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SHORT NOTE

The smectite to corrensite transition: X-ray diffraction results from the MH-2B core, western Snake River Plain, Idaho, USA

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ABSTRACT: The MH-2B borehole, a part of Project HOTSPOT, was drilled to a depth of 1821 m in late Cenozoic basalts, hyaloclastites and interbedded lake sediments, on the Mountain Home Air Force Base in southern Idaho, USA. Drillers encountered hot water (145°C) under artesian pressure at 1745 m in a narrow zone of highly fractured rock associated with a major sub-surface fault. X-ray diffraction (XRD) analysis identified corrensite (with and without smectite) between 1700 and 1800 m, but only smectite above 1700 m and below 1800 m. This corrensite horizon contains a relatively narrow zone of fracturing and hot artesian water near its centre but for the most part occurs in relatively massive basalt flows. No evidence was found for randomly interstratified chlorite-smectite.

KEYWORDS: smectite, corrensite, MH-2B borehole, XRD.

Because the occurrence and growth of clay minerals are thought to be functions of changes in temperature, composition and permeability, clay mineral transformations are potentially useful for evaluating geothermal resources. Understanding these growth relationships has the potential to clarify the thermal and spatial evolution of specific geothermal resources (Beaufort & Meunier, 1994; Patrier *et al.*, 1996; Robinson & Santana De Zamora, 1999; Robinson *et al.*, 2002; Rigault *et al.*, 2010). This paper describes an occurrence of the transformation of smectite to corrensite in a borehole in the western United States drilled by Project HOTSPOT (The Snake River Geothermal Drilling Project).

Project HOTSPOT (Shervais *et al.*, 2011) is an international consortium that drilled three boreholes of intermediate depth in the Snake River Plain in southern Idaho, USA, including one on the Mountain Home Air Force Base (AFB) near Boise, Idaho (Fig. 1). The purpose of the boreholes was to investigate the regional thermal system of the Snake River Plain, and to study the effects of the passing of the Yellowstone Hotspot as it moved under the region over the past 17 my. Cross sections of the Mountain Home AFB vicinity based on drilling logs, gravity surveys, and surface mapping (Fig. 2) indicate nearly 3000 m of late Cenozoic deposits, including lake sediments, basalt lavas and hyaloclastites and rhyolites, filling a graben bounded by steep normal faults. Gravity data suggest that near Mountain Home AFB a basement high (interpreted as a horst) rises several thousand feet into the graben deposits

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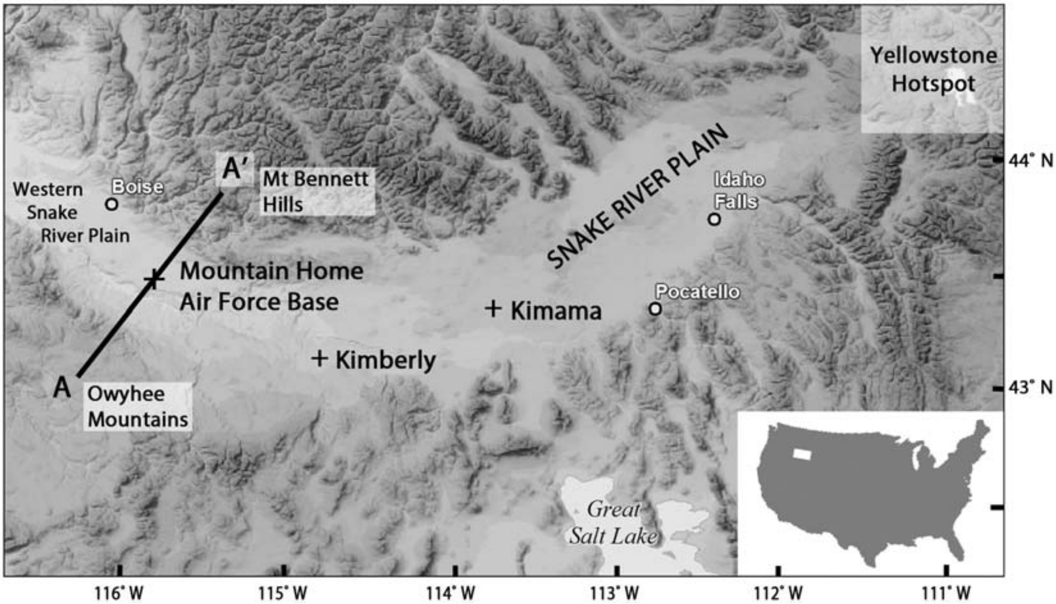

