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The Copper Harbor Conglomerate: A late Precambrian fining-upward alluvial fan sequence in northern Michigan

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ABSTRACT

The Keweenawan Copper Harbor Conglomerate, exposed in northern Michigan, is part of a thick succession of volcanics and terrigenous clastics deposited in the Keweenawan Trough, a failed intracontinental rift. It is a fining-upward wedge of volcanogenic conglomerate and sandstone deposited as proximal to distal braided-stream and sheet-flood facies on coalesced alluvial fans and sand flats. This unit, along with the lower portion of the overlying Nonesuch Shale, consists of an alluvial fan–shallow lake sequence that filled the rift during and following volcanic activity. The fining-upward nature of the sequence reflects a waning sediment supply probably due to lowering of the source area following faulting.

The Copper Harbor Conglomerate exhibits attributes of both arid-fan and humid-fan alluvial models. Coarse-grained facies are lithologically similar to alluvial-fan units deposited in modern humid regions. Conversely, finer distal Copper Harbor facies exhibit numerous features indicating flashy discharges and desiccation, processes typical of deposition in modern arid regions. Ambiguity of sedimentary features useful for climatic inference probably reflects the limited applicability of Holocene models to more ancient alluvial sequences, because Precambrian hydraulic regimes developed under various climatic settings may have differed from their Holocene counterparts.

INTRODUCTION

The earliest stage in the opening of an ocean basin is intracontinental rifting, commonly characterized by extensional faulting, volcanism, and the deposition of clastic sequences, often including red beds (Dickinson, 1974). Modern settings thought to be in this stage of tectonic evolution include the East African rift and the Baikal rift (Mitchell and Reading, 1978). Ancient sedimentary successions related to intracontinental rifting include Triassic-Jurassic deposits in basins along the eastern margin of the United States (Van Houten, 1977), the late Precambrian Mount Rogers and Mechum River Formations of the Appalachians (Schwab, 1974, 1976), and the late Precambrian sparagmite sequence of Norway (Bjorlykke and others, 1976). Ancient rifts that failed during the intracontinental stage include the Paleozoic Southern Oklahoma Aulacogen (Hoffman and others, 1974), the Proterozoic Athapuscow Aulacogen of the Slave Province of Canada (Hoffman and others, 1974), and the late Precambrian Keweenawan Trough of the Lake Superior region (Chase and Gilmer, 1973).

This paper describes sedimentary fill in one of the failed rifts, the Keweenawan Trough. Attention is focused on the sedimentology of the basal clastic unit, the Copper Harbor Conglomerate, with particular emphasis on problems encountered when attempting to make detailed paleoclimatologic interpretations.

GENERAL SETTING

The Copper Harbor Conglomerate is part of an approximately 1-b.y.-old sequence that fills the Keweenawan Trough in the Lake Superior region of North America (Fig. 1). This trough coincides with the mid-continent gravity high, a belt of linear positive gravity anomalies extending from the Great Lakes region into Kansas. In the Lake Superior region, the anomaly occurs over basaltic lavas and intrusive gabbros of Keweenawan age, which are thought to have formed during a late Precambrian period of continental rifting that failed during an early stage of development (Chase and Gilmer, 1973).

The rift-fill sequence is well exposed on the Keweenaw Peninsula of Michigan and in northern Wisconsin, both of which are on the southeastern limb of the Keweenawan Trough, and on Isle Royale, which is on the northwestern limb (Fig. 1). Along much of the Keweenaw Peninsula, the sequence begins with the Portage Lake Lava Series, a unit of mafic volcanics and subordinate clastics. This unit is overlain by the Copper Harbor Conglomerate, which is composed of conglomerate and sandstone with subordinate volcanics (Halls, 1966; White and Wright, 1960). The Copper Harbor Conglomerate is conformably overlain by, and locally interfingers with, black to green silts and shales of the Nonesuch Shale, which is in turn overlain by red sandstones and shales of the Freda Sandstone (Fig. 2). On the Keweenaw Peninsula, the rift sequence dips to the northwest and is separated from the younger Jacobsville Sandstone by a high-angle reverse thrust, the Keweenaw Fault (Halls, 1966). Although there is no definite evidence for extensional tectonism in the outcrop area, as indicated in the rift model (Fig. 2), an equivalent succession to the southwest in the subsurface of Minnesota is characterized by horst and graben structures (Morey, 1974).

Sedimentologic-stratigraphic aspects of the Copper Harbor Conglomerate were described by White and Wright (1960), Hamblin and Horner (1961), and Wolf and Huber (1973). These and other studies have provided information on the thickness, general lithology, sedimentary structures, paleocurrent directions, petrology, and depositional environment of the unit, which has been interpreted as a piedmont deposit that filled the rift from both basin margins (White and Wright, 1960; Hamblin and Horner, 1961).

SEDIMENTOLOGY OF THE COPPER HARBOR CONGLOMERATE

On the Keweenaw Peninsula, the Copper Harbor Conglomerate is a basinward-thickening, fining-upward wedge of red, volcanogenic conglomerate and sandstone that varies in thickness and lithology (White and Wright, 1960). The thickness ranges from 200 m to ~2,000 m (White and Wright, 1960). The Copper Harbor Conglomerate is composed of

