Relations between deformation and sediment-hosted copper mineralization: Evidence from the White Pine part of the Midcontinent rift system

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ABSTRACT

Detailed studies over the past decade have significantly extended and revised our knowledge of the geologic history of the well-known White Pine mining district of northern Michigan, and indicate that the location of faults exerted a strong control on copper mineralization in this part of the Midcontinent rift system. At White Pine there is evidence for three episodes of faulting: (1) synsedimentary faulting, (2) subsequent high-angle, dominantly normal faulting, and (3) thrusting. Two stages of copper mineralization are present at White Pine and in the nearby Presque Isle syncline. The first, main-stage mineralization, formed a classic sediment-hosted stratiform copper deposit during early diagenesis. Synsedimentary faults may have provided important conduits for cupriferous brines flowing from underlying red beds of the Copper Harbor Conglomerate into the reduced silts and shales of the Nonesuch Formation, where main-stage copper sulfides and native copper were precipitated. The second stage of copper mineralization was synchronous with thrusting and introduced additional copper to the White Pine ore body and the Presque Isle syncline. Thrust faults and cogenetic tear faults provided conduits for second-stage mineralizing fluids. Collectively, these observations indicate strong control by regional deformation on fluid migration and mineralization in the rocks of the Midcontinent rift, similar to proposed relations between deformation and mineralization in other tectonic settings.

INTRODUCTION

The Lake Superior part of the Midcontinent rift contains the world-class sediment-hosted stratiform copper deposit at White Pine and the native copper deposits of the Keweenaw district. One of the major enigmas of Michigan's "copper country" has been that native copper mineralization in the classic Keweenaw district 100 km northeast of White Pine was "contemporaneous with or later than much or most of the deformation" (White, 1968, p. 313), whereas, at White Pine, "most, if not all" of the economic mineralization was thought to have preceded deformation (Ensign et al., 1968). Herein we present evidence that a second phase of mineralization occurred at White Pine which may correlate with Keweenawan native copper deposition. We also demonstrate that regional compression controlled this second-stage copper mineralization at White Pine. These results lend further support to the increasingly recognized link between regional deformation, fluid migration, and chemical interactions in the upper crust (e.g., Oliver, 1986).

GEOLOGIC SETTING

The Lake Superior part of the 1.1 Ga Midcontinent rift is filled with up to 15 km of rift-related volcanic rocks, and up to 10 km of overlying sedimentary rocks (e.g., Green, 1983; Cannon et al., 1989; McGinnis, 1990; Fig. 1A). The stratigraphy near White Pine consists of a basal 5–13 km of mafic to intermediate flows of the Portage Lake lava series and the Unnamed Formation. Interstratified with and overlying the Unnamed Formation is the Copper Harbor Conglomerate, a red sandstone and conglomeratic unit up to 2 km thick. Overlying the Copper Harbor Conglomerate are 40–300 m of dominantly green to gray siltstones and shales of the Nonesuch Formation, which is overlain by up to 4 km of the dominantly red Freda Sandstone. The Copper Harbor Conglomerate, Nonesuch Formation, and Freda Sandstone form the Oronto Group (Thwaites, 1912; Daniels, 1982; Elmore et al., 1989). The rocks described above lie on the upper plate of the Keweenaw fault (Hinze et al., 1990); the Proterozoic Jacobsville Sandstone, which is believed to be younger than the Oronto Group, is to the south of the Keweenaw fault (Kalliokoski, 1982).

STRUCTURAL GEOLOGY

Since the last published descriptions of the structural geology at White Pine (Ensign et al., 1968), the mine has roughly doubled in area to about 50 km^2, and features of the structure and mineralization have been exposed that were inaccessible to earlier workers. On the basis of structural style, we have subdivided the White Pine mine into three domains (Fig. 1D). The northeastern domain is characterized by high-angle faults; normal faults outnumber reverse faults by a ratio of three to one. The southeastern domain also contains chiefly high-angle faults, but normal faults outnumber reverse faults by a ratio of three to two. The presence of thrust faults with throws of up to 75 m distinguishes the southwestern block, where reverse faults outnumber normal faults by a ratio of three to one.