FIG. 1. Location map of Snake River Plain and the Mountain Home Airforce Base with the MH-2B borehole site. The location of the cross section in Fig. 2 is shown. Also shown are locations of the other Project HOTSPOT boreholes at Kimberly and Kimama. The track of the Yellowstone hotspot runs from southwest to northeast along the axis of the Snake River Plain; the hotspot is currently located in the northeast corner of the map. Base map: U.S. Geological Survey. National Elevation Dataset. 1 arc second. The National Map. 2014. http://viewer.nationalmap.gov/basic. (May 25, 2016).

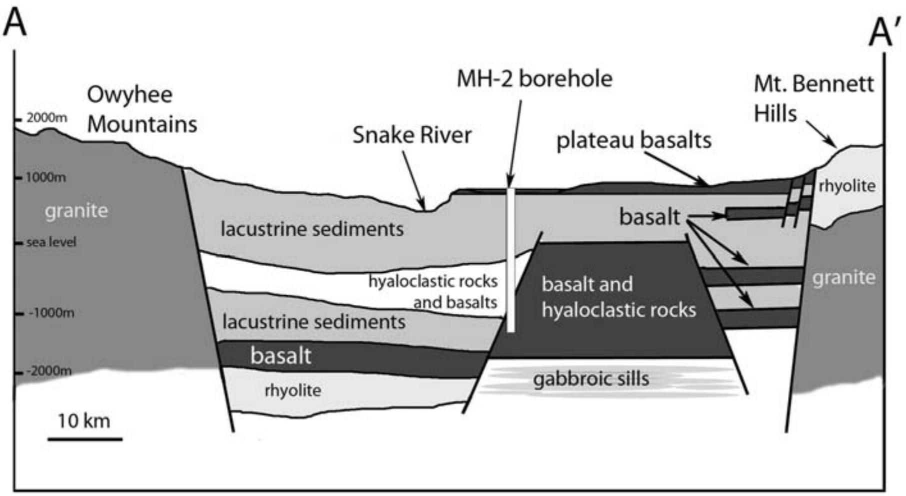

FIG. 2. Generalized cross section of Snake River Plain through location of MH-2B borehole shown in Fig. 1. Strata below the surficial plateau basalts and above the gabbroic sills and rhyolites are interpreted to be the Plio-Quaternary Idaho Formation (see text). The Snake River Plain lies between the Owyhee Mountains to the south (left) and Mt. Bennet Hills to the north (right), separated by steep boundary faults along the edges of the cross section. Note the horst into which the MH-2B borehole penetrated (after Shervais *et al.*, 2006, 2011; Breckenridge, 2012).

(Shervais *et al.*, 2002). It is postulated that the geothermal system is driven by the thermal effects of layered gabbroic sills intruded at depth within the graben (Shervais *et al.*, 2006). Recent detailed gravity studies indicate that the MH-2B borehole is located almost directly over the southern boundary fault of the horst (Breckenridge *et al.*, 2012).