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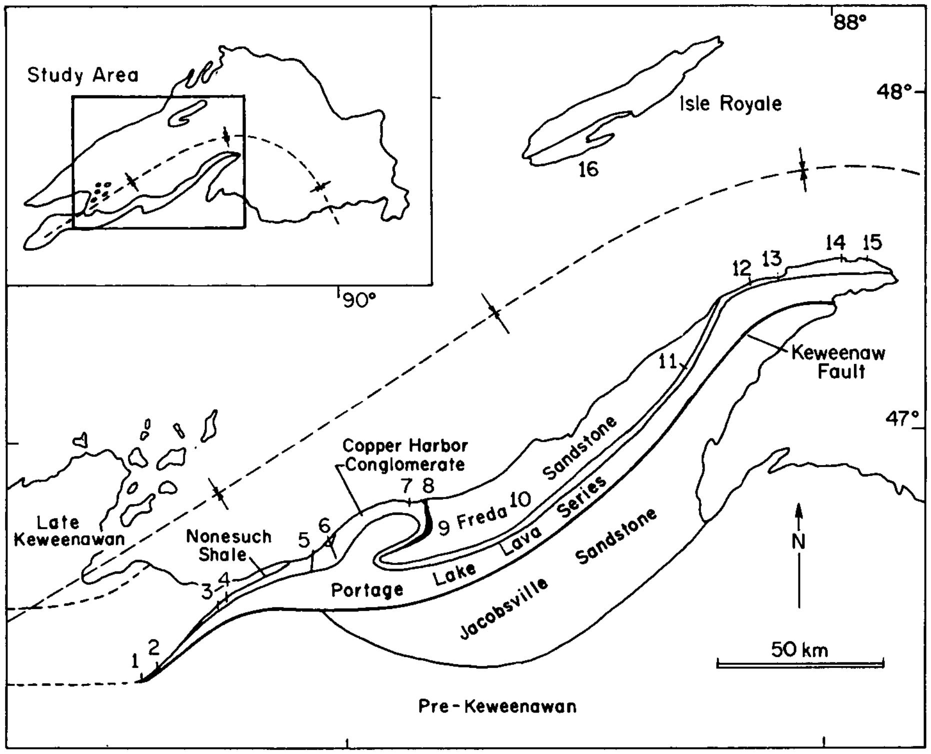


Figure 1. Index map of Lake Superior and geologic map of the study area. Numbers and bars refer to the major section locations. Axis of Keweenawan Trough is shown on both maps.

four major facies: conglomerate, conglomerate-sandstone, trough–cross-stratified sandstone, and rippled sandstone. In areas where the Copper Harbor Conglomerate is thickest, they occur in a general fining-upward sequence. These facies, with some minor modifications, make up the Copper Harbor Conglomerate all along the outcrop belt and on Isle Royale. A regular fining-upward trend, however, is not as well developed in all areas. In the southwest, the Copper Harbor Conglomerate is composed entirely of conglomerate, whereas to the northeast, exposures are not adequate to identify vertical grain-size trends. In addition, cryptalgal carbonates are interbedded with the clastic facies in the northeastern part of the Keweenaw Peninsula.

Conglomerate Facies

This facies directly overlies, and locally interfingers with, the volcanics of the Portage Lake Lava Series. It consists of well-rounded, poorly sorted, cobble to boulder conglomerate, exhibiting crude horizontal stratification, with interbedded thin lenticular sandstone (Figs. 3A, 4A). Rhyolitic volcanic rock fragments are the predominant clast type (White and Wright, 1960). The conglomerate units are laterally continuous for hundreds of metres in outcrop, but they are composed of discontinuous beds that are usually lenticular and less than 1 m thick. Most beds are clast-supported, although a few consist of cobbles and boulders in a medium sand matrix. These matrix-supported beds have nonerosional basal contacts, whereas clast-supported beds display irregular erosional contacts with underlying units. Grading in conglomerate beds is uncommon, although some clast-supported conglomerates exhibit a crude fining-upward trend. The clast-supported beds generally have a sand matrix, although the interstices between the clasts in some beds are unfilled or are filled by late diagenetic calcite and laumontite cement. Clasts within this facies are usually imbricated, with flattened pebbles and cobbles dipping to the southwest (Fig. 3A). This indicates that currents were flowing basinward to the northwest (Rust, 1972; Walker, 1975) (Fig. 3A).

Sandstone interbeds are typically 5 to 10 cm thick, are gradational with underlying gravels, and have sharp erosional tops. They exhibit either trough, ripple, or horizontal stratification, as well as mud drapes and mud cracks. The sandstones are primarily volcanic arenites or sublitharenites (Folk, 1974).

The conglomerate facies is similar to coarse-grained deposits in modern braided streams (Williams and Rust, 1969; Gustavson, 1974) and to ancient sequences interpreted as braided-stream deposits (Miall, 1977, 1978). The crude horizontal stratification, imbrication, erosional bases, and intercalated sandstone in the clast-supported conglomerate suggest deposition by fluvial processes on longitudinal bars (Gustavson, 1974; Boothroyd and Ashley, 1975; Miall, 1977). The alternation of beds with unfilled interstices between clasts and sediment-filled interstices records fluctuations in discharge; beds in the former were deposited during high discharge, when fine grains were in suspension, whereas the latter beds formed during lower discharge, when the fines were deposited with, or soon after, the gravel (Smith, 1974). Intercalated sandstone represents the filling of channels or the migration of sand bed forms over bars during waning flow (Boothroyd and Ashley, 1975; Miall, 1977).

