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Structural Evolution of a Grand Canyon Breccia Pipe: The Ridenour Copper-Vanadium-Uranium Mine, Hualapai Indian Reservation, Coconino County, Arizona

by

Earl R. Verbeek[1], Marilyn A. Grout[1], and Bradley S. Van Gosen[2]

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Hualapai Indian Tribe

[1]U.S. Geological Survey
Box 25046, MS 913
Denver Federal Center
Denver, CO 80225

[2]U.S. Geological Survey
Box 25046, MS 905
Denver Federal Center
Denver, CO 80225

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Earl R. Verbeek, Marilyn A. Grout, and Bradley S. Van Gosen
U.S. Geological Survey, M.S. 913, Denver Federal Center
Denver, CO 80225

ABSTRACT

The Ridenour Cu-V-U deposit, in western Coconino County, Arizona, was mined for copper intermittently from about 1887 to about 1916, and for uranium and vanadium in the early 1960's. The ore occurs within an arcuate belt of fractures in flat-lying beds of Permian sandstone along the periphery of a solution-collapse breccia pipe. The pipe formed by upward stoping into the Esplanade Sandstone, the host formation, from initial solution caverns of probable Late Mississippian age in the underlying Redwall Limestone. The time of stoping is not known with certainty, but U-Pb age determinations on ore from similar, nearby pipes show that the main phase of uranium mineralization occurred 200-220 Ma (Middle to Late Triassic). The ore is now oxidized, but studies in other pipes where the primary ore assemblage is better preserved show that copper was deposited mostly as sulfides and sulfosalts, and the uranium as uraninite. The original host minerals for vanadium in the Ridenour pipe are not yet known.

Strata bordering the Ridenour pipe are cut by a well-developed set of "ring fractures" that formed during stoping, and by five regional sets of joints. The ring fractures strike everywhere parallel to the pipe boundary, dip moderately away from it, and occupy a zone 40-130 ft (12-38 m) wide around the brecciated pipe core. These were the only fractures in existence at the time of mineralization. Permeability conduits during ore deposition, then, were limited to the breccia column of the pipe proper and to the open ring fractures surrounding it. Most ore from the Ridenour mine was produced from long, narrow stopes that followed dense vein arrays along the most heavily mineralized portions of the ring-fracture zone. The later joints contain only sparse films of secondary minerals, chiefly malachite and azurite, that formed upon late Cenozoic oxidation of the primary ore minerals and minor redistribution by ground water of metals derived from them.

INTRODUCTION

The Ridenour copper-vanadium-uranium deposit occurs within an arcuate belt of fractures bordering a partially eroded, solution-collapse breccia pipe on the Hualapai Indian Reservation in western Coconino County, Arizona. This pipe is one of hundreds of such features hosted by Paleozoic sedimentary rocks in the Grand Canyon region of the southwestern Colorado Plateau (fig. 1). The pipes initiated by local collapse of structurally unstable portions of large solution caverns within the underlying Mississippian Redwall Limestone, which, by the close of Mississippian time, had already been riddled by an extensive cave system (Billingsley, 1986). Continued collapse resulted in the upward propagation of nearly vertical, pipelike conduits clogged with collapse breccia derived from overlying strata. Locally the pipes penetrate the entire Paleozoic section above the Redwall and extend into the overlying Triassic Moenkopi and Chinle Formations (fig. 2), a vertical distance of 2,000 ft (600 m) or more. Some of the pipes and bordering country rock are conspicuously mineralized at the surface (Wenrich, 1985; Sutphin, 1986), and a few (nos. 2, 4, 5, 8, and 9 of fig. 1) were worked for copper before the turn of the century (Billingsley, 1974). All were small operations, and most were

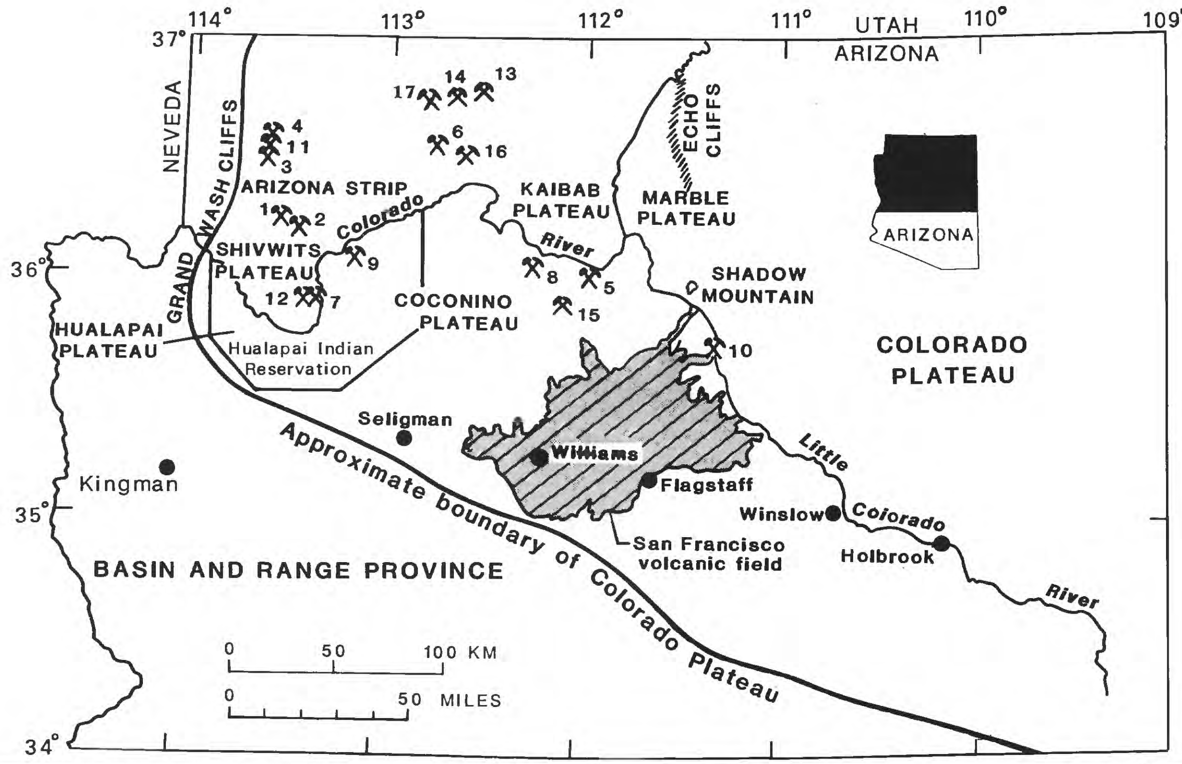


Figure 1. Index map of northern Arizona showing location of features discussed in text; modified from Wenrich (1985, 1986a). Numbered mines are as follows:

1 Copper House	6 Hack Canyon	11 Savanic	16 Pinenut
2 Copper Mountain	7 Old Bonnie	12 Snyder	17 Hermit
3 Cunningham	8 Orphan	13 Pigeon	
4 Grand Gulch	9 Ridenour	14 Kanab North	
5 Grandview	10 Riverview	15 Canyon	

soon abandoned. Interest in the Grand Canyon region was rekindled in the 1950's by the discovery of rich uranium ore in some pipes. Though the deposits generally were small and far from the nearest mill, and some were difficult to mine due to their location on sheer canyon walls, the abnormally high grade of their ores attracted sufficient attention that several mines were put into production. The most productive of these, the Orphan mine (pipe no. 8 on fig. 1), yielded 495,107 tons of uranium ore at an average grade of 0.43% U_3O_8, 6.68 million pounds of copper, 3,283 pounds of vanadium oxide, and 107,000 troy ounces of silver between 1956 and 1969 (Chenoweth, 1986).[1] During this period the number of known pipes was still small.

