40Ar/39Ar age and chemistry of manganese mineralization in the Moab and Lisbon fault systems, southeastern Utah

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ABSTRACT

Diagenetic iron and manganese mineralization is associated with the Moab and Lisbon faults and is an important indicator of fluid flow in Jurassic Navajo Sandstone of southeastern Utah. Reducing brines originating from the Pennsylvanian Paradox Formation (with or without hydrocarbons) mobilized disseminated iron and manganese in the Jurassic sandstones and mixed with shallow, oxygenated groundwater to precipitate both iron and manganese mineralization. Mineralization consists of colliform and concretionary hematite, pyrolusite, and cryptomelane in the hanging wall against Paradox Formation in the footwall. Red sandstones adjacent to the Moab fault were bleached by reductive formation in the footwall. The Moab fault (Fig. 1) is a 45-km-long, northwest-striking normal fault in the northeast part of the Paradox basin and forms the southwest margin of the collapsed Moab Valley. The Moab fault was active intermittently from the Triassic until the early Tertiary (Foxford et al., 1996; 1998). Maximum throw (~1 km) on the fault places Jurassic Morrison Formation in the hanging wall against Paradox Formation in the footwall. Red sandstones adjacent to the Moab fault were bleached by reducing fluids (Garden et al., 1997, 1998). The Lisbon Valley salt anticline southeast of the Moab Valley anticline is also faulted. Basin brines also migrated upward on the Lisbon fault, producing copper deposits (Morrison and Parry, 1986; Breit and Meunier, 1990).

INTRODUCTION

A suite of iron and manganese deposits with varying geometries ranging from concretions to pipes, ferricretes, and liesegang banding is prevalent in sandstones in southern Utah. Chan et al. (2000) used C, O, and Sr isotopic data, fluid inclusions, and geohydrologic reconstructions to show that reducing, saline fluids transmitted on fault systems mix with oxygenated groundwater to precipitate the mineralization. An accurate constraint on the age of mineralization is presented here.

Potassium-bearing cryptomelane along a fault in Jurassic Navajo Sandstone (Figs. 1 and 2) can be dated with Ar-Ar methods. Vasconcelos et al. (1994, 1995) found that cryptomelane faithfully retained radiogenic 40Ar both over geological time and during neutron irradiation, and that loss of 39Ar due to recoil artifacts was insignificant.

GEOLOGIC SETTING

Moab and Lisbon Faults

The Moab fault (Fig. 1) is a 45-km-long, northwest-striking normal fault in the northeast part of the Paradox basin and forms the southwest margin of the collapsed Moab Valley. The Moab fault was active intermittently from the Triassic until the early Tertiary (Foxford et al., 1996; 1998). Maximum throw (~1 km) on the fault places Jurassic Morrison Formation in the hanging wall against Paradox Formation in the footwall. Red sandstones adjacent to the Moab fault were bleached by reducing fluids (Garden et al., 1997, 1998). The Lisbon Valley salt anticline southeast of the Moab Valley anticline is also faulted. Basin brines also migrated upward on the Lisbon fault, producing copper deposits (Morrison and Parry, 1986; Breit and Meunier, 1990).

Field Occurrences and Manganese Mineralogy

Both iron and manganese minerals occur together in vein and fracture fillings along a well-sorted, fine-grained quartz arenite, dominated by large-scale eolian cross-stratification. The sandstone is homogeneous, has relatively high original depositional porosity and permeability (Chan et al., 2000), and is only weakly cemented with small amounts of quartz overgrowths and calcite.

This part of the Colorado Plateau in southeastern Utah is underlain by the Paradox basin, a late Paleozoic intracratonic basin filled with a mixture of carbonate, clastic, and evaporite sediments (Nuccio and Condon, 1996). The evaporites of the Pennsylvanian Paradox Formation are nearly 2 km thick and have been deformed to produce a series of northwest-southeast-trending salt anticlines, where the salt is locally thickened to more than 4 km. The salt anticlines were eventually covered by 2 km of Jurassic to Tertiary sediment, much of which has been removed by erosion since ca. 37 Ma (Nuccio and Condon, 1996). A network of fractures resulting from the movement of the Paradox salt largely influences the tectonic fabric of this study region.