Detailed mapping in the mine area as well as study of drill core between the Michigan-Wisconsin border and Houghton, Michigan, reveal zones of increased soft-sediment deformation and facies changes where the thicknesses of sedimentary units change abruptly. These linear belts, which are thought to reflect synsedimentary faults, commonly coincide with younger fault zones, indicating reactivation of many synsedimentary faults later in the basin's history. Observed stratigraphic relations and synsedimentary faults are compatible with the hypothesis of a rift composed of subbasins (e.g., Dickas, 1988; Dickas and Mudrey, 1989; Cannon et al., 1989; McGinnis, 1990).

The second episode of faulting in the White Pine part of the rift is characterized by high-angle, predominantly normal faulting, which produced the dominant extensional fabric in the northeastern domain of the mine. The White Pine fault (Fig. 1C), originally thought to be a strike-slip fault transecting the White Pine district and extending at least 15 km to the south (Ensign et al., 1968), actually terminates within the mine itself. High-angle faults in the northeastern and southeastern domains (Fig. 1C) curve from a north-south to a northeast-southwest orientation. Similarly, in the northeastern block, faults dip both to the east and west, but in the southeastern block, more than 90% of the faults dip to the southeast, typically at lower angles than faults to the north. Although other interpretations are possible, we hypothesize that compression during thrusting led to rotation of faults in the southeastern block into