A third cycle of interest in breccia-pipe deposits of the Grand Canyon region began in the mid-1970's, when it became apparent that their numbers are far greater than previously thought (Wenrich-Verbeek and others, 1980). The number of suspected pipes on the Hualapai Reservation alone now stands at more than 900 (Wenrich, Billingsley, and Van Gosen, 1986), of which about 100 have been confirmed. Though only a fraction of

[1]The corresponding metric equivalents are 449,154 metric tons (U ore), 3.03 million kg (Cu), 1,489 kg (V_2O_5), and 3,328 kg (Ag).

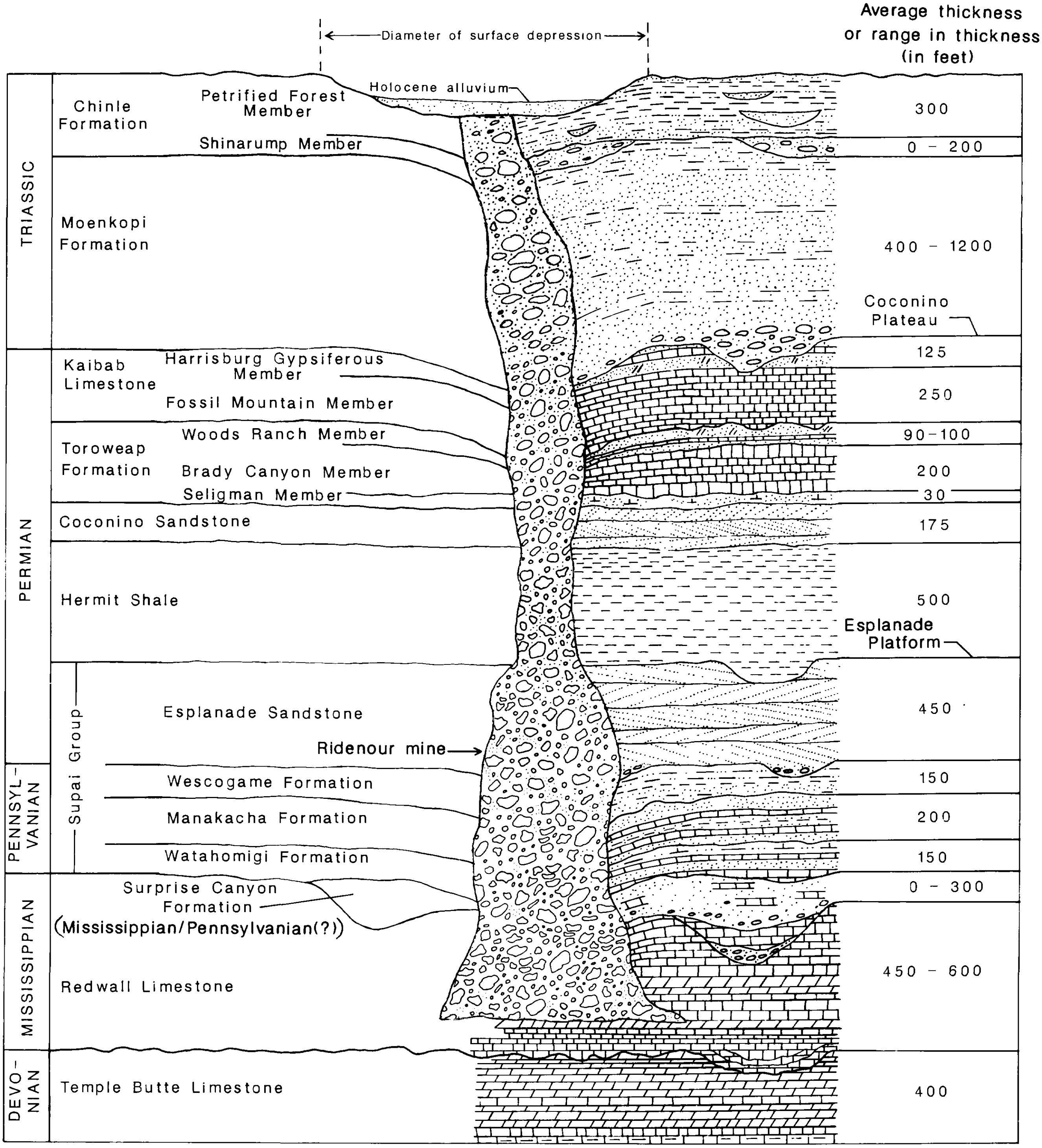


Figure 2. Generalized vertical section through a solution-collapse breccia pipe of the Grand Canyon region. Thicknesses of units shown are typical of those observed on the Hualapai lands.

these show surface indications of mineralization, the potential for extraordinarily high ore grades has encouraged continued exploration for new pipes and drilling of the most promising examples. In some pipes the ore averages 0.65% or more U_3O_8 (Mathisen, 1987) and is associated with potentially economic concentrations of Ag, Pb, Zn, Cu, Co, and Ni as byproducts (Wenrich and Silberman, 1984; Wenrich, Billingsley, and Van Gosen, 1986). By mid-1987, one company was already operating six breccia-pipe mines in the Grand Canyon region and had requested permits to open a seventh (Mathisen, 1987).

This report focuses on the structural evolution of a particularly well exposed, mineralized breccia pipe. Topics addressed include the development of the mineralized fracture zone peripheral to the pipe, the influence of pipe structure on alteration and mineralization, and the timing of pipe formation and ore deposition relative to faulting and jointing of the host rocks.

TERMINOLOGY

The literature on structural and economic geology is replete with multiple and often vague or curious definitions of the same term. Even such common terms as fault and joint seem to invite confusion, and thus some explanation of terminology used in this report is warranted. For the most part our usage conforms to that most commonly employed in recent literature on the Arizona breccia-pipe deposits.

Breccia pipe- One specific type of collapse feature (also defined below). Breccia pipes in the Grand Canyon region are roughly cylindrical, nearly vertical columns of broken rock, within which the clasts at any given level occur below their normal stratigraphic positions. Unlike breccia pipes from many other localities, the Grand Canyon examples are nonvolcanic and formed by progressive collapse of strata into solution caverns that formed in underlying carbonate rocks. The term as used in recent literature on the Grand Canyon area refers only to those breccia columns known or suspected to bottom in the Redwall Limestone, the principal cave-forming unit of the region.

Collapse feature, solution-collapse feature- Any feature formed by foundering of strata into an underlying opening created (for the Grand Canyon examples) by the removal in solution of carbonate rocks or gypsum. Included in this definition are such diverse features as (1) sinkholes in the Kaibab Limestone capping the Coconino and Marble Plateaus (Sutphin and Wenrich, 1988; Sutphin, 1986; Wenrich, Billingsley, and Huntoon, 1986), (2) structural basins formed by local dissolution of gypsiferous strata in the Toroweap Formation and Kaibab Limestone (Billingsley and others, 1986; Wenrich, Billingsley, and Huntoon, 1986), and (3) breccia pipes as defined above. The word collapse does not necessarily imply the sudden falling of rock into large subterranean voids; for some structures an origin by episodic subsidence into openings created gradually by solution seems more likely.

