic cross-section indicates that shale and slate are the major rock types above the fold-and-thrust belt detachment (Fig. 1). According to direct fluid pressure measurements taken in the western foothills and coastal plain of Taiwan, a permeable zone of hydrostatic fluid pressure gradients (with depths greater than 2–4 km) overlies less permeable sediments exhibiting an overpressured fluid gradient (Suppe and Wittke, 1977; Suppe et al., 1981; Davis et al., 1983). That is, the fluid pressure increases from hydrostatic towards nearly lithostatic at depths greater than about 4 km. This overpressured fluid gradient is rather constant throughout the western Taiwan.

However, zones with overpressured fluid gradients are now exposed in the region where the less permeable Plio-Pleistocene shale sediments had already eroded (Davis et al., 1983). This indicates that low permeability and arrested hydrofracture in the region is controlled by the collisional type stratigraphy, in this case, the slightly metamorphosed slate belt.

The petrochemistry of the veins stacked beneath the detachment suggests that stored fluid was of high temperature in origin and from great depths because of the presence of albite, K-feldspar and REE minerals. Existence of calcite veins and presence of calcite in quartz veins suggest that the migrated fluid contains $CO_2$. Underlying basement lithology beneath the slate layer is considered as the pre-Tertiary Tananao schist metamorphic complex, which suffered greenschist and amphibolite facies metamorphism. The Tananao schist complex consists of four major lithological types: marble, granodioritic ortho- and banded para-gneisses, pelitic and psammitic schists and chlorite schists (e.g. Ernst, 1983).

Therefore, carbon dioxide rich fluid could have arisen from the pre-Tertiary basement because of dehydration/decarbonation reactions.

Alternatively, fluid may also be derived from partial melting of the pre-Tertiary basement complex underlying the Taiwan slate belt. Recent study of shear-wave seismic atten-
ation has revealed low Qs zone beneath the slate belt of the Central Range at depths of 30–40 km (Wang et al., 2003). This low Qs zone correlates with a low velocity zone in both P- and S-waves, as determined from seismic tomography studies. These seismic features imply that there is a fluid or a melt dominant zone within the subducted continental crust or basement rock. The temperature conditions of the zone are roughly estimated to be higher than 600 °C from the presumed geotherm of 15 °C per km for the collisional type metamorphism (e.g. Spear, 1993). It is consistent with the max P, T conditions deciphered from the garnet submicron inclusion from the Tananao Schist (P > 8.3–8.8 kbar and T < 660–690 °C) (Hwang et al., 2001). The temperature conditions exceed the solidus temperature for the continental basement, implying that the low Qs zone is possibly a partially melting zone rather than a dehydration zone. The partial melt likely contains H₂O and CO₂, i.e. a volatile-rich fluid, which may separate from the melt during upward migration to the detachment fluid reservoirs at much shallower depths.

The deformation textures from the Lishan fault suggest that it may result from leaking of the stored fluid beneath the detachment leading to faulting at suprahydrostatic conditions. When ruptures in the link thrust transect suprahydrostatic gradients in fluid pressure, they have the capacity to react as valves promoting upwards discharge from overpressured portions of the detachment and a local reversion towards a hydrostatic gradient (Sibson, 1992). Such a ‘fault-valve-behaviour’ has also been postulated in large earthquake zones. The 1995 Kobe earthquake (M7.2) is one of the best examples. Zhao et al. (1996) and Zhao and Negishi (1998) determined 3-D P- and S-velocity and Poisson’s ratio structures in the Kobe source area. They found that the Kobe main-shock was located in a distinctive zone characterized by a low velocity and a high Poisson’s ratio, which was interpreted to be a fluid-filled fractured rock matrix that contributed to the initiation of the Kobe earthquake.

Leaked fluid from the detachment is considered to contain a certain amount of CO₂ because calcite is present in the silicified zone and gouge. Phase separation in H₂O–CO₂–NaCl crustal fluids is thought to occur in response to decompression during fault movements in the fault-valve model (e.g. Sibson et al., 1988). The phase separation process is dependent on the fluid chemical composition. Our fluid inclusion data as...
shown in Table 1 are consistent with the trapping of an H₂O–CO₂–NaCl fluid in the single-phase region. The phase separation of this leaking fluid along link faults can result from transient decompression during earthquake fault rupturing propagation. In addition, the phase separation can be greatly enhanced in zones of maximum dilation (Wilkinson and Johnston, 1996). The decompression triggered by earthquake was also well described in the 1997 Umbria-Marche seismic sequence, northern Italy (Miller et al., 2004). Although they considered that high-pressure CO₂ was from the mantle (see also Chiodini and Cioni, 1989), there is a possibility as suggested in our study that the CO₂ was quickly generated because of the phase separation of H₂O–CO₂ rich fluids, which were within the fluid reservoirs around and beneath a major detachment fault.

Concluding remarks

Although the overpressured fluid scenario has been employed to explain the conditions under which overthrusting may have taken place, the fluid source, fluid chemical characteristics and fluid storage remain largely uncertain. Thus, many efforts have been made to validate the scenario especially applying field data from petroleum companies (e.g. Suppe and Wittke, 1977; Suppe et al., 1981). The present study also lends supports to this scenario, although based on limited outcrops. Here we found investigations of surface outcrops with comparable metamorphic P/T conditions similar to those of the hypocentre of the Chi-Chi earthquake to be valuable for testing the presence of fluids and characteristics of fluids at such depths.

Table 1 Summary of microthermometric data of the study

<table>
<thead>
<tr>
<th>Two-phase inclusions (n = 22)</th>
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<tr>
<td>Degree of fill (%)</td>
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<tr>
<td>CO₂ melting (°C)</td>
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<tr>
<td>Ice melting (°C)</td>
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<tr>
<td>Clathrate melting (°C)</td>
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<td>Salinity (wt% NaCl)</td>
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<tr>
<td>Total homogenization (°C)</td>
</tr>
<tr>
<td>CO₂ wt%</td>
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<td>CO₂ mol%</td>
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