Geochemistry of mud volcano fluids in the Taiwan accretionary prism

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Abstract
Taiwan is located at the collision boundary between the Philippine Sea Plate and the Asian Continental Plate and is one of the most active orogenic belts in the world. Fluids sampled from 9 sub-aerial mud volcanoes distributed along two major geological structures in southwestern Taiwan, the Chishan fault and the Gutingkeng anticline, were analyzed to evaluate possible sources of water and the degree of fluid-sediment interaction at depth in an accretionary prism. Overall, the Taiwanese mud volcano fluids are characterized by high Cl contents, up to 347 mM, suggesting a marine origin from actively de-watering sedimentary pore waters along major structures on land. The fluids obtained from the Gutingkeng anticline, as well as from the Coastal Plain area, show high Cl, Na, K, Ca, Mg and NH\textsubscript{4}, but low SO\textsubscript{4} and B concentrations. In contrast, the Chishan fault fluids are much less saline (1/4 seawater value), but show much heavier O isotope compositions (\(\delta^{18}O = 5.1–6.5\%\)). A simplified scenario of mixing between sedimentary pore fluids and waters affected by clay dehydration released at depth can explain several crucial observations including heavy O isotopes, radiogenic Sr contents (\(^{87}\text{Sr}/^{86}\text{Sr} = 0.71136–0.71283\)), and relatively low salinities in the Chishan fluids. Gases isolated from the mud volcanoes are predominantly CH\textsubscript{4} and CO\textsubscript{2}, where the CH\textsubscript{4}-C isotopic compositions show a thermogenic component of \(\delta^{13}C = -38 \%\). These results demonstrate that active mud volcano de-watering in Taiwan is a direct product of intense sediment accretion and plate collision in the region.

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1. Introduction
Mud volcanoes are unique features in tectonically compressed areas, e.g., Taiwan, Trinidad, Indonesia, Russia, and Barbados (see Yassir, 1987; Milkov, 2000; Kopf et al., 2003; Fig. 1A). Studying the chemical characteristics of expelled fluids associated with mud volcanoes activity helps to delineate possible fluid origins and/or sediment–water interactions at depth within the accretionary prisms. Recent Ocean Drilling Program (ODP) drill holes in the Barbados ridge complex, the Peru Margin, and Nankai Trough have drawn further attention to possible impacts of the fluid expulsion fluxes on oceanic chemical budgets (Gieskes et al., 1989; Kastner et al., 1991). The first order estimated water fluxes range from 0.01 to 2 km\textsuperscript{3}/a globally based on calculations of porosity reductions or clay dehydration in worldwide convergent margins (Bray and Karig, 1985; Kastner et al., 1991). These fluids with their unique chemical compositions, are transported upward along faults, through permeable layers (Gieskes et al., 1993; Moore et al., 1988; Vrolijk et al., 1991) or through activity of mud volcanoes and, eventually, return to the ocean (Barber et al., 1986; Brown, 1990; Kopf et al.,

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Active mud volcano fluid expulsion or seafloor seepage has been reported in various areas: the Japan Trench (Boule`gue et al., 1987), the Nankai Trough (Gamo et al., 1992), the Oregon Margin (Kulm et al., 1986), the Barbados accretionary complex (LePichon et al., 1990; Martin et al., 1996), and the Mediterranean Sea (de Lange and Brumsack, 1998). Hitherto no direct measurements of chemical fluxes have been made. However, calculations based on progressive porosity reductions have suggested potentially large water fluxes that may have important impacts on oceanic budgets of B, 81B, Li, and Ca (Han and Suess, 1989; Martin, 1993; You et al., 1993, 1995a,b; Chan and Kastner, 2000).