Fracture- a general term for any surface within a rock across which cohesion has been lost (or had been lost, if healed by mineralization); a break. The term thus includes faults, joints, and fissures, all defined below.

Fault- a fracture in which the dominant component of movement has been shear, parallel to the fracture walls.

Fissure- an open fracture; one in which the dominant component of movement has been extension normal to the fracture walls, resulting in their separation.

Joint- a fracture associated with no significant displacement in any direction. What constitutes "significant" is arbitrary and more a question of semantics than science, but most workers would probably call any fracture associated with readily visible offset at the outcrop scale a fault rather than a joint. We retain that convention here and restrict usage of joint to refer only to fractures whose walls have not moved more than 0.4 inch (1.0 cm) relative to each other in any direction. Upon subsequent shear or extension a joint can become a fault or fissure, respectively; these are reactivated joints.

Joint, as defined here, is strictly a geometric term, in keeping with common usage. Note, however, that the common definition of joint as "a surface of fracture or parting in a rock, without displacement" (Bates and Jackson, 1980) is nonsensical: if the rock along one joint wall did not move in any direction relative to rock along the opposing wall, the crack between them could not exist.

Fracture length, fracture height- in horizontal beds, the dimensions of a fracture as measured parallel to its strike and dip lines, respectively. Few fractures are exposed in their entirety, however, so true lengths and heights commonly are not measurable. Some dimensions cited in this paper refer to exposed (partial) heights and lengths and are so termed where appropriate.

Ring fracture, ring-fracture zone, annular ring- related terms with at least two contrasting meanings. An annular zone of concentric, outward-dipping fractures, often highly mineralized, occurs within country rock along the periphery of some breccia pipes. To these fractures some workers apply the term ring-fracture zone or, less accurately, ring fracture. Our usage conforms to this definition. Others, however, use ring fracture in a quite different sense, to refer to the contact between brecciated rock of the pipe proper and the country rock surrounding it. The term "annular ring" is redundant and not recommended.

UNITS OF MEASUREMENT

Nearly all mining reports on mineralized breccia pipes of the Grand Canyon region employ English units as the basis of measurement, and topographic maps of the area still show elevations and contour lines in feet rather than meters. For these reasons, all measurements in this paper are stated first in English units followed by their metric equivalents in parentheses.

Wherever a number is used only in an approximate sense, as in such statements as "Diameters of most breccia pipes range from about 100 to 400 ft", the given metric equivalent is approximate also and has been rounded to the nearest simple number ("30 to 120 m"). Exact metric equivalents are provided for values based on actual measurements reported to higher standards of accuracy.

MINE LOCATION AND ACCESS

The Ridenour mine (fig. 3) is located in the northeastern part of the Hualapai Indian Reservation in sec. 6, T31N, R8W, high on the west wall of an unnamed canyon at an elevation of 4,480 ft (1,365 m). The canyon drains northwestward into the Colorado River, 2.0 mi (3.3 km) distant and several thousand feet lower. Access to the mine from Peach Springs, the nearest town, is by paved road 30 mi (48 km) to Frazier Wells (elev. 6,058 ft, or 1,846 m), and thence by generally good dirt roads that ascend northward across the Coconino Plateau and then descend within stream valleys through the Aubrey Cliffs. From there, other roads lead to the rim of the Grand Canyon at an elevation of 6,320 ft (1,926 m). A steep 4-wheel-drive road blasted into the cliff face descends into a tributary valley to the Colorado River, where a series of unimproved dirt roads leads eventually to the Ridenour mine. Total distance from Peach Springs to the mine is 59 mi (94 km) by road.

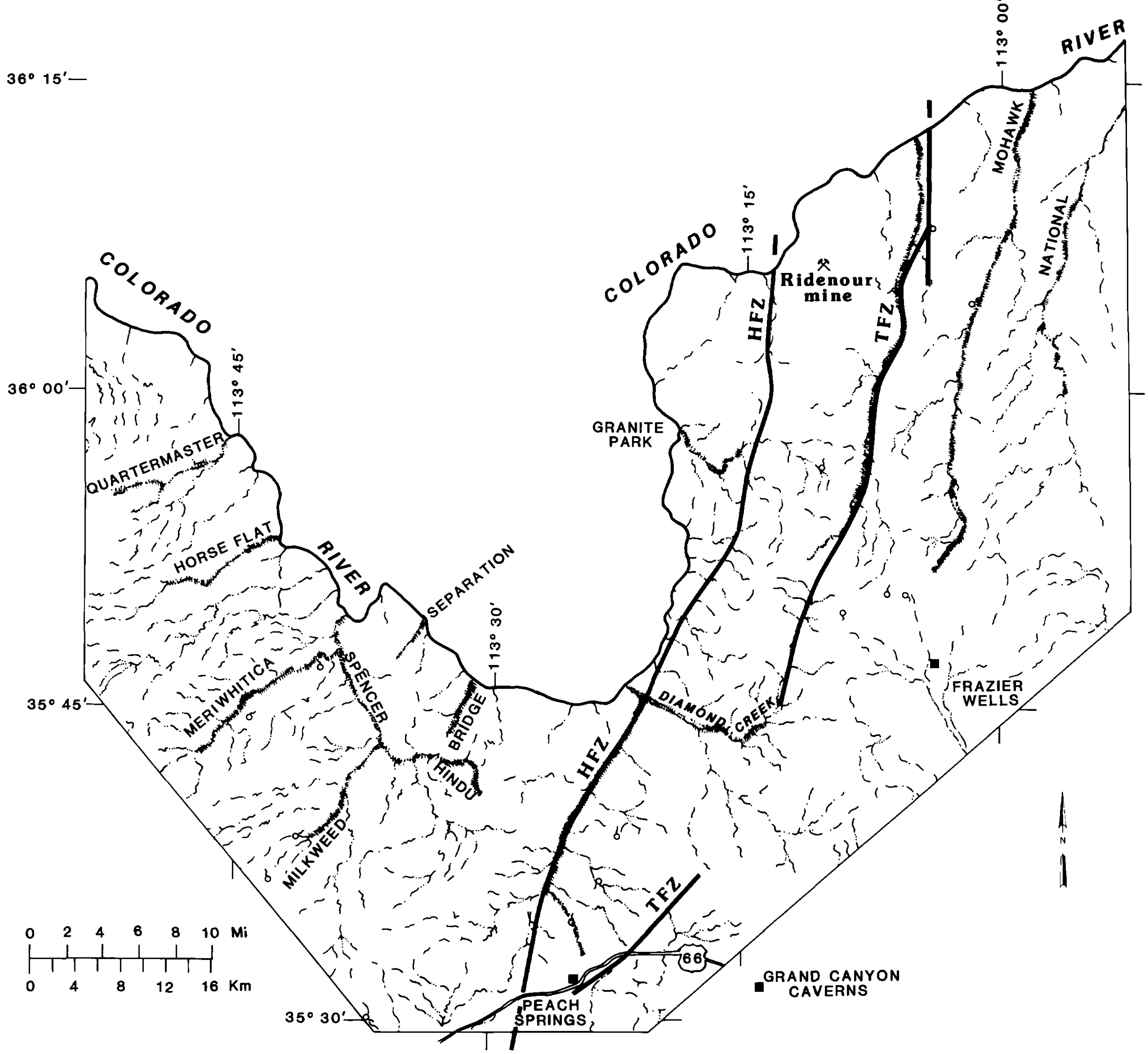


Figure 3. Map of Hualapai Indian Reservation, showing major structural features and localities discussed in text. HFZ = Hurricane fault zone; TFZ = Toroweap fault zone. Modified from Wenrich (1986a).