FIELD OCCURRENCES AND MANGANESE MINERALOGY

Both iron and manganese minerals occur together in vein and fracture fillings along a
steep fault striking 310°–320°. Mineralization consists of dark gray to black hematite, pyrolusite, and cryptomelane in the host Navajo Sandstone. These precipitates (cementing quartz sand grains) occur as vein-filling to colliform and concretionary forms cutting across primary eolian stratification. Typically, the geometry of colliform banded mineralization suggests that fluids emanated from the fault. The manganese oxide minerals occur as several irregular, curved bands, the center of curvature being near the fault (Fig. 3). Each band consists of fingers of manganese minerals a few millimeters in diameter perpendicular to the band. Each finger is cored by cryptomelane surrounded by a rim of pyrolusite and a thin outer rim of hematite (Fig. 4). Hematite-stained sandstone occupies the interfinger area. The chemistry of the manganese minerals (Table 1) conforms closely to the crypto-

| TABLE 1. ELECTRON MICROPROBE ANALYSES OF PYROLUSITE AND CRYPTOMELANE-HOLLANDITE |
|----------------|----------------|----------------|----------------|
|               | Rim pyrolusite | Rim pyrolusite | Core cryptomelane | Core cryptomelane |
| K              | 0.02           | 0.00           | 1.58             | 0.32             |
| Na             | 0.01           | 0.00           | 0.42             | 0.15             |
| Ba             | 0.07           | 0.00           | 6.92             | 0.40             |
| Ca             | 0.17           | 0.00           | 0.45             | 0.09             |
| Mg             | 0.01           | 0.00           | 0.14             | 0.05             |
| Fe**           | 0.00           | 0.00           | 0.00             | 0.00             |
| Mn**           | 63.65          | 1.00           | 44.27            | 6.45             |
| Mn**           | 37.16          | 2.00           | 31.96            | 16.00            |
| H₂O            | 4.49           | 2.00           | 4.49             | 2.00             |
| *Calculated by stoichiometry. |

Figure 3. Colliform banding of iron and manganese mineralization emanating from fractures within Navajo Sandstone at Flat Iron Mesa (see X in Fig. 1). Scale card is 16.5 cm long.

Figure 4. Digitate fingers of cryptomelane-hollandite (C) with rim of pyrolusite (P) and outer rim of hematite with red Navajo Sandstone occupying interfinger area, Flat Iron Mesa locality. A: Side cross-sectional view. B: Photomicrograph showing quartz grains (Q) cemented by cryptomelane-hollandite (C) at center of finger, surrounded by pyrolusite (P) showing good cleavage (reflected light).

All aliquots of cryptomelane separates were vacuum encapsulated for ⁴⁰Ar/³⁹Ar age measurement and analyzed using the procedures of Dong et al. (1995). Two analyses were performed, but one of the irradiation capsules failed, and we were unable to directly estimate the effects of recoil loss of ³⁹Ar for that one sample.

Ar-Ar METHODOLOGY AND RESULTS

Cryptomelane samples were prepared by crushing, wet sieving, and then retaining the ~100 to ~140 mesh size fraction. A cryptomelane mineral separate was obtained by magnetic separation, and finally purified by handpicking to remove all grains containing visible silicate minerals. The mineral separate was a mixture of cryptomelane and pyrolusite. Quartz and feldspar were undetected in the separate by petrographic or X-ray diffraction analysis.

40Ar/³⁹Ar Ages

The results of duplicate laser probe step-heating analyses (Fig. 6) include plots of apparent Ca/K (from ³⁷Ar/³⁹Ar) and Cl/K (from ³⁸Ar/³⁹Ar). The successful vacuum encapsulation analysis (run 1) had virtually no ³⁹Ar (0.0012% of the total) and no detectable radiogenic ⁴⁰Ar, thereby confirming the findings of Vasoncelos et al. (1995).

In the initial steps (to 20% of ³⁹Ar), apparent ages increase from near zero, Ca/K is variably elevated, and Cl/K drops from ~0.005 to 0.002. From 20% to 70% of the ³⁹Ar release, apparent ages are roughly constant between about 20 Ma and 30 Ma, with no true plateau. Above 70% release, ages climb sharply, especially for the second analysis. In this part of the spectra, Ca/K is slightly depressed, especially in run 2. The total gas ages (equivalent to K-Ar) are discordant, being 24.94 ± 0.22 Ma and 35.92 ± 0.22 (1 σ) Ma for runs 1 and 2, respectively.

We interpret the results as indicating that there are three phases present: (1) a poorly retentive, relatively Cl- and Ca-rich phase that degasses at low temperature (T) (pyrolusite?); (2) the main cryptomelane component, with Cu/K (Fig. 6) approximately the same as in the electron microprobe results (Table 1), that dominates in the middle part of the age spectrum; and (3) a variable amount of a K-rich, Ca-poor silicate contaminant (K-feldspar or K-mica) that dominates at the highest T part of the age spectra. In order to estimate the crystallization (or blocking) age of the cryptomelane, we calculated apparent ages by summing the gas released from the parts of each spectrum between about 20% and 70% of the ³⁹Ar released. The results are 22.53 ± 0.23 Ma for run 1 and 21.05 ± 0.14 (1 σ) Ma for run 2. Although still discordant, the greatly improved agreement between the analyses indicates that the effects of the highly retentive contaminant are dramatically reduced. The K-silicate component is highly variable on the scale of our samples (i.e., 5.7 mg for run 1, 4.0 mg for run 2).