Previous studies on mud volcanoes have mostly focused on structure, geomorphology, geophysics, and geology.
mineralogy (Higgins and Saunders, 1974; Barber et al., 1986; Brown, 1990). Until recently only a very limited number of chemical analyses have been conducted on fluids separated from mud diapirs. Key examples are in the Barbados area (Martin, 1993; Martin et al., 1996), in the Nankai Trough (Boulègue et al., 1987), and in the Caucasus mud volcanoes (Kopf et al., 2003). An interesting study of the chemical and isotopic composition of mud volcano fluids in Trinidad was reported recently, revealing critical information on geochemical processes at depth in convergent margins (Dia et al., 1999). In this paper, attention is focused on examining the chemical and isotopic compositions of fluids and gases from 9 sub-aerial mud volcanoes on land in southwestern Taiwan. The principal objectives are: (1) to compare the fluid chemistry from different geological settings locally, (2) to investigate the origin of fluids and associated gases, (3) to deduce possible sediment–water interactions at depth, and (4) to make a comparison with mud volcanoes from other areas globally in order to investigate common trends.

2. Methods

2.1. Geological settings

Taiwan is located at the boundary between the Philippine Sea Plate and the Eurasian Plate and constitutes a well-known arc-continent collision belt in the western Pacific (Li, 1976; Suppe, 1980). The island consists of 5 major morpho-tectonic units separated by N-S oriented major thrust faults. From west to east, there are the Coastal Plain, the Western Foothills, the Hsuehshan Range, the Central Range, and the Coastal Range (Fig. 1B). The Coastal Plain, the Western Foothills, and the Hsuehshan Range are composed of Cenozoic shallow-marine siliciclastic overlain by Quaternary alluvial deposits. The Central Range is composed of Miocene deep-marine turbidites and Mesozoic to Late Paleozoic metamorphic rock. In contrast, the Coastal Range in eastern Taiwan is composed of Miocene volcanic rocks overlain by Plio-Pleistocene turbidite deposits (Fig. 1C; Teng, 1990; Chang et al., 2000). Intense compressional tectonism has caused an extremely high rate of uplift and erosion island-wide (Liu, 1982; You et al., 1988) and consequently abundant mud volcanoes have erupted on land (Shih, 1967) and offshore (Huang et al., 1992; Liu et al., 1997) due to a focused expulsion of pore fluid.

There occur at least 17 active mud volcanoes in southwestern Taiwan, mainly located within the Western Foothills zone (Wang et al., 1988). Typical mud volcanoes on Taiwan are characterized by the flow of muddy waters accompanied by vigorous out-gassing of CH$_4$ and CO$_2$ (Shih, 1967). Among the nine sub-aerial mud volcanoes visited, Wushanting (WST#01) and Hsiaofenway (HFW#06) are located near the Chishan fault and Kunshuiping (KSP#03), Hsiaokunshui (HKS#04), Takunshui (TKS#05), Lungchuan (LC#07) and Chunglun (CL#02) are distributed along the axis of the Gutingkeng anticline (Figs. 1b and 2). Detailed morphological descriptions of these mud volcanoes are summarized in Table 1. Both structures mainly occur in the Western Foothills. The Liushan (LYS#08) mud volcano is located in the Coastal Plain near Pington and Losan (LS#09) and is the only mud volcano field discovered within the Longitudinal Valley in the Coastal Range, eastern Taiwan. Thick overlying marine sediments, estimated to be over 5000 m, are present in both the Gutingkeng and the Chishan regions in southern Taiwan, and no associated igneous activity has ever been reported.

2.2. Sampling and analytical methods

Muddy waters with a range of porosities from less than 10% to greater than 90% were collected directly inside individual mud volcano craters using 50 cm$^3$ centrifuge tubes. The corresponding fluids were separated subsequently by filtration and/or centrifugation. Natural gases, local meteoric water, and river waters were also collected for the purpose of C, O or H isotopic analyses. A portable GC was employed in the field for continuous monitoring of gas compositions and fluxes in a few mud volcanoes. Salinity, pH, and temperature were also measured in the field. Alkalinity, Cl, Ca, Mg, NH$_4$, SO$_4$, B, Li, Na, K, Sr, and Be, as well as $^{6}$Li,
$\delta^{11}$B, and CH$_4$ $\delta^{13}$C were measured at Scripps Institution of Oceanography and the department of Earth Sciences, National Cheng Kung University. The isotopic compositions of $^{87}$Sr/$^{86}$Sr, $\delta^{18}$O, and $\delta^{D}$ were analyzed at Institute of Earth Sciences, Academia Sinica, Taipei. The isotopic compositions of B, Li, O, D and C were calculated relative to standard reference materials SRM951, L-SVEC, SMOW, SMOW and PDB, respectively, and are expressed in terms of delta notation in per-mil ($\%$). Detailed sampling and analytical procedures have been presented elsewhere (Gieskes et al., 1991; You, 1994).
3. Results and discussion