STRATIGRAPHIC SETTING

The stratigraphic level of the Ridenour mine was said by Miller (1954) to be about the middle of the (then unnamed) Esplanade Sandstone of early Permian age, but newer mapping by Wenrich, Billingsley, and Huntoon (1986) shows it to be near the base of this formation. The Esplanade Sandstone--the uppermost formation of the Supai Group--averages about 450 ft (135 m) thick in this area and consists predominantly of pale red to reddish orange, cross-stratified, fine to medium-grained sandstone with subordinate siltstone and limestone (Wenrich, Billingsley, and Huntoon, 1986).

The Esplanade Sandstone caps a minor plateau surface (the Esplanade Platform) for several square miles north and southwest of the mine, at a general elevation of about 4,800 ft (1,460 m), and is well exposed within stream valleys and canyons cut into that surface. Farther south and east, toward the rim of the Grand Canyon, successively younger strata are exposed along prominent cliff faces ascending to a broad plateau capped by the Kaibab Limestone at elevations of 6,300-6,600 ft (1,920-2,010 m). To the north and west lies the Inner Gorge of the Grand Canyon, whose south rim is less than a mile distant from the mine. Stepped cliffs lead downward through the Paleozoic section to the Colorado River, where, at elevations of about 1,600 ft (490 m), Precambrian metamorphic rocks of the Vishnu Group crop out sparingly. Nearly the entire succession of Paleozoic strata, about 4,800 ft (1,460 m) thick, is exposed in this area.

STRUCTURAL SETTING

Dominant structures of the region are the Hurricane and Toroweap fault zones, both coincident for much of their extent with monoclines of the same name (fig. 3). The monoclines, as expressed at the level of the Esplanade Sandstone, are gentle ramplike features of overall northerly trend and with gently tilted (5°-10°) limbs averaging 1-1.5 mi (1.6-2.5 km) in width (Wenrich, Billingsley, and Huntoon, 1986). Each monocline warps the strata downward to the east and is a relatively young feature of Laramide age (Huntoon, 1981). The faults with which they are associated, however, are of Precambrian ancestry and have a complex and lengthy history of movement, often in opposing senses. A brief listing of the major Phanerozoic events of the region, derived from Wenrich, Billingsley, and Huntoon (1986) and references cited therein, is as follows:

(1) Regional subsidence and accumulation, from Cambrian through Cretaceous time, of 8,000 to 13,000 ft (2,440 to 3,960 m) of sediment. These sediments were deposited on deeply eroded metamorphic rocks (the Vishnu Group) that had already been offset, in Precambrian time, along numerous normal faults.

(2) Laramide (Late Cretaceous through Eocene) crustal compression. During this time some of the old Precambrian normal faults--those most favorably oriented to accomodate subhorizontal, ENE-directed crustal compression--were reactivated as reverse faults. Ramplike folds, among them the Hurricane and Toroweap monoclines, developed above the principal zones of reverse movement. Structural relief along most of the length of both monoclines ranges from 300-900 ft (90-270 m), east side down.

Regional uplift and unloading by erosion began during the Laramide movements and continued through the whole of Cenozoic time. Post-Laramide faults and joints, then, probably developed at shallower crustal levels (lesser confining pressures) than the Laramide monoclines.

(3) Recurrent Miocene, and later, normal faulting accompanied by continued uplift and erosion. During the Miocene epoch the southwestern margin of the Colorado Plateau became structurally and topographically distinct from the Basin and Range Province (Young and Brennan, 1974). Normal slip, west side down, occurred along some of the same faults that earlier, in Laramide time, had accomodated reverse slip to form the major monoclines of the region. The structurally high, west limbs of the monoclines now were faulted downward to positions below their eastern limbs. As crustal extension continued through the late Cenozoic, new faults striking within 20° of due north formed in progressively greater numbers within the previously little-faulted areas between the major fault zones of Precambrian ancestry. Today much of the region is riddled with minor faults and grabens, and faulted Quaternary deposits suggest that crustal extension is continuing.

GENERAL CHARACTER OF BRECCIA PIPES

SOLUTION-COLLAPSE ORIGIN

Horizontal to gently dipping Paleozoic and Mesozoic strata of the Grand Canyon region are penetrated by hundreds of pipelike bodies of breccia that are circular to broadly elliptical in plan view and whose axes are vertical, or nearly so (fig. 2). These structures are considered by most recent workers (Bowles, 1965, 1977; Gornitz and Kerr, 1970; Wenrich-Verbeek and others, 1980; Wenrich, 1985; Sutphin, 1986) to have formed by progressive collapse and consequent upward stoping of gravitationally unstable portions of large solution caverns in the Mississippian Redwall Limestone. The stoping process in many pipes likely was aided by the gradual breakdown of carbonate-cemented sandstone clasts, derived from overlying Pennsylvanian and Permian strata, into their component grains through dissolution of carbonate cement. Removal of some of this material, both in solution and by downward sifting of loose grains through the pipe and flushing through the Redwall cavern system, created the additional room necessary for continued collapse and upward propagation of pipes through, in some cases, more than 2,000 ft (600 m) of section. The pipes thus are sedimentary features, unlike the mineralized pipes of many other areas that owe their origin to explosive volcanism. Evidence for a solution-collapse origin of the Grand Canyon pipes is voluminous and includes the following facts: (1) With the local exception of several enigmatic breccia bodies in Cambrian rocks (Wenrich, Billingsley, and Huntoon, 1986), no exposed breccia pipes in the Grand Canyon region occur below the Redwall Limestone. Hundreds, however, occur above it. (2) Test drilling in one well-studied pipe--the Orphan pipe--confirmed that the breccia column terminated downward within the Redwall Limestone (Chenoweth, 1986). (3) The Redwall Limestone is honeycombed with numerous caverns, entrances to many of which are seen along the imposing cliffs of this unit throughout much of the length of the Grand Canyon. The bases of several pipelike bodies of breccia are exposed in some recently explored caves (Wenrich and Sutphin, in press). (4) Clasts within pipes have dropped to levels below their normal stratigraphic positions, indicating that all movement has been vertically downward.

DIMENSIONS

Vertical dimensions of individual pipes rarely are known with certainty, for the bottoms of few pipes are exposed and the tops of many have been removed by erosion. Nevertheless, exploratory drilling has established the minimum vertical extent of a few pipes. The well-known Orphan pipe, for example, cuts at least 1,660 ft (506 m) of section (Chenoweth, 1986), an amount that probably is not unusual. Diameters of most pipes range from about 100 to 400 ft (30 to 120 m), and 250 ft (about 75 m) may be taken as a practical average (Wenrich, Billingsley, and Van Gosen, 1986). Topographic expressions of pipes on plateau surfaces flanking the Grand Canyon, however, are as much as 5 times the actual pipe diameter (fig. 2) due to local removal, in solution, of gypsum and carbonate from soluble beds of the Toroweap Formation and Kaibab Limestone encircling the pipes (Wenrich, Billingsley, and Huntoon, 1986; Krewedl and Carisey, 1986). The resultant thinning of the affected strata and sag of overlying beds are expressed at the surface as structural basins considerably greater in diameter than the pipes themselves. The diameters of many pipe-related collapse depressions mapped by Sutphin (1986) on the southern Marble Plateau, for example, range from about 300 to 1,600 ft (90 to 490 m) and have an average diameter of about 850 ft (260 m).