The origin of matrix-supported beds is more problematic. The open framework and nonerosive bases of these rare beds suggest emplace-

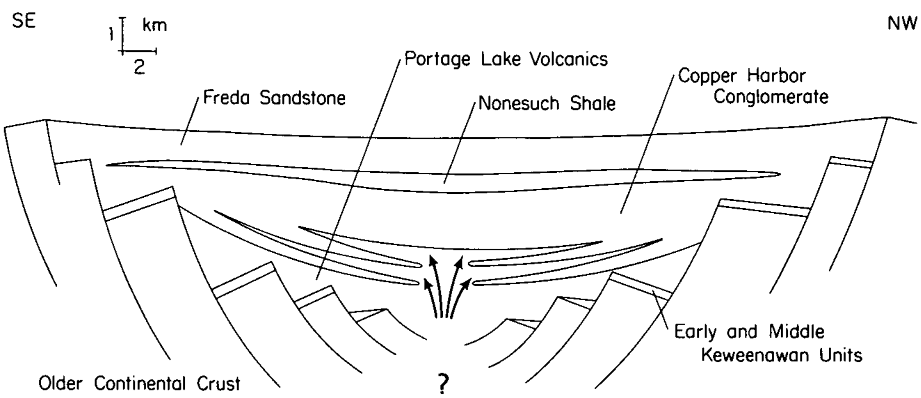


Figure 2. Tectonic model for the Keweenawan Trough during deposition of the Freda Sandstone. Cross section is schematic and could represent any section across the basin. Arrows denote the source of the volcanics in the center of the basin. Modified from Fowler and Kuenzi (1978).

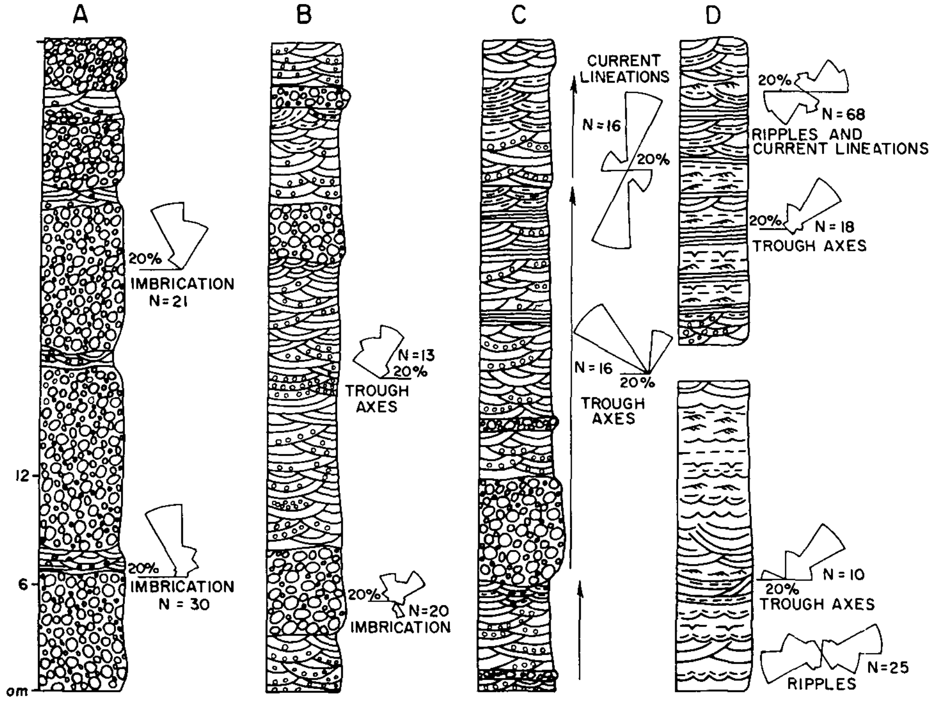
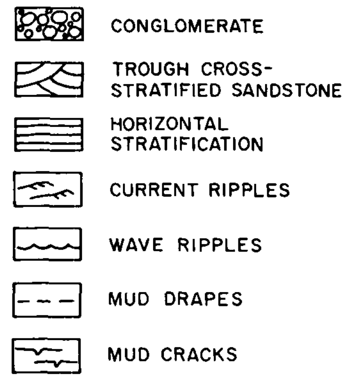


Figure 3. Representative sections from the Copper Harbor Conglomerate facies with rose diagrams of current directions. The rose diagrams correspond to the adjacent section to the left, and measurements were taken from the adjacent unit. Conglomerate clasts are not to scale. A. Conglomerate facies (sec. 5). B. Conglomerate-sandstone facies (sec. 5). C. Trough-cross-stratified sandstone facies (sec. 5). Arrows refer to crude fining-upward cycles. D. Rippled-sandstone facies (sec. 7; lower column, sec. 6).



ment by gravity processes, although sand is uncommon in modern debris-flow deposits that have a mud matrix (Bull, 1972; Walker, 1975). Sand-supported conglomerate beds like those in the Copper Harbor Conglomerate were called "debris flood" deposits by Miall (1970), but Eriksson (1978) preferred the term "mass flow" because it implies no specific support mechanism during transport. Sand-supported conglomerate beds in the Copper Harbor Conglomerate probably were deposited as mass flows or sediment gravity flows during large floods. Subsequent reworking by braided-stream processes may account for the paucity of mass-flow deposits in the Copper Harbor Conglomerate.

Conglomerate-Sandstone Facies

The amount of sandstone gradually increases vertically within the Copper Harbor Conglomerate, whereas conglomerate gradually decreases, resulting in a second facies, conglomerate-sandstone. It is composed of two end members, conglomerate similar to that described above but thinner, and pebbly trough–cross-stratified medium to coarse sandstone (Figs. 3B, 4B, 4C). The two rock types are gradational, with the conglomerate grading through trough–cross-stratified gravel into the pebbly trough–cross-stratified sandstone. The trough–cross-stratified sandstone generally occurs as multiple sets of troughs ~5 m thick, with individual troughs typically 30 to 70 cm thick. Troughs have widths of as much as 3 m and lengths of as much as 5 m. Gravel stringers, as well as isolated pebbles, cobbles, and, sporadically, boulders, occur within these sets. Ripple–cross-stratified sandstone and thin, discontinuous mud drapes that are often mud-cracked are common in this facies. Current directions, determined from trough axes and imbricated pebbles, indicate that sediment was transported into the center of the basin (Fig. 3B), a direction consistent with the results of earlier paleocurrent studies (White and Wright, 1960; Hamblin and Horner, 1961). Reddish-brown sandstone in this facies and in overlying facies varies in composition from volcanic arenite to sublitharenite.