The chemical and isotopic compositions of the mud volcano fluids analyzed are grouped into 3 categories according to their geological settings and are summarized in Table 2. For the purpose of separating the various mud volcano fields, plots of Cl versus alkalinity, NH₄, and SO₄ are presented in Fig. 3. From these plots it is evident that the Gutingkeng mud volcanoes are characterized by high Cl contents (roughly 65% of the average seawater concentration of 558 mM). On the other hand, the Cl contents of Chishan fluids are relatively low. In the anticline region, SO₄ contents are low, ranging between 0.045 and 0.13 mM. But the CL#2A and 2B and LYS#8 mud volcanoes show much higher SO₄, presumably because of contamination from surface sources including meteoric waters, local rivers and/or groundwater. High SO₄ content has been reported in local wet precipitation as a result of acid rain industrial pollution. Ammonium contents of the fluids from the Gutingkeng anticline indicate high values (up to 2.3 mM), mainly as a result of contributions from organic matter diagenesis during SO₄ reduction and CH₄ formation processes. Important observations are of note at the Chunglun mud volcano (CL#2), where linear relationships with Cl concentrations indicate possible mixing relationships or surface evaporation. This relationship also characterizes the plot of δ¹¹B vs. 1/B, where CL#2B showed a large deviation (see Fig. 7). Below the observations on the Taiwanese mud volcanoes are briefly described.

The LS#09 mud volcano sampled from the Coastal Range in eastern Taiwan has distinctive chemical and Sr isotopic compositions compared to the others. It shows low alkalinity, NH₄, SO₄, and Na/Cl, slightly elevated Mg and Cl, high Ca, and a low ⁸⁷Sr/⁸⁶Sr isotopic ratio (0.70691). Gases isolated from this site are predominantly CO₂ and CH₄ (>53%) and CH₄ shows a light C isotopic composition (δ¹³C = -38.8 ‰).

The fluids sampled from the Chishan fault area are characterized by relatively low concentrations of Cl, Na, K, Ca, Mg and NH₄ and relatively high values of alkalinity, SO₄ and B. The most striking features of the fluids associated with this fault zone are the very high δ¹³C values (5.1–6.5 ‰) and the radiogenic Sr isotopic compositions (⁸⁷Sr/⁸⁶Sr = 0.71136–0.71283). In contrast, the fluids from the Gutingkeng anticline axis and the Coastal Plain fluids are characterized by relatively high Cl contents, up to 347 mM, and a seawater-like ⁸⁷Sr/⁸⁶Sr ratio, 0.70982.

Three meteoric waters, one stream water and one pond water were collected in this study. Two of these, however, deviate greatly from the average meteoric water composition (Figs. 4 and 5). SL#06 was collected during a severe thunderstorm event and SKS#03 was taken after a storm from a pool that perhaps was contaminated by mud volcano overflows.