BRECCIA CLASTS AND RING FRACTURES

Breccia clasts within pipes vary greatly in size, from small pebbles to large blocks and slabs more than 10 ft (3 m) on a side. The breccias generally have a sandy to silty matrix. Much of the matrix material probably represents the insoluble quartz component of calcareous sandstone clasts decemented by fluids circulating through the pipe, but downward sifting of loose sand from unconsolidated strata intersected by pipes has been cited as an alternative or supplemental source (Gornitz and Kerr, 1970; Chenoweth, 1986). Movement of clasts within pipes has been exclusively downward, for all occur below their normal stratigraphic positions. Reported amounts of downdrop are 370 ft (113 m) at the Orphan pipe (Chenoweth, 1986), 500 ft (150 m) at the Ridenour pipe (this paper), and 740 ft (225 m) at the Kanab North pipe (Wenrich, 1986b). Displacements in some pipes increase from the margins of the pipe inward (Kofford, 1969; Gornitz and Kerr, 1970) and with increasing depth.

The contact between brecciated rock of the pipe core and the surrounding country rock is quite sharp in most pipes. Outside this contact, and extending for variable distances beyond it, the country rock commonly is cut by abundant, concentric, outward-dipping fractures that developed during stoping and that represent incipient foundering of large, arcuate slabs of rock around the pipe proper. This is the ring-fracture zone, a common site of rich concentrations of ore in mined pipes. Information on total widths of ring-fracture zones is scant in the literature; at the Ridenour mine it ranges from about 40 to at least 130 ft (12-38 m).

MINERALIZATION AND ALTERATION

Mineralization and alteration of breccia pipes in the Grand Canyon region span as wide a stratigraphic interval as the pipes themselves, from the Mississippian Redwall Limestone to the Triassic Chinle Formation (Wenrich, 1985). U-Pb dating of uraninite ores from several pipes places the main stage of uranium mineralization at about 200-220 Ma (Ludwig and others, 1986). The source and character of the mineralizing fluids have been long debated. Volcaniclastic sediments and tuffs of the Triassic Chinle Formation have been cited as one convenient source for the uranium (Krewedl and Carisey, 1986), implying downward transport of U-laden waters in pipes or through connecting aquifers, but Huntoon (1986) states unequivocally that flow within pipes could only have been upward during mineralization. Wenrich (1986b) noted that the levels of enrichment of numerous metals within breccia-pipe ores are incompatible with derivation from the Chinle Formation and suggested instead that the uranium was derived from volcanic rocks of the Mogollon Highlands to the south, from where it was transported northward, down the regional hydrologic gradient, to the breccia pipes. Data on fluid inclusions from breccia-pipe ores suggest that temperatures during ore deposition ranged between 80° and 173° C, and that salinities of the ore fluid generally were greater than 9 wt % eq. NaCl (Wenrich, 1985; Rasmussen and others, 1986; Wenrich and Sutphin, in press). These data would appear to preclude a low-temperature ground-water source for the ore and associated gangue minerals (Wenrich, 1986b).

A complex, multi-stage history of alteration and mineralization has been documented in several pipes for which detailed mineralogic studies have been completed or are in progress. Inasmuch as the timing of such events relative to fracturing of the host rocks is a principal focus of this paper, we briefly summarize the paragenetic sequence below.

(1) Bleaching and decementation of pipe breccia.

Although pipe-core breccias as seen in many places today are highly altered and locally mineralized, it is not difficult to imagine the basic character of a newly formed collapse breccia: a loose aggregate of poorly sorted, polylithologic, angular fragments resting in point contact with one another, and with abundant void space between. The exceptional permeability of such material would have continually exposed it to reaction with whatever fluids were circulating through the pipe at any given time. The earliest recognized effect, common to nearly all pipes studied in the Grand Canyon region, was removal of carbonate and consequent decementation of carbonate-cemented sandstone and siltstone clasts. Much of the stratigraphic section above the Redwall Limestone, including large parts of the Supai Group and Moenkopi Formation, consists of sandstone and subordinate siltstone cemented partly or wholly by calcite and dolomite. Freeing of individual quartz grains from clasts of such rocks was the probable source of most or all of the sandy matrix typical of pipe-core breccias. The same process resulted in rounding of those clasts most susceptible to solution. The resultant product, still preserved in the unmineralized portions of some pipes, was a polylithologic aggregate of breccia clasts--some angular, some rounded--in a porous matrix of loose quartz sand and sandy silt. The breccia in some places remains clast-supported, but matrix-supported breccias are common in other areas where dissolution of carbonate cement was more extreme.

Breccia within the pipes and strata immediately surrounding them commonly are bleached to ivory or buff tones, rendering some pipes, particularly those hosted by red, hematite-pigmented sandstones, visible from afar. The bleaching was effected by the reduction of finely divided hematite and redeposition of the iron in solution as disseminated pyrite (Gornitz and Kerr, 1970; Hoffman, 1977; Sutphin, 1986; Wenrich, 1986a; Gornitz and others, 1988). Considerable remobilization of iron is also indicated in many pipes by large masses of "zebra rock", an informal term used locally (albeit incorrectly) for bleached sandstones within which goethite-rich layers, generally noncoincident with bedding, alternate with goethite-poor layers to create a prominently striped appearance. Bleached and goethite-stained rock is of widespread occurrence in many pipes, whether mineralized or not. Conversely, none of the primary ore minerals discussed below are known to occur in unbleached rock. These observations led H.B. Sutphin (oral commun., 1987) and Gornitz and others (1988) to conclude that bleaching and remobilization of iron were early effects that predated ore mineralization within pipes.

(2) Deposition of carbonate and sulfate minerals.

Coarsely crystalline calcite, dolomite, and barite were among the most common and earliest of phases to be precipitated within the sandy matrix of the solution-collapse breccias of mineralized pipes (Wenrich and Sutphin, in press). Quartz was simultaneously removed, as shown by corrosion of once well-rounded detrital grains. Gypsum, anhydrite, siderite, and kaolinite are minor to rare phases assigned to the same stage of mineralization. The widespread deposition of carbonate minerals in rocks formerly depleted in carbonates apparently was common in the Grand Canyon breccia pipes. Later deposition of the ore minerals generally affected much lesser volumes of rock.

(3) Deposition of Ni-Co-Fe sulfides and Ni arsenides.

Deposition of small, scattered, euhedral and commonly zoned crystals of such phases as siegenite, bravoite, pyrite, and rammelsbergite corresponds to an intermediate stage of mineralization (Wenrich and Sutphin, in press). These minerals are hosted by the carbonate and sulfate minerals deposited previously. Massive, anhedral pyrite of slightly younger age locally enclosed the smaller crystals and crystal aggregates of the Ni-Co-Fe minerals by replacing the host grains of carbonate or barite.

(4) Deposition of uraninite and Cu-Fe-Zn-Pb sulfides.