These error estimates are strictly from an-
alitical statistics and do not include an estimate of accuracy in separating the effects of the low $T$ and K-silicate components. Given that uncertainty, our results suggest formation of the cryptomelane at 25±20 Ma.

**DISCUSSION**

Each of the two cryptomelane spectra (Fig. 6) shows high age spikes. The first run shows a spike at 49.2 ± 0.29 Ma and the second run stair-steps up to a spike at 171 ± 0.49 Ma. The Ca/K values for these spikes in Figure 6 show a systematic decrease to values below 0.19. For the high age spikes, the Ca/K value is 0.17 in run 1, and 0.12 in run 2. The mean of nine microprobe spot analyses on one cryptomelane core gives Ca/K = 0.284, and the mean of five spots in another core gives Ca/K = 0.270. This suggests that the high ages come from domains that have Ca/K < 0.19 and that the anomalously old date could be a high-K contaminant such as K-feldspar or K-mica that could not be removed during the separation and purification of the cryptomelane.

Maps of Al and Si produced by the electron microprobe (Fig. 5) show micrometer areas within the cryptomelane that contain anomalously high Si and Al consistent with aluminosilicate inclusions. Thus, the consistency of the 25–20 Ma part of the age spectra appears to be the true cryptomelane age, and the range of the spectra shows how sensitive Ar dating can be to small contaminant phases. The formation of cryptomelane represents the age of reducing brine movement upward along northwest-striking faults from the Paradox salt beds below.

The Moab fault has a long and complex history that includes a pre–Late Jurassic phase, a post–middle Cretaceous phase (Foxford et al., 1996), and a Tertiary history (Doelling, 1988). Foxford et al. (1996) suggested that iron reduction took place in Late Cretaceous to early Tertiary time, on the basis of spatial association with veins and the Moab fault, and R. Garden (2000, personal commun.), on the basis of paleomagnetics, estimated that the age of iron reduction is 43–63 Ma.

Several stages of uplift of the Colorado Plateau are recognized: (1) Laramide crustal thickening and formation of monoclines at 85–50 Ma (Elston and Young, 1991; Young, 1996; McQuarrie and Chase, 2000); (2) thermal expansion beginning at ca. 25 Ma (Ritter and Smith, 1996; Wendlandt et al., 1996); (3) development of present topography along with Basin and Range extension at 20–15 Ma (Christiansen et al., 1992; McQuarrie and Chase, 2000); and (4) latest incision of river systems at 5.5–0 Ma (Hunt, 1969; Luchitta, 1979; Huntoon, 1988). Uplift due to La Sal Mountains volcanism is dated as 25–28 Ma (Nelson et al., 1992). The cryptomelane ages postdate Laramide events and predate the latest stage of uplift of the Colorado Plateau. An earlier stage of uplift of the Colorado Plateau or La Sal Mountain volcanism most nearly coincides with the cryptomelane age of mineralization (25–20 Ma) on the Moab-Lisbon fault system.

In the Moab area, groundwater is responsible for dissolved salt in collapsed anticlines (Doelling, 1988), mobilized iron and bleached rocks (Morrison and Parry, 1986; Breit and Meunier, 1990; Foxford et al., 1996), and pre-
cause precipitation of the mineralization as both fluids within the Navajo Sandstone aquifer to flow towards the Moab and Lisbon faults in zone of fluid mixing. Cretaceous and Triassic are relatively low permeability intervals, and Jurassic is high-permeability regional aquifer.

SUMMARY
Iron and manganese mineralization near the juncture between the Moab and Lisbon fault systems occurs along faults and fractures that are likely conduits for fluids originating from the Paradox Formation. These reducing fluids originating from depth mixed with oxygenated groundwater. In the southeastern Sal Mountains, and the salt anticline crests to the southeast and southwest from recharge areas in the La Sal Mountains, and the salt anticline crests towards the Moab-Lisbon fault system. Fluid mixing along the fault system facilitated the Oligocene-Miocene mineralization.

Figure 7. Schematic northeast-southwest hydrostratigraphic cross section with approximate Oligocene-Miocene topography (A–A' in Fig. 1) showing possible topographically driven groundwater flow paths. Mineralization (25–20 Ma) occurred along Moab and Lisbon faults in zone of fluid mixing. Cretaceous and Triassic are relatively low permeability intervals, and Jurassic is high-permeability regional aquifer.

Topographically Driven Ground Water Flow
Reducing Water
Mississippian
Paradox Formation
Pennsylvania-Permian
Triassic
Jurassic
Tertiary Igneous

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