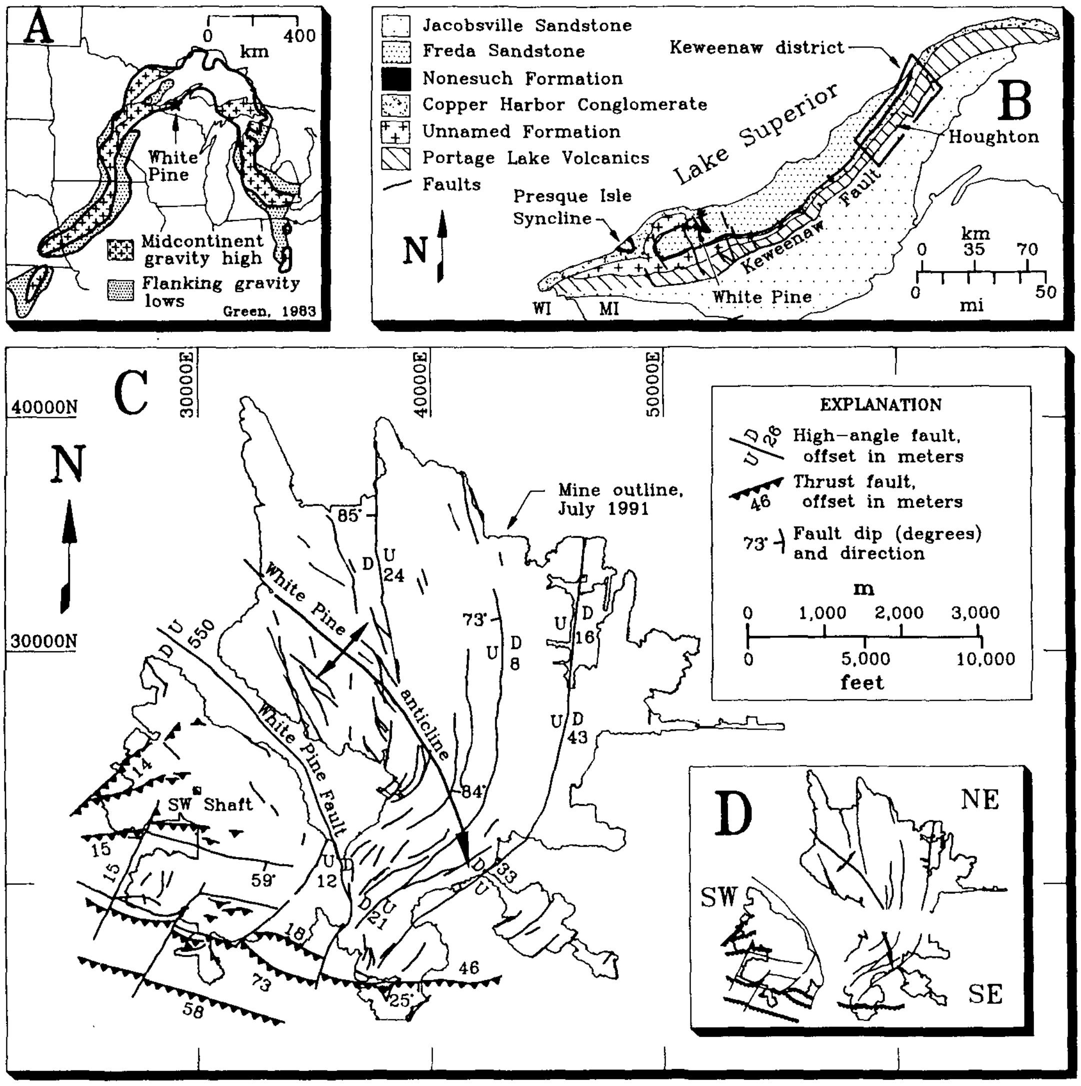


Figure 1. A: Location of Midcontinent rift system, modified from Green (1983). B: Generalized geologic map of Midcontinent rift rocks in study area, modified from Cannon (1986) and Morey et al. (1982). C: Generalized structure map of White Pine mine. Tick marks represent mine coordinates (in feet). D: Simplified structure map of White Pine mine showing location of three structural domains.

their present attitude and local reactivation of normal faults to reverse faults.

South-dipping thrusts with throws of 2 to 75 m occur only in the southwestern domain of the mine (Fig. 1C), although minor thrusts with throws of up to 1 m exist in the northeastern and southeastern domains. Tear faults, which offset or terminate thrust faults, are common in the southwestern domain (Fig. 1C). The age of thrusting is ~1060 Ma, on the basis of Rb-Sr model ages of calcite veins at White Pine (1060 ±20 Ma; Ruiz et al., 1984) and uplift along thrust faults south of the Keweenaw fault (1060 Ma; Rb-Sr, biotite; Cannon et al., 1990). The Presque Isle syncline, near the Michigan-Wisconsin border, also contains thrust faults, but the exact extent and offsets of thrust faults in this area remain poorly known. Regionally significant high-angle reverse faults like the Keweenaw fault record a late-stage compressional event that closed the rift (e.g., Cannon et al., 1989; Behrendt et al., 1988; Fig. 1B); recent seismic data indicate that thrust faults cut rift sediments underneath Lake Superior (McGinnis, 1990; Thompson et al., 1990).

COPPER MINERALIZATION

The White Pine area underwent two principal episodes of copper mineralization. The first, or main-stage mineralization, is classic sediment-hosted stratiform copper (e.g., White and Wright, 1954, 1966; Ensign et al., 1968; Brown, 1971). Chalcocite, which ranges from 0.5 cm clots to micrometre-scale grains, contributes ~80% of the copper currently extracted from the mine and is the dominant copper mineral in main-stage mineralization. The balance of the copper extracted from the mine occurs as native copper, of which perhaps as much as 50% is a product of second-stage mineralization. The average grade of the ore extracted from the mine is 1.09% copper.

Within the White Pine mine only the basal 1 to 4 m of the Nonesuch Formation contain economic concentrations of copper. The top of the cupriferous horizon is marked by a narrow, typically 5–30-cm-thick zone called the fringe, where, in ascending order, copper-bearing sulfides give way to copper-iron sulfides and finally to pyrite (Brown, 1971). The fringe crosscuts the strata at a low angle, so that strata relatively high in the lower Nonesuch Formation are mineralized in the mine area, but are not mineralized in the Presque Isle syncline to the west or in drill core to the east of the mine (Ensign et al., 1968).

Main-stage mineralization is believed to have formed during early to mid-diagenesis from oxidized cupriferous fluids driven updip out of the compacting basin through red beds of the Copper Harbor Conglomerate (Brown, 1971; White, 1971). Sand dikes and fluid escape structures commonly contain anomalous enrichments of chalcocite and/or native copper, indicating that entry of main-stage mineralizing fluids into the relatively impermeable silts and shales of the Nonesuch Formation was facilitated by cross-stratal sedimentary structures after sedimentation and some compaction had occurred (Fig. 2). In the northeastern domain there

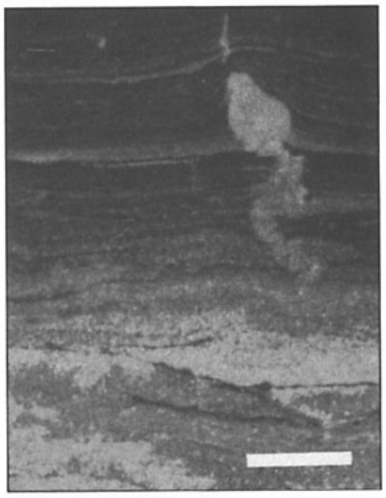


Figure 2. Fluid escape structure filled by chalcocite. Scale bar equals 1 cm.