The latest stage of mineralization discussed by Wenrich and Sutphin (in press) resulted in deposition of botryoidal aggregates of uraninite around detrital quartz grains and within small vugs in the calcite-cemented sand of the collapse breccia. Also important in some pipes, including the Ridenour pipe, was the deposition of such Cu and Cu-Fe sulfides and sulfosalts as chalcocite, digenite, chalcopyrite, bornite, djurleite, and covellite. Minor galena, sphalerite, and tennantite were also deposited locally at this time. The ores formed during this stage are compositionally and texturally complex and tend to occur within vertical, discontinuous, pod-like bodies within the pipe core and as vein arrays within the ring-fracture zone bordering the pipe proper (Gornitz and Kerr, 1970; Krewedl and Carisey, 1986; Gornitz and others, 1988).

(5) Supergene alteration of primary ores.

Late Cenozoic uplift elevated the upper reaches of many pipes into the zone of oxidizing ground waters and resulted in extensive supergene alteration of primary ore. Common products include such Cu and Zn carbonates, sulfates, and hydrous silicates as malachite, azurite, brochantite, cyanotrichite, chrysocolla, hemimorphite, and smithsonite (Wenrich and Sutphin, in press). Goethite commonly is conspicuous and occurs variously as concretions, botryoidal masses, boxwork fracture fillings, and pseudomorphs after pyrite crystals (Wenrich, 1986b). Uranium in soluble complexes derived from the original uraninite was removed completely from the near-surface portions of some pipes and was locally redeposited in others as disseminated grains and fracture coatings of tyuyamunite and metatyuyamunite, uranophane, torbernite and metatorbernite, zeunerite and metazeunerite, uranospinite, and schroeckingerite (Chenoweth and Blakemore, 1961; Kofford, 1969; Sutphin, 1986; and data from this study). The Ridenour pipe is one of those in which supergene alteration of the primary mineral assemblage has been carried nearly to completion, at least within the visible portions of the pipe as reached through the mine workings.

FRACTURE NETWORK NEAR RIDENOUR MINE

The fracture network of the Paleozoic rocks near the Ridenour mine comprises two broad classes of fracture: (1) discrete faults, many of which are shown on geologic maps of the area, and (2) joints, which generally are not. Descriptions of the faults of the Grand Canyon region--their origins, relative ages, and movement histories--have appeared in more than a century of geologic literature. Summary papers by Huntoon (1974) and Lucchitta (1974) provide useful introductions to the topic. Faults in and near the Ridenour mine, however, are neither numerous nor large--all are normal faults with less than 30 ft (9 m) of offset in nearly horizontal beds, and the largest fault on the mine property has an offset of only 3 ft (1 m). Local faults seem to have had little influence on the penetration of the Ridenour pipe through the Esplanade Sandstone, and our discussion of them is accordingly limited. On a regional basis, however, faults at deeper stratigraphic levels may have controlled the locations of some breccia pipes, and that topic is considered in a later section.

In contrast to faults, which are few near the mine, joints pervade every outcrop of the Esplanade Sandstone examined. Despite their ubiquity, published information on joints in Paleozoic rocks of the Hualapai Reservation was almost nonexistent until recently, when Roller (1987) worked in an area 35-50 mi (56-80 km) southwest of the mine site. Study of the fracture history of the Ridenour pipe and surrounding area is of more than academic interest, for some aspects of pipe genesis, mineralization, and supergene alteration cannot be fully understood without knowledge of the fracture network of the host rocks and the age of those fractures relative to pipe formation. The mechanics of upward stoping of an initial cavern by gravity collapse, for example, are quite different for jointed versus unbroken rock. The movement of mineralizing fluids and later oxidizing ground waters through pipes also is strongly affected both by the structure of the pipe and of the surrounding fracture network in communication with it. The nature of that network changed with time and increased in complexity as successive sets of joints--five in all--developed in the rock. Additional complications stemmed from the gradual closure of old joints by precipitation of minerals within them, and by their local reopening during minor phases of crustal movement. Accordingly, the fracture history of the Esplanade Sandstone near the Ridenour mine is described below at some length.

METHODS OF STUDY

The local fracture network was documented in detail at 23 sites on the plateau surface capped by the Esplanade Sandstone. Four of these sites, stations RM-1 through RM-4, are within the ring-fracture zone along the periphery of the Ridenour pipe, and the other 19 are at various localities within an area of about two square miles (5 km^2) surrounding the pipe (fig. 4). At these sites all visible characteristics of the joints (orientation, dimensions, shape, surface structures, mineral coatings or fillings, spacings, and the geometry of abutting or cross-cutting relations with other fractures) were recorded for the joints of each set. Many intervening areas were examined more cursorily.

Particular attention was paid to evidence of the mode of failure and relative age of each set, for from such information a partial stress history of the region can be reconstructed. Given reasonably favorable conditions of preservation, modes of failure (by shear or extension) among joints can be inferred from the detailed morphology of the fracture surfaces themselves. In the simplest case, if opposing walls of a fracture are irregular but perfectly matched, such that the absence of net shear offset can be demonstrated, the fracture most likely is an extension (Mode I) joint. If this condition is common to many joints of the same set, an extensile origin for the entire set can be regarded as established. An obvious limitation is that this method cannot be used to distinguish true shear fractures from extension joints later reactivated in shear. If, however, the fracture walls are relatively unweathered, at least locally, the presence of surface features such as plumose structure, twist hackle faces, and arrest lines can be taken as direct evidence of extensile failure. Detailed discussion of the formation and interpretation of these and other fracture-surface features is given in Kulander and others (1979), Pollard and others (1982), and Barton (1983).

The relative ages of multiple fracture sets can be determined in the field primarily from abutting and cross-cutting relations among the various fractures. The criteria for shear fractures (faults) and filled dikes and veins are well established and generally known: younger faults offset older, and continuous, unbroken dikes or veins are younger than those they cut across. Relative-age criteria for unfilled extension fractures also exist (a good summary is given by Kulander and others, 1979) but are not yet in general use among field geologists. The prime consideration is that a tensile stress cannot cross a cohesionless boundary. Thus, a given extension fracture will terminate against any older fracture unless the opposing walls of the older fracture are bonded together in stress-transmitting contact, generally through cementation by some secondary mineral (Grout and Verbeek, 1983). Even if the older fracture is "healed", however, the mechanical contrast between the wall rock and the mineral filling often is sufficient to stop a younger joint from propagating across the contact. Depending on the degree of cohesion between fracture walls, then, younger extension joints will either terminate against, or cut across, older fractures.

A more complete discussion of field methods used in this study and their application to various topics concerning joints in general is given in Grout and Verbeek (1983).