Borehole MH-2B, completed in January, 2012 (Breckenridge *et al.*, 2012), was cored continuously with ~95% core recovery except within a highly fractured zone at ~1745 m. The general lithology of the well (Fig. 3) is basalt to 210 m, lake sediments with interbedded basalt flows to 950 m, and altered basalt and hyaloclastitic rocks to 1821 m. The surface rocks

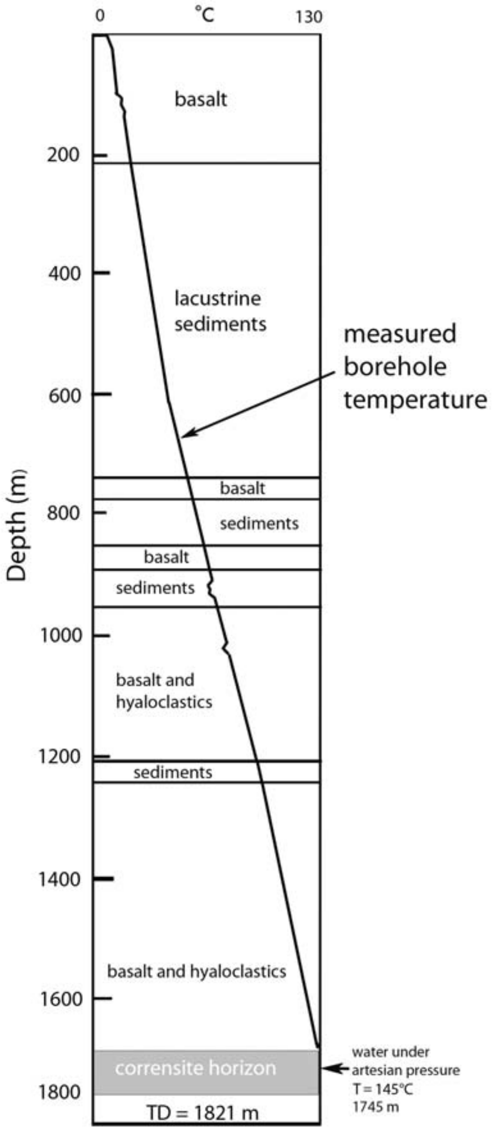

FIG. 3. Borehole lithological section showing a measured temperature gradient and locations of the corrensite horizon and the zone of warm water under artesian pressure. Note that the temperature scale ends at 130°C, the limit of the instrument used to measure borehole temperature. Flowing artesian water from ~1745 m depth measured 145°C at the wellhead. TD = total depth of borehole.

TABLE 1. Sample numbers, depths and clay minerals present.

Sample #	Depth (m)	Smectite	Corrensite
762JW	762	x	
848JW	848	x	
935JW	935	x	
996JW	996	x	
1089JW	1,089	x	
1182JW	1,182	x	
1269JW	1,269	x	
1364JW	1,364	x	
1453JW	1,454	x	
1491JW	1,491	x	
1555JW	1,555	x	
1615JK	1,615	x	
1650JW	1,650	x	
1663JK	1,663	x	
1679JK	1,679	x	
1693JK	1,693	x	
1708JK	1,708		x
1719JK	1,719		x
1730JW	1,730		x
1735JK	1,735		x
1738JK	1,739		x
1752JW	1,752	x	x
1763JK	1,764		x
1771JW	1,771	x	x
1787JW	1,787		x
1788JK-A	1,788		x
1788JK-B	1,788		x
1791JW	1,791	x	x
1793JW	1,793		x
1806JK	1,806	x	
1807JK	1,807	x	
1807JW	1,807	x	
1810JW	1,810	x	
1813JW	1,813	x	
1819JW	1,819	x	
1820JW	1,820	x	