3.1. Fluids in the coastal range

The LS#09 is the only mud volcano situated in the Coastal Range, Eastern Taiwan (see Fig. 1B) and shows distinctive fluid chemical compositions compared to the
## Table 2
The chemical compositions of mud volcano fluids in Southwestern Taiwan

<table>
<thead>
<tr>
<th></th>
<th>The Chishan Fault</th>
<th>The Gutingkeng anticline and the coastal plain</th>
<th>CR#</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>WST-01A</td>
<td>WST-01B</td>
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<tr>
<td>T(°C)</td>
<td>28</td>
<td>28</td>
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<tr>
<td>pH</td>
<td>5.8</td>
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<tr>
<td>Cl⁻ (mM)</td>
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<td>Alkalinity (mM)</td>
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<td>NH₄⁺ (mM)</td>
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<td>0.2</td>
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<tr>
<td>SO₄²⁻ (µM)</td>
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<td>1700</td>
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<td>Ca²⁺ (mM)</td>
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<td>0.26</td>
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<td>Mg²⁺ (mM)</td>
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<td>K⁺ (mM)</td>
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<tr>
<td>Na⁺ (mM)</td>
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<tr>
<td>Na⁺ (mM)-calculated</td>
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<tr>
<td>B (µM)</td>
<td>5.46</td>
<td>5.62</td>
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<td>δ¹³B (%o)</td>
<td>52</td>
<td>65</td>
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<td>Be (µM)</td>
<td>443</td>
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<td>Sr (µM)</td>
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<td>Li (µM)</td>
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<tr>
<td>δ⁶Li (%o)</td>
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<td>T(°C)</td>
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<td>102</td>
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<td>δD (%o)</td>
<td>-18</td>
<td>-23</td>
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<td>δ¹⁸O (%o)</td>
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<td>δ¹³C (%o)-methane</td>
<td>-1.8</td>
<td>-0.1</td>
<td>-38.8</td>
</tr>
<tr>
<td>Methane (%)</td>
<td>50</td>
<td></td>
<td></td>
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<tr>
<td>Isotopic compositions of B, Li, H, O, and C were calculated relative to SRM 951, L-SVEC, SMOW, SMOW, and PDB, respectively; #: The Coastal Range.</td>
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</tbody>
</table>
others. The low alkalinity, NH₄, SO₄ and Na/Cl, as well as the slightly elevated Mg and high Ca concentrations suggest the possible influence of the igneous basement in this region. This is particularly evident from the low (0.70691) isotopic ratio of ⁸⁷Sr/⁸⁶Sr, which indicates a Sr contribution from adjacent young basaltic rocks. High Ca and low Sr isotope ratios have often been inferred to indicate interaction between fluids and volcanic ash or underlying basaltic basement rocks in many oceanic drill holes (e.g., Gieskes et al., 1989). Methane isolated from this site indicates a thermogenic C isotopic composition, δ¹³C = -38.8 ‰. This CH₄ δ¹³C value is heavier than that observed in mud volcanoes in the Barbados area (Martin, 1993; Martin et al., 1996), but is comparable to those in the Caspian basin, Azerbaijan (Dadashev and Guliev, 1989). Similarly δ¹³C values in CH₄ have been reported in mud volcanoes in the Caucasus (Kopf et al., 2003). Most geochemical and isotopic results obtained in LS#09 are consistent with a scenario that the mud volcano fluids have been affected by underlying basaltic basement or volcanic rocks.

3.2. Fluids in the Western Foothills and the coastal plain

Numerous active mud volcanoes occur in the Western Foothills region, mainly along the Gutingkeng anticline and the Chishan fault. The fluids from the Gutingkeng anticline axis are characterized by relatively high salinity, with Cl concentrations up to 347 mM. On the other hand, the fluids from the Chishan fault show relatively low concentrations of Cl, Na, K, Ca, Mg and NH₄, but relatively high values of SO₄ and B. Chloride is the most conservative major ion in pore waters and its distribution in mud volcano fluids provides crucial information regarding possible water sources. Previously pore waters with low Cl concentrations, as low as that of 1/3 seawater concentration, have been reported during DSOP/ODP studies of the Barbados accretionary complex (Martin, 1993; Vrolijk et al., 1991) and in the Nankai Trough (Gieskes et al., 1993). Several mechanisms have been invoked for explaining the Cl variations, including meteoric water intrusion, clay dehydration, gas-hydrate dissolution, and membrane
filtration (Gieskes et al., 1989). Contributions by gas hydrate dissolution are difficult to evaluate at this stage. Milkov (2000), however, found a close association between gas hydrate and deep-water mud volcanoes worldwide and there are extensive distributions of bottom simulating reflectors (BSR) in the continental shelf area offshore in southwestern Taiwan (Liu et al., 1997). Instability of gas hydrate can release significant amounts of CH₄ and CO₂ gases and dilute the fluid salinity at the same time. Clay dehydration at temperatures greater than 60 °C was proposed to explain the low salinity of fluids recovered during ODP Legs 110 and 131 (Vrolijk et al., 1991; Kastner et al., 1991, 1993). Such dehydration processes are likely to have contributed to the low salinity of mud volcano fluids, but additional meteoric water dilution cannot be ruled out. Fitts and Brown (1999), however, suggest that, especially in smectite-rich sediments, clay dehydration under moderate excess pressures, even at lower temperatures, can cause dilution of the pore fluids from dehydration.