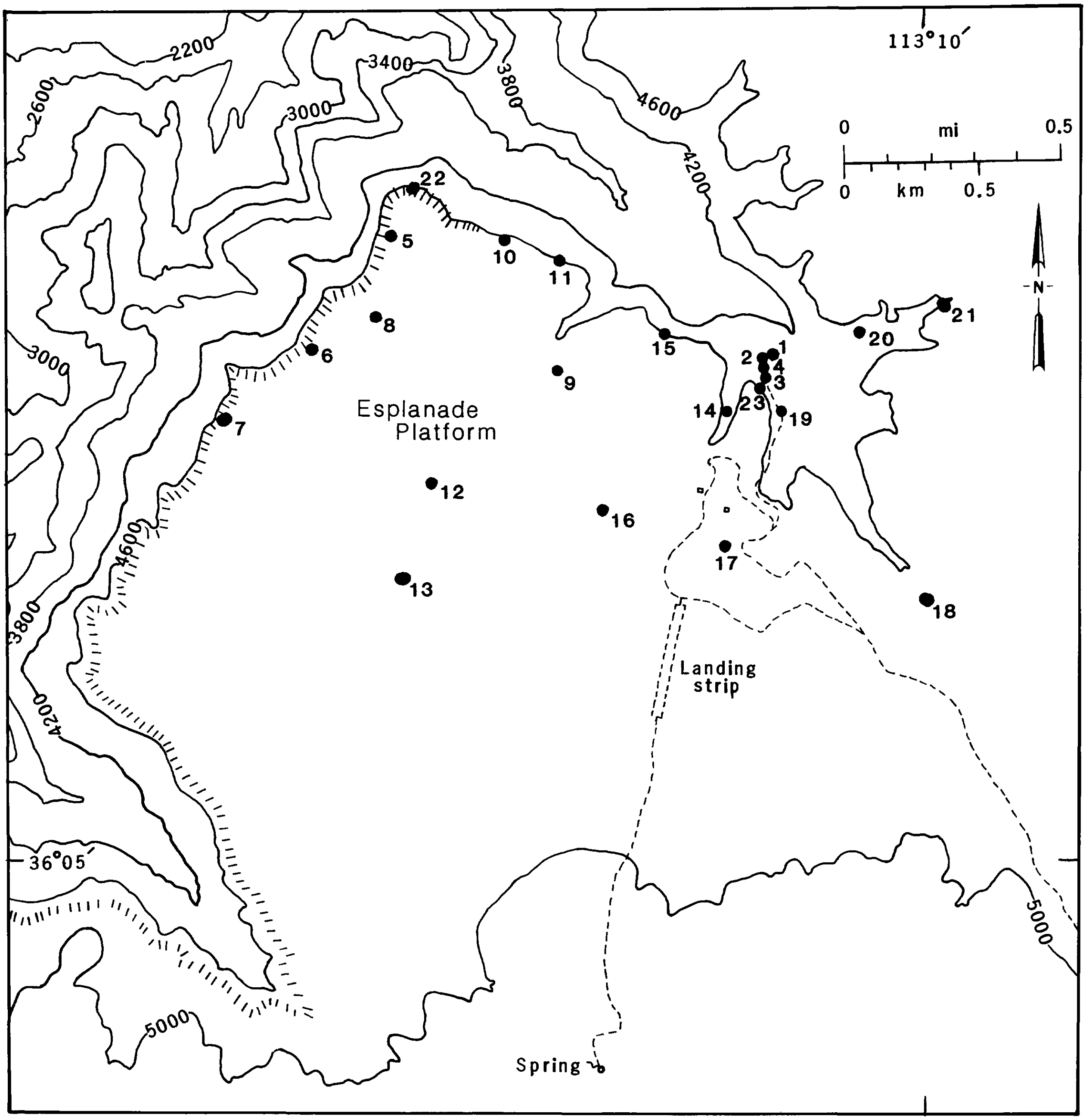


Figure 4. Generalized topographic map of area around Ridenour mine, showing location of fracture stations in Esplanade Sandstone. Stations RM-1 to RM-4 are within the ring-fracture zone of the Ridenour pipe. Hachured line is rim of the Inner Gorge of the Grand Canyon. Map from Vulcans Point SW quadrangle, 1:24,000 scale.

DESCRIPTION OF JOINT SETS

A first impression of the fracture network of the Esplanade Sandstone near the Ridenour mine can be gained from aerial photographs, for the openings of many of the larger joints have been accentuated by weathering and are prominently visible from afar. The map of Figure 5, prepared from true-color aerial photographs at 1:27,000 scale, discloses several fracture sets of consistent orientation but varying relative prominence from place to place. Because the fractures are nearly vertical and the mapped surface is a plateau with only gentle relief, fracture trends mapped from vertical aerial photographs are equivalent to fracture strikes as measured on the ground. A set of about N60W strike appears dominant in most areas, but fractures of other trends--particularly about N-S and N70E--are common locally. Only the most prominent fractures are visible on the photographs, however, and the actual fracture network as documented in the field is considerably more complex than that suggested by Figure 5. The results of the field studies are consistent from site to site and show that the local joint network of the Esplanade Sandstone is the product of five sequential episodes of fracture. Joints formed during those episodes are referred to in the descriptions below as J1 (oldest) through J5 (youngest).

Episode 1: N-S joints

Prominent, nearly vertical J1 joints of N8W-N4E strike are present at 7 of the 23 sites studied (fig. 6). At each site they were the earliest set to form. These joints are extension fractures, as shown by prominent plumose structure and local twist hackle on some of their faces where these have been most protected from weathering. Their surfaces are planar, or nearly so, and are of large size--exposed lengths of 15-30 ft (5-10 m) and exposed heights of 10-15 ft (3-5 m) are common in many areas. The full dimensions of these (and other) joints are best viewed along the canyon rim, where apparently single J1 surfaces, as much as 50 ft (15 m) high and 140 ft (43 m) long, form broad, flat cliff faces (fig. 7).

The J1 joints are sporadically distributed and are absent from much of the study area. In many places only one or two large J1 joints are present within outcrops hundreds of feet across. Locally, however, they are present in sufficient numbers to constitute a recognizable set, and in a few outcrops they are spaced only 1-3 ft (0.3-0.9 m) apart. Domains of abundant J1 joints tend to be small, in some places only 20-40 ft (6-12 m) wide, but soil cover on the plateau surface near the mine is too extensive to permit determination of the shapes of those domains or to recognize any pattern among them.

Episode 2: N70E joints

Subvertical J2 joints, ranging in strike from about N60E to N79E, are present in many localities and were documented at 16 of the 23 stations examined in detail (fig. 8). In appearance these joints much resemble those of the J1 set: they tend to be large, with exposed heights of 20-50 ft (6-15 m) and trace lengths of 25-70 ft (8-21 m), and their surfaces are planar to gently sinuous. The traces of some apparently single J2 joints on aerial photographs are 300-450 ft (90-140 m) long. Such large J2 joints cut multiple beds of sandstone and form vertical cliff faces at many points along the canyon rim north of the mine. Smaller J2 joints with trace lengths of only 1.5-6.0 ft (0.5-2 m) are present within thin sandstone beds at a few localities, but these are uncommon.

The prominence of the J2 joint set is highly variable from place to place, as suggested by photogeologic evidence (fig. 5) and confirmed in the field. At a few stations the J2 joints are spaced as little as 3 inches (8 cm) apart and divide the rock into thin vertical slabs. More commonly, spacings range from 3-10 ft (1-3 m), but in some areas only one or two J2 joints are seen over large expanses of outcrop, and at still other