This facies is also similar to alluvium in modern braided streams and to other ancient units interpreted as braided-stream deposits. The conglomerate beds are interpreted as the erosional remnants of longitudinal bars. Trough–cross-stratified sandstone suggests deposition as migrating dunes in channels, probably during waning flow (Miall, 1977). Cross-stratified conglomerate may have been the result of lateral outbuilding from longitudinal bars into adjacent channels (Rust, 1979).

Trough–Cross-Stratified Sandstone Facies

Higher in the Copper Harbor Conglomerate there is found less conglomerate and an increase in the proportion of sandstone. Trough–cross-stratified sandstone, generally without pebbles, is the major lithology in this facies (Figs. 3C, 4D). Pebbly trough–cross-stratified sandstone, like that in the conglomerate-sandstone facies, grades into smaller-scale trough–cross-stratified sandstone without pebbles. Other abundant lithologies include current-rippled sandstone and horizontally laminated sandstone with parting lineation (Fig. 3C). Planar cross-beds are rare. Conglomerate beds are less than 5 m thick and display sharp irregular basal contacts. Beds with high concentrations of heavy mineral laminations are found locally within this facies.

All of the sandstones within this facies are associated with mud-cracked mud drapes (Fig. 5A) and mud intraclasts. Some of these occur in repetitive cycles 5 to 10 cm thick, with a complete sequence being composed of horizontally laminated sandstone, rippled sandstone, and a desiccation-cracked mud drape (Fig. 5A). Mud intraclasts are found lateral to mud drapes on the same bedding plane. These sequences commonly occur within one trough–cross-bedded set and may dominate entire outcrops.

There are also crude 5- to 10-m-thick cycles that fine upward from conglomerate to pebbly trough–cross-stratified sandstone, to trough–cross-stratified sandstone without pebbles, horizontally laminated sandstone, and rippled sandstone with abundant mud drapes, mud intraclasts, and mud cracks (Fig. 3C). Similar sequences with mudstone have been reported from the Solor Church Formation, an equivalent to the Copper Harbor Conglomerate in