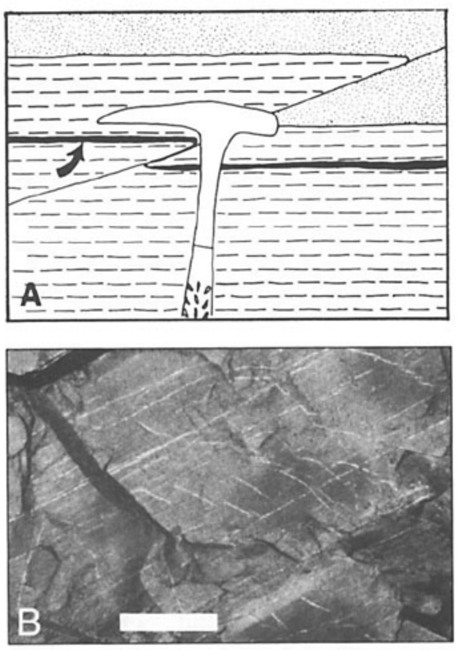


Figure 3. A: Sketch based on photographs and field notes showing sheet copper wrapping through thrust and relative offset of bedding and copper sheet. B: Stockworks and bedding-plane–parallel veins of chalcocite adjacent to thrust fault. Scale bar equals 5 cm.

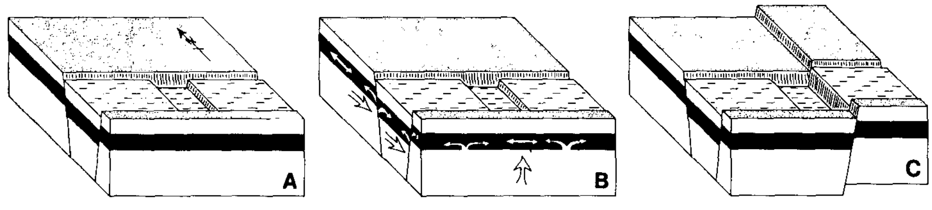
is no evidence for significant changes in stratigraphic position of the fringe adjacent to high-angle faults, nor is there significant enrichment of copper adjacent to these faults, except adjacent to the White Pine fault, indicating that main-stage mineralization preceded high-angle extensional faulting.

Areas adjacent to tear and thrust faults commonly contain two styles of copper enrichment: (1) strata that are unmineralized elsewhere locally contain copper adjacent to compressional faults, and (2) ore-grade strata are 20% to 30% higher grade near thrust and tear faults than in unfaulted regions. Second-stage mineralization refers to these fault-related, post–main-stage enrichments. We recognize four types of second-stage mineralization: (1) sheet copper, (2) bedding-plane–parallel chalcocite veins, (3) stockworks, and (4) disseminated native copper in the uppermost Copper Harbor Conglomerate.

Some areas in the southwestern domain contain sheets of native copper up to 5 mm thick that are parallel to bedding for tens of metres (type 1). A few critical exposures contain sheets of native copper that follow bedding planes, then wrap into thrust-fault planes, and reemerge from the thrusts to follow bedding at a different level. The offset of bedding consistently *exceeds* the offset of sheets, indicating that thrusting both preceded and postdated formation of sheet copper (Fig. 3A). Our interpretation of these field relations is that sheet copper formed after thrusting began, but continued to form during thrusting. When traced out to terminations, copper sheets pass to bedding-plane–parallel veins of chalcocite (type 2), indicating that thrusts acted as conduits for mineralizing fluids with relatively high f_{O_2} and low f_{S_2}.

In most places, strata near the top of the lower Nonesuch Formation are unmineralized or only weakly mineralized. However, adjacent to tear and thrust faults, these strata commonly contain bedding-parallel veins and stockwork veins of chalcocite (types 2 and 3; Fig. 3B). The abundance and thickness of chalcocite veins diminishes away from compressional faults, indicating that these faults acted as conduits for cupriferous fluids. Adjacent to these bedding-plane–parallel veins, copper sulfides have locally replaced disseminated pyrite in the wall rock.