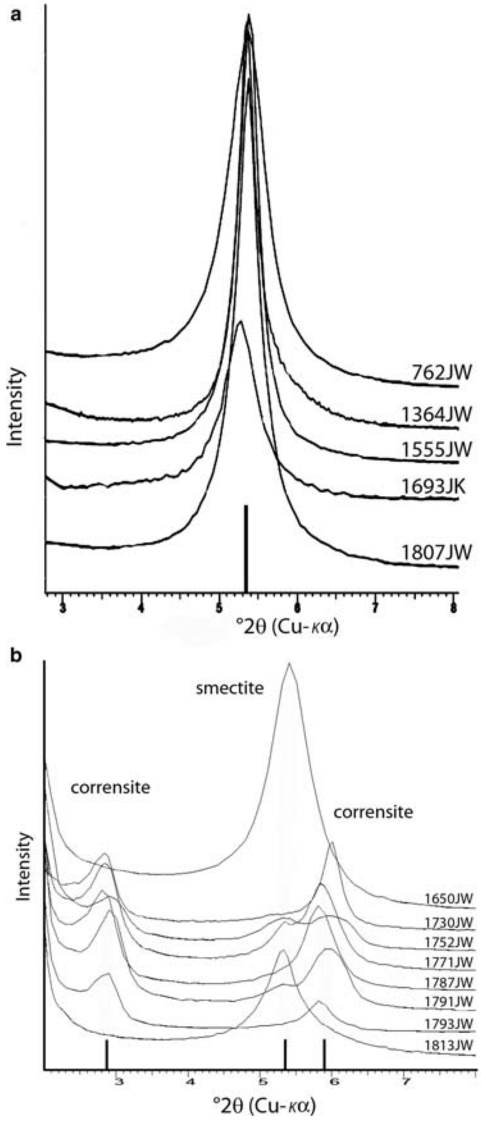

FIG. 4. (a) Selected XRD patterns of ethylene glycol-solvated smectites at various depths throughout the MH-2 borehole showing the relative similarity of the smectite (001) peak shapes irrespective of sampling depth. The corrensite horizon lies between samples 1693 JW and 1807 JW. The dark bar on the horizontal axis shows the position of the smectite (001) at 5.35°2θ ($d = 16.9$ Å). (b) Selected XRD patterns of ethylene glycol-solvated samples within and immediately adjacent to the corrensite horizon (between 1700 and 1800 m deep). Note that some samples within the corrensite horizon contain both corrensite and smectite while others do not. Dark bars on the horizontal axis show positions of corrensite (001) at 2.84°2θ ($d = 31$ Å), smectite (001) at 5.22°2θ ($d = 16.9$ Å) and corrensite (002) at 5.7°2θ ($d = 15.6$ Å).

are interpreted to be Quaternary-age plateau basalts (Fig. 2), whereas the lacustrine sediments and underlying basaltic materials have been assigned to the Plio-Quaternary Idaho Group. No felsic materials were recovered.

Borehole temperatures of 130°C were measured (Fig. 3) at 1700 m in MH-2B; below that, temperatures could not be measured because of equipment limitations but were estimated to be ≥145°C based in part on the temperature of water recovered from that depth (see below; Breckenridge *et al.*, 2012).

A fracture system containing water at 145°C under artesian pressure was encountered at 1745 m (Nielson *et al.*, 2012). Preliminary chemical analyses indicate that the water is relatively dilute and that Ca^{2+} and Mg^{2+} are very low in relation to Na^{+}. Deuterium and oxygen-18 isotope analyses suggest that MH-2B water is either a result of mixing of meteoric and juvenile magmatic waters or has undergone significant fractionation during equilibration with altered volcanic rocks (Lachmar *et al.*, 2012). Temperatures calculated from mineral equilibria range from 132 to 154°C, consistent with measured or estimated borehole temperatures (Lachmar *et al.*, 2012). Preliminary analysis of fluid inclusions in the deepest samples gave temperatures of 195°C for primary inclusions and 145°C for secondary inclusions (Lachmar *et al.*, 2012).