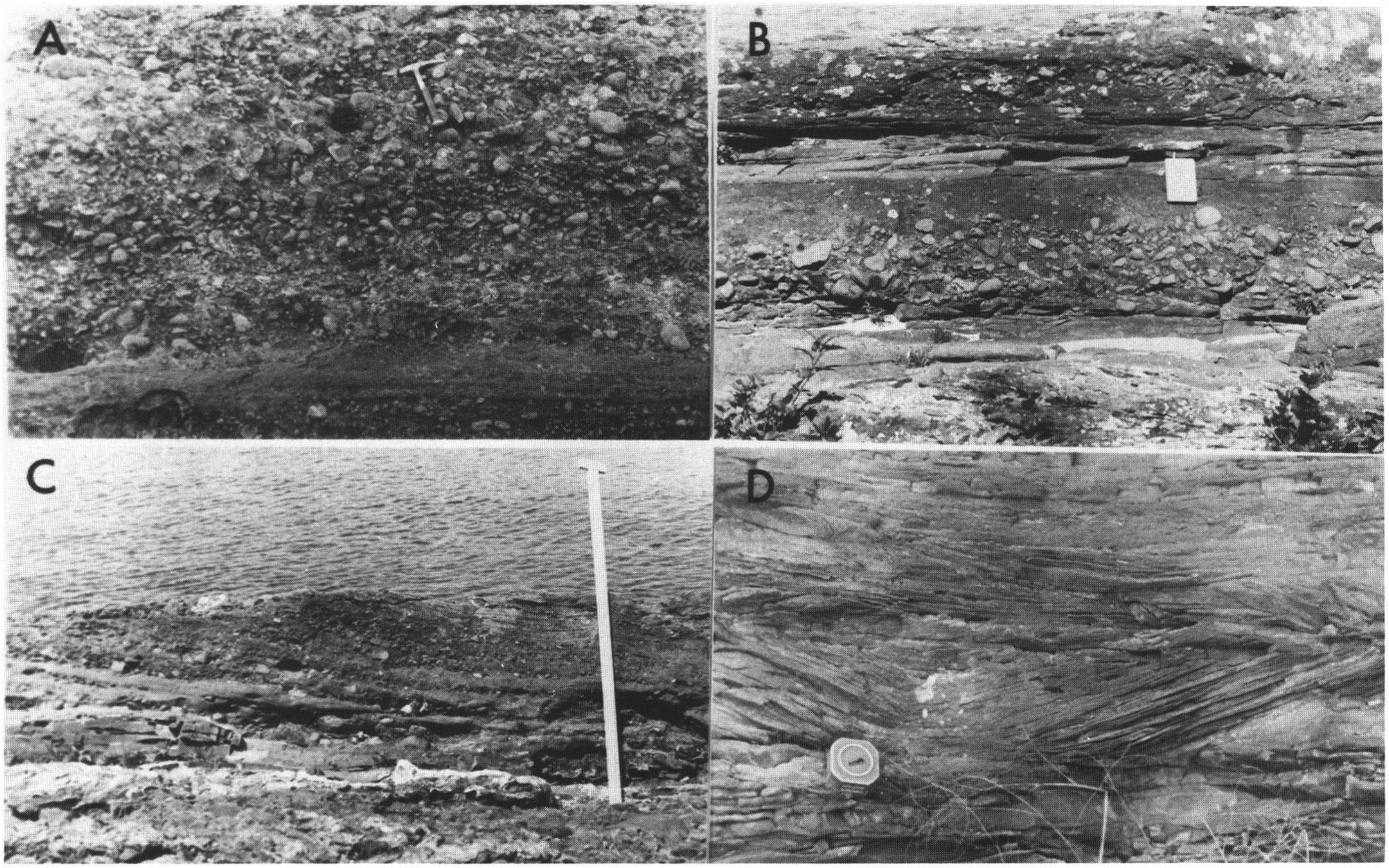


Figure 4. Copper Harbor Conglomerate facies. A. Conglomerate facies. 5 m of clast-supported cobble gravel overlying 50 cm of medium sandstone. This facies occurs at the base of the Copper Harbor Conglomerate throughout much of the study area. B. Conglomerate-sandstone facies. Cobble gravel grading upward into medium sandstone. Field book is 10 cm long. C. Conglomerate-sandstone facies. 1 m of trough–cross-stratified gravel overlying a 20-cm stromatolite horizon. White cobbles in upper conglomerate are coated by stromatolite. Jacob's staff is 1.5 m long. D. Trough–cross-stratified sandstone facies. Trough–cross-stratified medium to fine sandstone.

Minnesota (Morey, 1974). Current directions determined from a variety of structures in this facies also indicate flow into the center of the basin (Fig. 3C).

The discontinuous and thin nature of most conglomerate beds in this facies, as well as their erosive basal contacts, suggests they are channel lags formed during waning flow. The thicker and more continuous beds, however, suggest deposition on small longitudinal bars. Trough–cross-stratified sandstone was deposited by migrating dunes, whereas the small-scale cross-stratification resulted from migration of ripples on dunes during waning flow. The horizontally laminated sandstone records deposition during upper-flow regime, probably as a result of rapid lowering of water level during flood stages (Boothroyd and Ashley, 1975). Mud drapes resulted from the settling of fine material in pools after flood waters receded (Miall, 1977), or from percolation of water into porous sediment during low-flow stages. Mud cracks resulted from desiccation of such mud drapes, and mud intraclasts formed when mud flakes were transported by water and/or wind.

Thin sequences with desiccation-cracked mud drapes overlying sandstone resulted from waning flow during individual floods. They are common in modern ephemeral streams (Karcz, 1972) and are considered characteristic of such systems (Glennie, 1970). Although no unequivocally eolian sandstones were identified, the presence of well-rounded and sorted sands, large-scale cross-bedding, and abundant desiccation features suggests some eolian contribution, which is also characteristic of ephemeral streams (Glennie, 1970; Picard and High, 1973). Crude large cycles fining from conglomerate and cross-bedded sandstone to units with abundant desiccation features are interpreted as shallowing sequences that formed during the abandonment of depositional lobes or channeled complexes, possibly because of channel migration during avulsion (Miall, 1977).

Rippled Sandstone Facies

This is the finest-grained facies in the Copper Harbor Conglomerate and consists predominantly of reddish-brown rippled, trough–cross-stratified, and horizontally laminated fine to medium sandstone with ubiquitous mud drapes, mud intraclasts, and mud cracks (Fig. 3D). Beds of mudstone greater than 1 cm do occur, but they are rare. This facies generally corresponds to the "red facies" of White and Wright (1960). Ripples are the most common structures; both current and wave types are present, as well as interference ripple patterns (Fig. 5B). Trough–cross-stratified sandstone occurs as single troughs or as multiple sets 5 to 10 m thick. Horizontally laminated sandstone with parting lineation typically occurs in beds less than 1 m thick. Conglomerate beds are rare, have erosional bases, and are less than 1 m thick. Thin, 5- to 10-cm sequences similar to those in the trough–cross-stratified sandstone facies are also