Unlike the preceding types of second-stage copper, there are no mesoscopic or microscopic structural fabrics directly linking disseminated native copper in the uppermost Copper Harbor Conglomerate (type 4) with thrusting (Brady, 1960; Hamilton, 1967; Kelly and Nishioka, 1985). However, economic concentrations of disseminated copper in the uppermost Copper Harbor Conglomerate occur only in the southwestern domain of the mine and immediately adjacent to the White Pine fault in the northeastern domain; individual occurrences are spatially associated with thrust faults or tear faults. We therefore hypothesize that this type of copper was also related to compressional faulting. Copper grades in areas with second-stage mineralization are typically 20%–30% higher than in areas with only main-stage mineralization, indicating that second-stage mineralization represents additional copper brought into the region, rather than remobilized copper from main-stage ore.



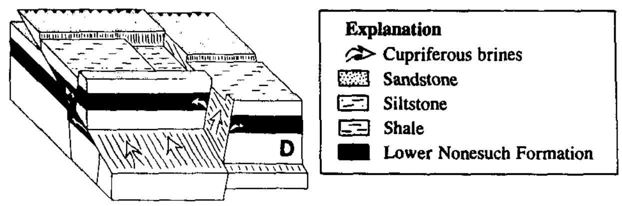


Figure 4. Schematic block diagrams illustrating geologic history of White Pine part of Midcontinent rift. A: Sedimentation and syndepositional faulting. B: Main-stage sediment-hosted stratiform copper mineralization. C: High-angle faulting. D: Thrusting accompanied by second-stage mineralization.

CONCLUSIONS

The White Pine part of the Midcontinent rift contains evidence for a close relation between deformation and copper mineralization. The earliest event in this part of the rift was sedimentation and syndepositional faulting (Fig. 4A). Subsequently, main-stage sediment-hosted stratiform copper mineralization occurred at White Pine and in the Presque Isle syncline (Fig. 4B). Mineralizing fluids probably flowed through the red beds of the Copper Harbor Conglomerate, and their entrance into the reduced host rocks of the lower Nonesuch Formation was facilitated by synsedimentary faults and sedimentary structures that provided cross-stratal permeability. Once these solutions had entered the Nonesuch Formation, flow was most likely parallel to bedding and concentrated along more permeable sandstone and siltstone horizons within the lower Nonesuch Formation. We speculate that these early-stage, copper-bearing solutions may have been expelled by compaction and diagenesis of sediments in axial parts of the rift, and migrated updip through the Copper Harbor Conglomerate to produce the early stratiform mineralization in the base of the Nonesuch

Formation at White Pine. High-angle faults cut the sediments and main-stage ore, but at this time influx of mineralizing fluids was either nonexistent or trivial, because there is no evidence of copper enrichment adjacent to these structures (Fig. 4C). However, thrusting associated with the closing of the rift expelled additional fluids from the axis of the rift, including cupriferous brines (Fig. 4D). These cupriferous fluids formed the second-stage copper mineralization at White Pine that postdates main-stage copper mineralization.

Although our study has been confined to the White Pine district, the results may clarify certain long-standing, enigmatic relations between mineralization in this district and that of the well-known Keweenaw native copper district about 100 km to the northeast in the Keweenaw Peninsula. White (1968, p. 313) concluded that copper mineralization in the Keweenaw native copper district was "contemporaneous with or later than much or most of the deformation." Second-stage copper mineralization described herein may correlate with this syntectonic to posttectonic mineralization in the Keweenaw district, and thus the two districts may have undergone mineralization during the same compressional stage of rift evolution. Although the main part of the Keweenaw native copper district is 100 km northeast of White Pine, scattered occurrences exist along trend toward White Pine and also in the Porcupine Mountains to the northwest of White Pine, demonstrating spatial overlap of the two mineralized systems. Thus, the Proterozoic Midcontinent rift is similar to other tectonic settings in that it expelled metalliferous fluids during regional deformation.

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Reviewers' comments

White Pine is a major copper ore body whose origin has been debated for many years. This paper helps place the mineralization in the context of regional native copper mineralization.

William Cannon

This is a good example of how fluids migrate out of basins during deformation.

Charles Foster