Other possible factors that may affect the fluid salinity are surface evaporation and/or subsurface groundwater mixing. To evaluate this problem, 3 fluids from the CL area, CL#02A, #02B and #02C, were collected for detailed chemical and isotopic analyses. The CL#02C fluid was collected from a small pond with vigorous gas bubbling, roughly 500 m from the major mud volcano pool where #02A and #02B were collected. In the Cl vs. element plots (see Figs. 3, 6 and 7), the major constituents of alkalinity, NH₄, SO₄, B, Li and δ¹¹B in the 3 CL fluids fall on a linear mixing trend, suggesting that mixing processes may be operative in this region. Sample #02C has the highest alkalinity, Cl, Na, NH₄, Li and B, but the lowest SO₄ and Ca. Its high Na/Cl ratio (1.4), with an excess of Na associated with a large enrichment in HCO₃, indicates possible reaction between high CO₂ solutions and sediments. Alkalinity and NH₄ data suggest enhanced HCO₃ and NH₄ as a result of organic matter degradation in the CH₄ generation zone, which agrees with the low SO₄ concentrations. The slightly enhanced SO₄ in #02A and B is partly due to an addition of local meteoric water, which has [SO₄] of ~0.5 mM. These results suggest that fluids emanating from Taiwanese mud volcanoes are originally sedimentary pore waters, but mixing with meteoric water or surface evaporation may have occurred during discharge and recharge processes.

3.3. Stable isotope systematics

It is of particular interest to evaluate the data on δ¹⁸O and δD in mud volcano fluids (Figs. 4 and 5). A combination of H and O isotopic results of fluids collected

![Fig. 5. A comparison of δ¹⁸O and δD compositions in Taiwan and Trinidad mud volcano fluids (Dia et al., 1999).](image-url)
from the CL#2A and #2B region, with values from the literature, indicates a line with a slope of approximately 2.5. This indicates possible surface evaporation and isotopic exchange with atmospheric moisture or water–sediment interaction at depth (Sakai and Matsubaya, 1977; Chan et al., 2000). The depletion of δD in #2C is significant, possibly due to addition of δ18O-enriched fluids with a low δD of −26‰. Such δ18O and δD isotopic characteristics in fluids agree with the addition of waters derived from clay dehydration. However, more complicated humidity controlled surface evaporation and associated isotopic exchange cannot be ruled out. The associated radiogenic Sr isotopic compositions, 87Sr/86Sr = 0.71136–0.71283, compared with the modern seawater value of 0.70925, suggest intense sediment–water exchange at elevated temperatures and are consistent with the observed large Na enrichment in fluids associated with Mg and Ca depletion compared with the seawater composition. The latter chemical characteristic cannot be explained by surface evaporation alone.