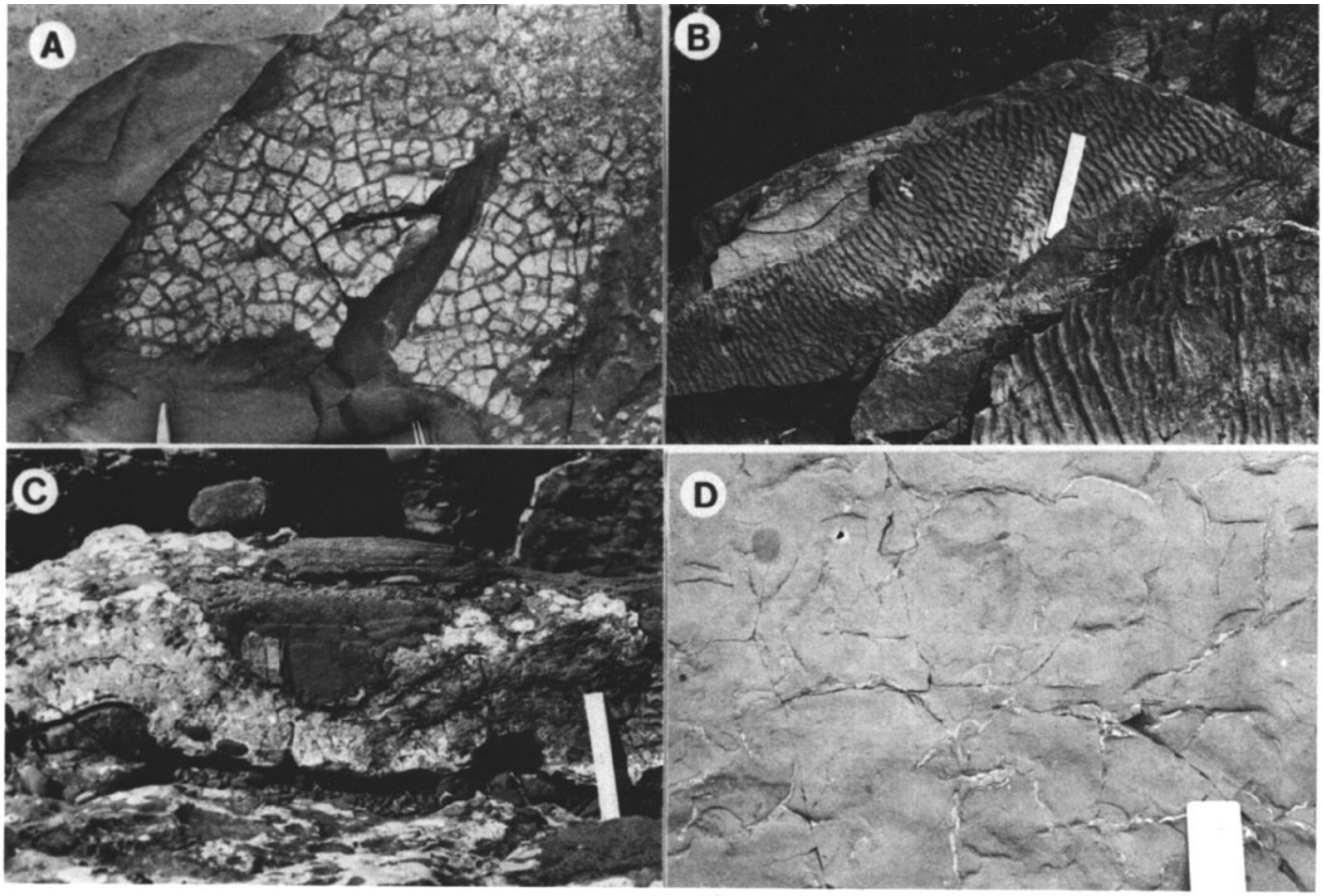


Figure 5. Sedimentary structures in the Copper Harbor Conglomerate. A. Mud-cracked mud drape overlying sandstone from the trough–cross-stratified sandstone facies. White material is a bleached mud drape. B. Interference wave ripples from the rippled sandstone facies. Ruler is 15 cm long. C. Stromatolite hemispheroids interbedded with clastic lithologies. D. Carbonate-filled shrinkage cracks found associated with the stromatolite.

present. Current directions determined from ripple crests and trough axes indicate flow into the basin, although, locally, current directions exhibit wide dispersion (Fig. 3D).

The predominance of rippled and horizontally laminated sandstone, as well as abundant mud drapes, suggests that most deposition resulted from waning sheet floods. The horizontally laminated sandstone with parting lineation was deposited during flood stage, whereas current-rippled sandstone and trough–cross-stratified sandstone were deposited during waning flow. The thicker trough–cross-stratified units may be channel deposits or possibly thick sheet-flood deposits. That water was ponded at times is indicated by abundant wave ripples and mud drapes. Channels were rare and, where present, were probably very shallow. The lithology of this facies is similar to that of modern sandy aprons at the toes of some modern arid alluvial fans, which were called sand flats by Hardie and others (1978).

Cryptalgal Carbonates

In the northeastern part of the Keweenaw Peninsula, the conglomerate-sandstone and the trough–cross-stratified sandstone facies merge and are interbedded with laminated cryptalgal carbonate (sections 14–15 in Fig. 1). The stromatolites occur as laterally linked drapes over cobbles (Figs. 4C, 5C), as laterally linked contorted beds in reddish-brown mudstone-siltstone, as oncoids, and as poorly developed mats in coarse sandstone. Reworked carbonate-coated cobbles and boulders also occur in the conglomerate (Fig. 4C). The stromatolites are interbedded with oolite, pisolite, and intraclastic carbonate. Calcite pseudomorphs after gypsum are also found associated with the stromatolites.

In addition, a variety of calcite-filled shrinkage cracks is found in the mudstones and siltstones associated with the stromatolites (Fig. 5D). These include cracks with a polygonal pattern, incomplete cracks with triple junctions, and spindle-shaped cracks.

DISCUSSION

Depositional Model

Coarse braided-stream deposits similar to those inferred for the Copper Harbor Conglomerate are most commonly found on, or associated with, modern alluvial fans (Bull, 1972; Boothroyd and Nummedal, 1978). Exposures of the Copper Harbor Conglomerate are not adequate, however, to identify radial paleocurrent patterns, which would indicate fan morphologies. The coarse gravels in the lower Copper

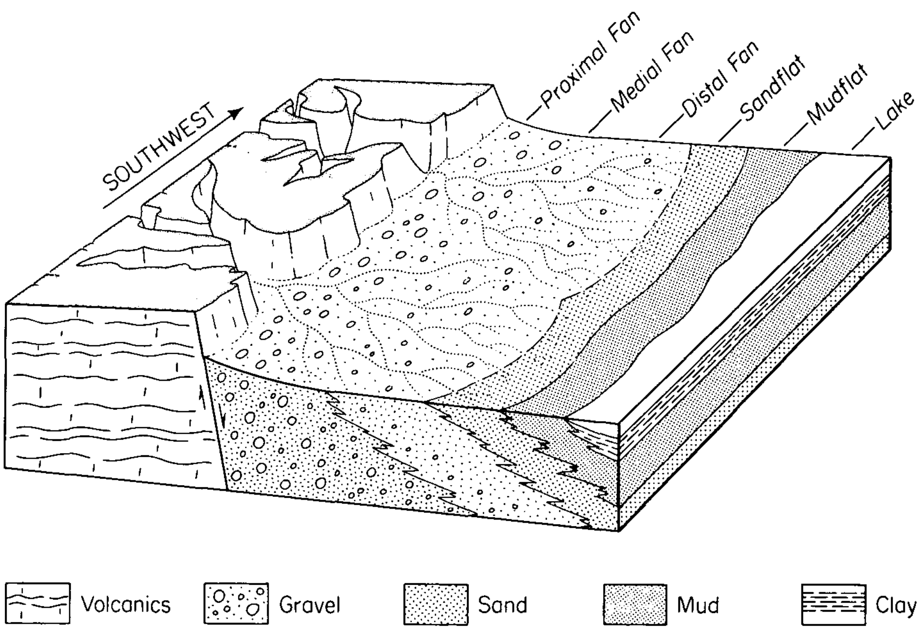


Figure 6. Depositional model for the Copper Harbor Conglomerate and the lower Nonesuch Shale. Proximal, medial, distal, and sand-flat settings correspond to the Copper Harbor Conglomerate. The mud-flat and perennial-lake settings correspond to the lower one-half of the Nonesuch Shale.