Samples from the MH-2B borehole were obtained from drill core stored at Project HOTSPOT headquarters (Department of Geology, Utah State University, Logan, Utah, USA). Preliminary core logs were used to identify clay-rich intervals. The core is mostly fine-grained but at intervals it has visible secondary crystals of calcite and laumontite and is altered to a greenish-grey colour (Breckenridge *et al.*, 2012; A. W. Walton, pers. comm., 2015). In all, 36 samples of basaltic material from between 750 m and 1820 m depth were sampled (Table 1). These samples were of two different types: (1) chips from the core (suffix "JW"); and (2) whole-rock powders supplied by James Kessler (Utah State University) (suffix "JK") (Kessler *et al.*, 2013). Sampling density was greatest in the interval between 1700 and 1800 m (Table 1) where warm fluids under artesian pressure were reported, and where preliminary results indicated the presence of corrensite (Wheeler & Walker, 2013).

Samples that were not already powdered were crushed in a jaw crusher, ground lightly for 2–3 min in a Cole Parmer model 4301-00 analytical mill, and sieved to <250 µm grain size. Whole-rock powder samples were front-loaded for X-ray diffraction (XRD) analysis. Clay mineral fractions (<2 µm) were exchanged with Ca^{2+} (Moore & Reynolds, 1997), separated by centrifugation, and sedimented onto 3.5 cm glass slides to create oriented mounts that maximize sample length and thickness (D. McCarty, pers. comm., 2012). Oriented mounts were analysed air-dry and after exposure to ethylene glycol vapour at 60°C for at least 12 h.

The XRD analyses were performed using a Bruker D-2 Phaser θ:θ diffractometer with a Ni filter, 0.6° divergence slits, a diffracted beam Soller slit, and a LynxEye detector with the detector opening set to half of the start angle. Whole-rock powders were analysed from 5 to 50°2θ with a 0.1° step and 2 s/step count time (2.5° LynxEye detector opening). Air-dry and glycolated oriented mounts were analysed from 2 to 35°2θ with a 0.1° step and 4 s/step count time (1.0° LynxEye detector opening).

The XRD results are shown in Table 1. Representative XRD patterns of oriented mounts of Ca-saturated and ethylene glycol-solvated samples of smectite covering the entire sampled interval are shown in Fig. 4a. The peaks at ~16.9 Å (5.35°2θ) indicate the presence of smectite, which is pervasive throughout the core. These peaks have relatively consistent peak shapes throughout the core suggesting no systematic variations in crystallite size. More detail is provided (Fig. 4b) of the corrensite horizon between ~1700 and 1800 m where the peaks at ~31 Å (2.84° 2θ) and ~15.6 Å (5.7°2θ) indicate the presence of corrensite. Some of these samples are pure corrensite, whereas others, including 1752JW and 1771JW, contain both corrensite and smectite. Pure smectite again dominates the clay fraction below the corrensite horizon. The transition from smectite to corrensite at both the top and bottom of the corrensite zone occurs over a small depth interval (~15 m), and there is no evidence for disordered (R0) chlorite-smectite in the immediate vicinity of the transition or anywhere else in the core. It is likely that the transformation of smectite to corrensite is related to the flow of warm water through the fracture zone and the associated heating of the wall rocks.

This study has identified a restricted horizon of corrensite crystallization in a borehole core dominated by smectite. The center of the corrensite horizon corresponds roughly to a zone of fractured rock where heated, partly juvenile water at ~145°C flows under artesian pressure, transporting solutes advectively. The bulk of the corrensite horizon, however, is in relatively massive lavas in which heating is probably by conduction and solute transport is by diffusive flow. The transition from smectite-bearing to corrensite-bearing rocks and back again is abrupt, and no evidence has been found for intermediate chlorite-smectite phases at either interface.

Even though the depth and thickness of the corrensite horizon are well constrained by this study, details of the conditions under which corrensite forms are not known. Study of mineral compositions and of thermal and fluid-flow conditions at the boundaries of the corrensite horizon and in the zone of artesian flow will help to clarify the geochemical conditions under which smectite transforms to corrensite. The abrupt nature of the transition from smectite to corrensite at both the upper and lower boundaries of the corrensite horizon in the MH-2B borehole suggests that study of these samples has the potential to greatly expand our knowledge of corrensite formation and stability.

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