As mentioned above, the Chishan fault fluids show relatively low concentrations of Cl, Na, K, Ca, Mg and NH₄ compared with the Gutingkeng anticline (Fig. 3). The most striking features of these fluids, however, are the very high δ18O values (up to 6.5‰) associated with this fault zone (Figs. 4, 5). The observed δ18O values are among the most 18O enriched fluids on the Earth’s surface, except those of high temperature spring waters on land (Peters, 1993; Davison et al., 1994; Petrucci et al., 1994) or in the mud volcanoes in Trinidad (Dia et al., 1999). Submarine hydrothermal vent fluids from sedimented ridges (Campbell et al., 1994), as well as pore waters in the deeper sedimentary column in Nankai Trough (δ18O = −4 to 2‰; Kastner et al., 1993), have similar 18O enriched fluids, although to a lesser degree. Clay dehydration and transformation at depth provides a mechanism for explaining both the relatively low salinity, excess Na, and the heavy 87Sr/86Sr in the Chishan samples compared with those from Gutingkeng and the Coastal plain area. Recently a systematic geochemical study of the mud volcano fluids of Trinidad has also shown high δ18O values, which were explained by interaction with sediment or wall rocks (Dia et al., 1999). The Trinidad data are shown in Fig. 5 and show a similar trend as the Taiwan mud volcanoes, suggesting intense sediment/water exchange has also occurred.

The fluid–rock interaction temperatures estimated for Trinidad mud volcanoes (Dia et al., 1999) are approximately 150°C and these fluids show similar δ18O ranges as Taiwanese mud volcanoes. The δ18O values in Nankai Trough pore waters fall in a range between −4 and +2‰, where the in situ temperature near the décollement zone is approximately 110°C. The Taiwanese mud volcano fluids extend the trend of Nankai Trough to higher δ18O values (+6.5‰). This, again, is suggestive of deep fluid sources and/or intense water–sediment interactions at elevated temperatures. Alternatively, clay diagenesis leading to the release of interlayer water enriched in 18O and elevated in 87Sr/86Sr (Kastner et al., 1993) can explain these observations. The Na enrichment associated with Mg and Ca depletion in Taiwanese mud volcano fluids, however, indicates influence of diagenetic effects due to modification of smectitic clays. The H and O isotopic compositions in the “andesitic waters” in convergent margins (Giggenbach, 1992; Taylor, 1992) are strikingly similar to the mud volcano fluids reported here and in Trinidad (Dia et al., 1999). This can be understood in terms of addition of slab-derived fluids, which were generated at different depths during sediment subduction at convergent margins (You et al., 1996).

The Li and B isotopic compositions in pore waters are sensitive indicators of retrograde alteration at low temperatures. The Li concentration in CL#02C fluids is 815 μM with δ7Li of −13.2‰. Pore waters with similar
Compositionshavebeenisolatedfromthedécollement zoneinSite808atNankaiTrough(Youetal.,1995a; Chanetal.,1994).Fluidssampledfrommuddiapirson theBarbadosaccretionarycomplexdisplayenrichedLi concentration,butwithseawater-likeisotopiccomposi-
tions($\delta^{6}\text{Li} = 20\%$,Martin,1993;Martinetal.,1996).

The mudvolcanofluidshavedissolvedBconcentra-
tionsfargreaterthanthatofseawater(asmuchas20 times)andshowlargevariationsin$\delta^{11}\text{B}$($\sim22$ to $65\%$).

Similar observations were made in the mud volcano fluids of the Caucasus(Kopfetal.,2003),while$\delta^{11}\text{B}$ values in Taiwan exceed at times the seawater values (Fig. 7). Two possible processes for the extreme variation in$\delta^{11}\text{B}$values are (1) B-bearing mineral formation with large isotope fractionation or (2) significant chemisorption at clay surfaces or preferential removal of$^{10}\text{B}$ in retrograde alteration reactions at low temperatures. The enhanced B concentrations in the Taiwanese mud volcano fluids, however, cannot be explained by the abovementioned mechanisms. Chemisorption leads to fluids with lower B and heavy$\delta^{11}\text{B}$, but surface evaporation or sedimentary contributions will enrich B with lighter$\delta^{11}\text{B}$(Leemanetal.,1992;Spivacketal.,1987). Significant bulk B mobilization has been observed as a result of fluid expulsion in accretionary prisms(You et al.,1993;Kopfetal.,2003),aswellasinalaboratory hydrothermal water–sediment interactions(You,1994;YouandGieskes,2001).