Harbor Conglomerate suggest deposition on the proximal parts of alluvial fans. The predominance of braided-stream facies and their thickness, lateral extent, and facies successions in the remainder of the Copper Harbor Conglomerate indicate that the facies coalesced to form a horizontal alluvial plain or braid plain (Fig. 6). The setting was probably similar to, but on a smaller scale than, large fans that spread onto the Indogangetic plains (Gole and Chitale, 1966; Parkash and others, 1980), with fans and braid plains extending from both margins toward the basin center.

The plain graded basinward into a sand-flat environment represented by the rippled sandstone facies, which in turn graded into a mud flat and lake represented by lower units of the Nonesuch Shale (Fig. 6). Lower Nonesuch units have many similarities with modern playa mud flats (Hardie and others, 1978) and other ancient units interpreted as playa mud flats (Eugster and Hardie, 1975).

The Copper Harbor Conglomerate and lower Nonesuch Shale constitute a fining-upward alluvial fan–lake sequence (Fig. 6). Similar ancient sequences have been interpreted as resulting from waning sediment supply due to erosion of the source area, usually following faulting along the basin margin (Bluck, 1967; Deegan, 1973; Steel and Wilson, 1975; Heward, 1978). Some of these examples are actually composed of thin fining- and coarsening-upward sequences, which have been interpreted as resulting from cyclic fan processes, such as lateral migration and abandonment of channels (Miall, 1977; Heward, 1978), or from fan progradation due to repeated basin-margin faulting and source-area rejuvenation (Steel and others, 1977; Heward, 1978).

Waning sediment supply due to a lowering of the source area following faulting, with marginward spread of the central basin-lake facies, is a reasonable interpretation for the fining-upward Copper Harbor Conglomerate–Nonesuch Shale succession, although no basin-margin faults are exposed (White, 1966). The lack of well-defined cyclic sequences argues against repeated fault activity in the source area and indicates that deposition took place during a period of relative tectonic quiescence. High regional subsidence rates relative to sedimentation rates in the basin also may have contributed to the fining-upward trend. Initial subsidence may have been caused by thermal decay of thin crust following failure of the rift (Dickinson, 1974), with further isostatic subsidence caused by sediment loading.

Comparison with Other Deposits

Study of modern alluvial fans has documented a spectrum of fan types that range from "dry" fans formed by ephemeral stream and debris-flow processes in arid climates, to "wet" fans formed by perennial-stream processes in humid climates (Schumm, 1977; Boothroyd and Nummedal, 1978). The vertical facies succession of the Copper Harbor Conglomerate is similar to the downstream facies changes documented on modern proglacial braided outwash rivers, which serve as a model for alluvial-fan deposition in humid climates (Boothroyd and Nummedal, 1978). Where these perennial rivers are unconfined by valley walls, they form outwash fans as much as 30 km in length. Proximal-fan areas are dominated by longitudinal bars with crudely stratified and imbricated gravels that grade downstream into dunes with cross-bedded sands (Boothroyd and Ashley, 1975; Boothroyd and Nummedal, 1978). The Kosi River Fan of the Himalayan foothills is another example of a humid fan dominated by braided-stream deposits (Gole and Chitale, 1966). Ancient braided-stream deposits with facies associations similar to those of the humid-fan model include the Moodies Group (Eriksson, 1978) and the Witwatersrand sequence (Vos, 1975) in South Africa, and the Van Horn Sandstone in Texas (McGowen and Groat, 1971).

If the humid-fan models were applied to the Copper Harbor Conglomerate, the conglomerate facies would correspond to the proximal-fan setting, the conglomerate-sandstone facies to the mid-fan setting, and the trough–cross-stratified sandstone facies to the distal fan. The rippled sandstone facies has no direct analogue in modern humid fans, although some of the stratification is similar to that in wind-tidal flat environments at the distal ends of some outwash fans (Boothroyd and Nummedal, 1978).

There are, however, some major differences between deposits of humid fans and the Copper Harbor Conglomerate. Trough–cross-bedding, for example, predominates in the Copper Harbor Conglomerate, but in glacial outwash fans both trough and planar types are common. Another major difference is the abundance of mud drapes, mud intraclasts, and desiccation features in the Copper Harbor Conglomerate. Although these features are found in outwash fans (Miall, 1977), they are more abundant in the Copper Harbor Conglomerate and are a common characteristic of modern ephemeral streams in arid regions (Glennie, 1970; Karcz, 1972).

Modern arid fans are best known from the mountainous semiarid regions of the southwestern United States (Bull, 1972). These consist of cone-shaped accumulations of coarse-grained sediment, typically dissected by radial networks of ephemeral streams that become shallower and less distinct toward the fan toe. Four major types of deposits are found on these fans: (1) shallow braided-channel or sheet-flood deposits, (2) deeper channel deposits, (3) sieve deposits, and (4) debris-flow deposits. The deep-channel, sieve, and debris-flow deposits predominate at the fan apex, whereas shallow-channel and sheet-flood deposits predominate in the mid- and distal-fan areas. Some arid fans grade basinward into a sandy apron, or sand flat, where braid channels become less distinct and floodwaters spread as unchanneled sheet floods across a flat plain (Hardie and others, 1978). The sand flat in turn grades into a mud flat that grades into a saline lake (Hardie and others, 1978). Many ancient deposits have been interpreted in terms of the arid-fan model, including the Old Red Sandstone in Great Britain (Steel, 1974), the LaHood Formation of Montana (Boyce, 1975), and the cyclic deposits of the Hornelen Basin of Norway (Steel and others, 1977; Larsen and Steel, 1978). Other units, like the Eocene Green River Formation, contain alluvial fan, sand-flat, and lacustrine facies similar to the deposits in modern arid fan–lacustrine settings (Eugster and Hardie, 1975; Hardie and others, 1978).

The vertical facies succession in the Copper Harbor Conglomerate is also similar to facies tracts in modern arid fan–lake settings. Clast-supported beds within the conglomerate facies correspond to proximal channel deposits, whereas the rare matrix-supported beds correspond to debris-flow deposits. Lithologies of the conglomerate-sandstone and the trough–cross-stratified sandstone facies correspond to braid-channel and sheet-flood deposits of arid mid- to distal fans, and the rippled sandstone facies corresponds to sheet-flood and rippled sand-flat deposits. Overlying units of the Nonesuch Shale correspond to distal mud-flat and perennial-lake deposits.

Paleoclimatology

An implication of humid-fan and arid-fan models is that ancient fan deposits might provide information on past climates. Examples of ancient deposits for which humid climates have been inferred include the Van Horn Sandstone (McGowen and Groat, 1971), the Witwatersrand sequence (Vos, 1975), and the Moodies Group (Eriksson, 1978). Ancient deposits for which an arid climate has been inferred include the LaHood Formation in Montana (Boyce, 1975) and a number of Devonian units (Bluck, 1967; Steel, 1974; Steel and Aasheim, 1978). An important question that has not been adequately evaluated, however, is whether or not the processes and resultant deposits in the two end-member fan types are sufficiently distinct that they can be differentiated in the rock record and therefore provide unambiguous paleoclimatologic as well as paleohydraulic information.

The crucial question for the Copper Harbor Conglomerate is whether perennial–humid-stream or ephemeral–arid-stream and debris-flow processes formed the deposit. The scale and abundance of braided-stream deposits suggest perennially flowing rivers and, therefore, a humid climate. The lack of argillaceous debris-flow deposits, considered characteristic of arid-type fans, although some do occur in humid climates (Curray, 1966), also argues against arid conditions. As previously mentioned, however, the rare sand-supported conglomerate could be the equivalent of modern debris-flow deposits. In addition, the abundance of mud drapes and mud intraclasts, as well as the thin waning-flow sequences, suggests deposition by ephemeral streams in an arid or semiarid setting. The presence of deposits similar to those forming modern sand flats also suggests an arid environment.

Although evidence for one particular fan model and inferences about paleoclimate are ambiguous in the context of Holocene systems, most features of the Copper Harbor Conglomerate record ephemeral-stream processes in an arid climate. This ambiguity is compounded, however, if viewed in the context of Precambrian hydrologic regimes. Due to a lack of land vegetation during the Precambrian, greater runoff and sediment yield would have resulted in a preponderance of bed-load rivers with flashy discharges in humid as well as in arid climates (Schumm, 1977). Such flashy discharges in humid climates might have resulted in deposits similar to those in arid climates today. There is, therefore, no compelling reason for equating the presence of features indicating flashy discharges in the Copper Harbor Conglomerate with arid conditions. In addition, some humid fans experience seasonal variations in climate. For example, the Kosi River Fan is in a monsoonal region, with both wet and dry seasons. If sedimentary features produced during the dry season were preserved in the rock record, the deposit might be interpreted as an arid-fan deposit. In summary, the ambiguity of sedimentary features useful for climatic inference probably reflects the limited applicability of Holocene models to pre-Devonian (pre–land-vegetation) alluvial sequences.

Despite the fact that the clastic facies of the Copper Harbor Conglomerate do not provide unambiguous climatic information, other evidence in the unit, such as carbonate-filled shrinkage cracks, the red coloration, and calcite pseudomorphs after gypsum, suggests an arid or semiarid climate. Although arid conditions probably occurred in the distal lake basin, conditions in the proximal source area may have been more humid, as is the case with some modern playa systems (Hardie and others, 1978). Alternatively, conditions may have been variable, with both a wet and a dry season, similar to those found in areas of monsoonal circulation today.

CONCLUSIONS

1. The Copper Harbor Conglomerate and Nonesuch Shale were deposited in the Keweenawan Trough, an intracontinental rift that failed during an early stage of development. These clastic units constitute a fining-upward sequence that filled the basin following volcanic activity.

2. The Copper Harbor Conglomerate is a reddish-brown, fining-upward wedge of volcanogenic conglomerate and sandstone deposited as proximal to distal braided-stream and sheet-flood facies on large coalesced fans and lake-margin sand flats.

3. Although the Copper Harbor Conglomerate has similarities with both the perennial deposits of modern humid alluvial fans and the ephemeral deposits of modern arid alluvial fans, most features suggest deposition by ephemeral streams. In that Precambrian hydrologic regimes in humid climates probably were similar to those in arid climates today, there is no reason to equate ephemeral-stream deposits in the Copper Harbor Conglomerate with an arid climate. Other evidence in the sequence, however, does suggest at least seasonally arid or semiarid conditions in the depositional basin.

4. The ambiguity of sedimentary features in the Copper Harbor Conglomerate useful for climatic inference demonstrates the problems encountered when attempting to apply Holocene models to ancient alluvial sequences. These problems particularly apply to pre-Devonian alluvial sequences, because early Paleozoic and Precambrian hydraulic regimes developed under various climatic settings may have been little like their Holocene counterparts.

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