Efficient sedimentary B mobilization at depth, where in situ temperatures are greater than 100°C, and subsequent chemisorption on clays near surface when fluids discharge, can explain both B and$\delta^{11}\text{B}$ compositions observed. Assuming deep-generated fluids have a Cl concentration similar to that of seawater chlorinity (559 mM), an average end-member B in mud volcano fluids of 10 mM can be estimated. This seawater chlorinity assumption is justified as no major Cl-bearing minerals occur in marine sediments and Cl behaves conservatively in porewaters. Using the end-member fluid compositions, the mean B concentration calculated for Chihsan Fault and the Gutingken anticline is 27 and 8 mM respectively, which are comparable to those of mud volcanoes in Trinidad, [B] = 2.5–31.6 mM. A significant B return flux of $1 \times 10^{10}$ mol/a to the ocean is assigned in worldwide convergent margins if B concentration is 10 mM and de-watering flux is 1 km$^3$ H$_2$O/a (Kastneretal.,1991). This flux of B is more than 1/4 of river flux estimated (LeMarchandetal.,2000), which may affect the oceanic budget of B significantly (You,1994).

**3.4. Comparison with Trinidad mud volcanoes**

In the section above the similar trends in$\delta^{18}\text{O}$and$\delta\text{D}$ in the Taiwan and Trinidad fluids have already been shown. Here the data obtained for other chemical constituents in other mud volcano fluids is also compared. The contents of Na and Cl have been analyzed in a number of mud volcanoes, both on land and in the ocean. Data on mud volcanoes near the Barbados Accretionary Prism (Martinetal.,1996) and on Trinidad(HigginsandSaunders,1974;Diaetal.,1999)have been discussed in great detail. In Fig. 6, plots are given of Na vs. Cl and the Na/Cl ratio vs. Cl, including the Taiwan data. In most instances, Na/Cl ratios are well above the seawater ratio, presumably as a result of sediment–pore water interaction. Only mud volcano LS#9 has much lower Na and Na/Cl values, as a result.
of Na uptake during volcanic matter alteration processes.

Boron contents of the Trinidad and the Taiwan mud volcano fluids are plotted in Fig. 7. In both cases, most fluids have increased B concentrations over those of seawater. The δ11B values in Taiwanese fluids are also elevated above the seawater value. This presumably is a result of the generation of B at higher temperatures in the deep sediments (You et al., 1996).

The data on I and Br in the Trinidad mud volcanoes are plotted in Fig. 7. Though no data on NH4 were available for these samples, both the I and Br, as well as NH4 (see Taiwan data of Fig. 3), are the result of regeneration at depth of organic matter under CH4 generation conditions (below the SO4 reduction zone). This is typically observed in rapidly deposited sediments on continental margins (e.g., Martin et al., 1996).

4. Conclusions

The fluids associated with Taiwanese mud volcanoes show distinct chemical characteristics in different local geological settings. The samples distributed at the Gutingkeng anticline axis and Coastal Plain area are characterized by high Cl contents, up to 2/3 seawater, indicating a marine sedimentary pore water origin. This fluid was subsequently expelled to the surface along possible fracture zones. The fluids sampled from the Chishan fault show the lowest salinity and other chemical constituents, but with anomalously high δ18O (5.1–6.5 ‰) and 87Sr/86Sr (0.71136–0.71283). A scenario involving mixing of the original sedimentary pore fluids (like the Gutingkeng fluids) and waters from sediment–water interactions released at higher temperatures with high δ18O and 87Sr/86Sr is proposed to describe the Chishan fault mud volcanoes. Overall, the Taiwanese mud volcanoes show great similarity to those in Trinidad and in the Caucasus, indicating intensive de-watering in accretionary wedges via mud diapiric structures. The high abundance of B in these fluids implies an important impact on oceanic B budgets and deserves further systematic investigation.

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