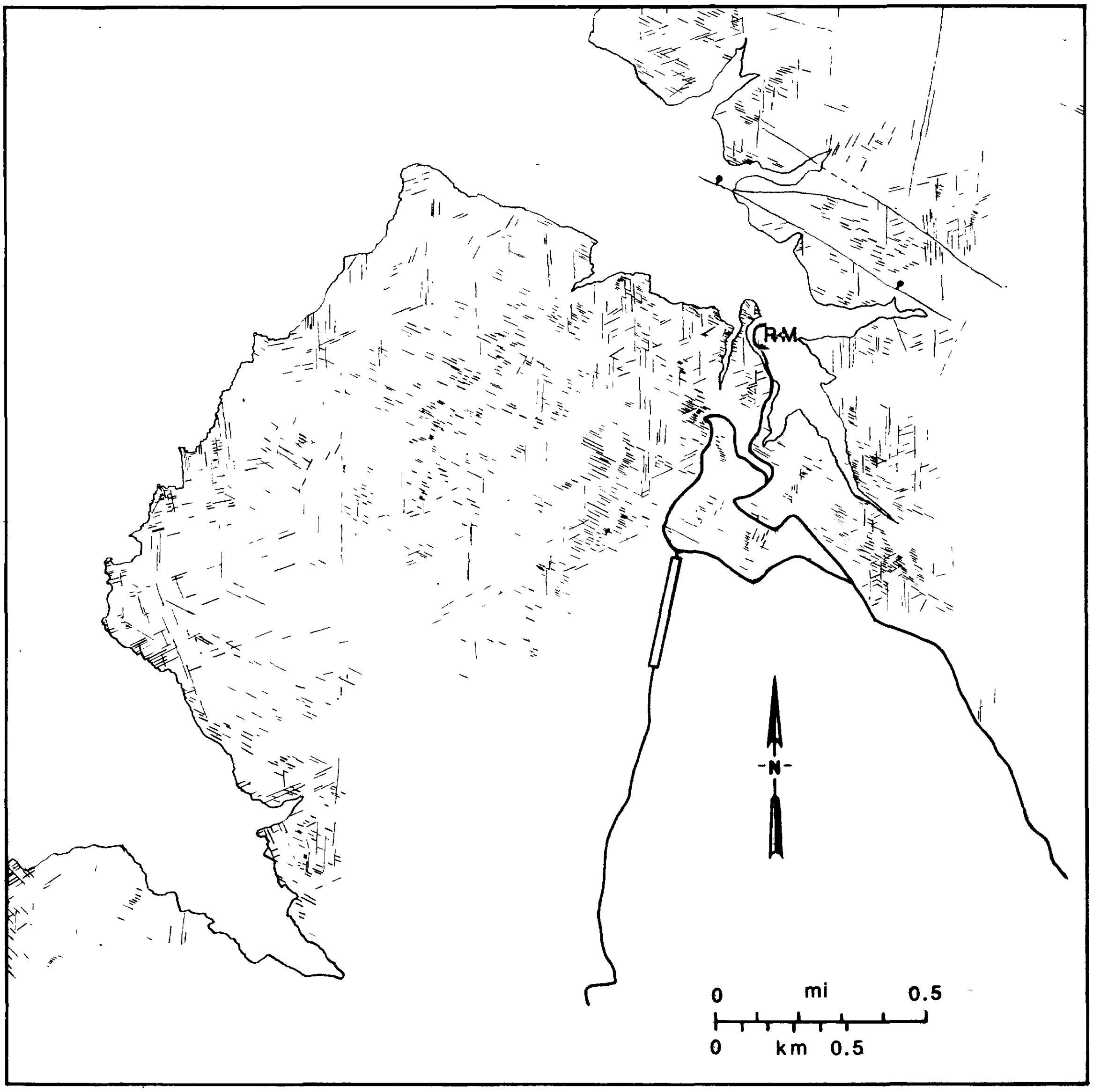


Figure 5. Photogeologic fracture-trace map of Ridenour mine area, prepared from 1:27,000 true-color aerial photographs. Shown at same scale as mapped. RM = Ridenour mine.

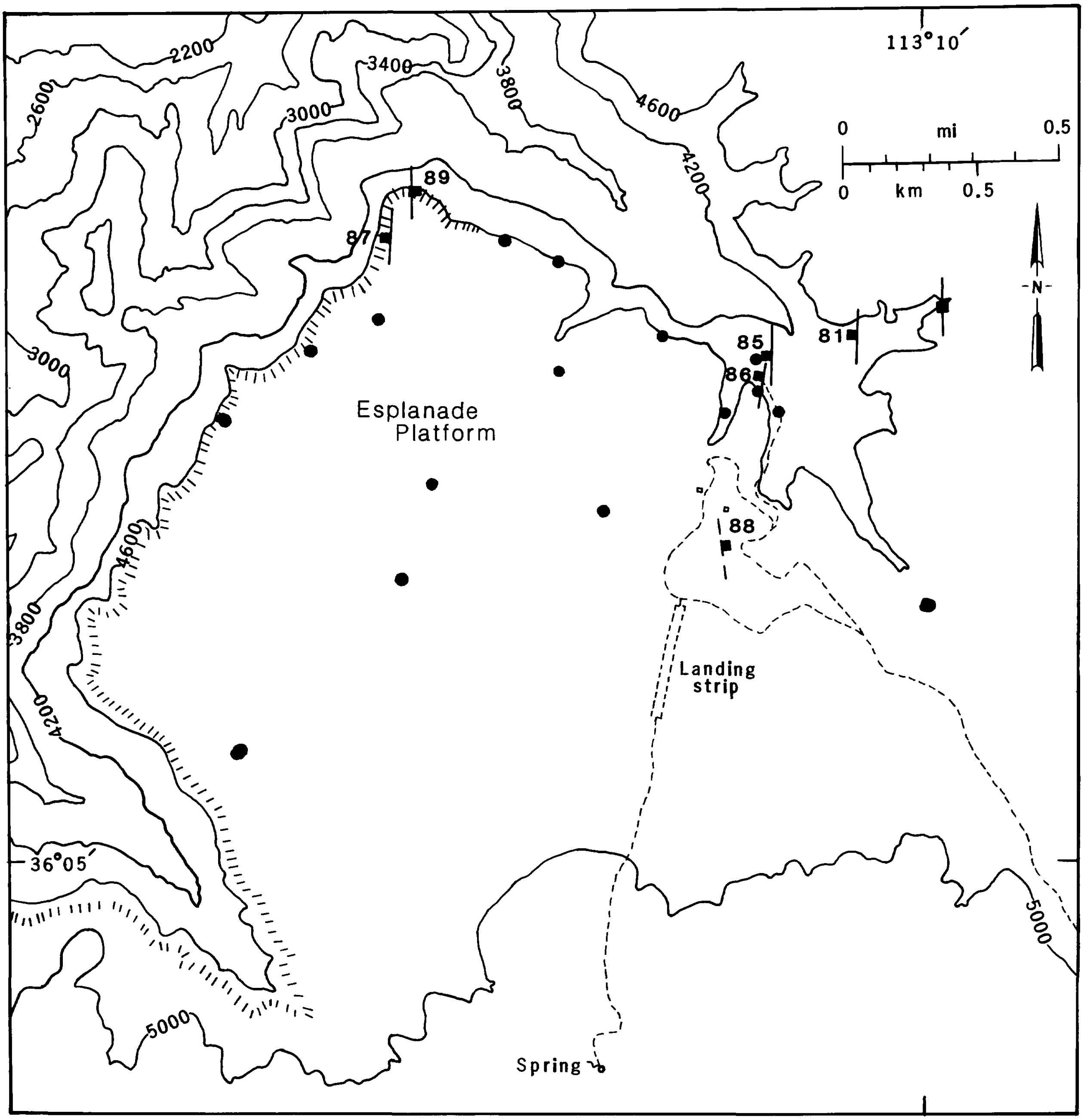


Figure 6. Orientations of J1 joints in Esplanade Sandstone around Ridenour mine. Most symbols represent the median of 12-20 readings; dashed symbol indicates sparse data. Overall median for entire area is N1W.

Figure 7. Large cliff-forming J1 joints along canyon rim west of Ridenour mine.

locations they appear to be missing entirely. As with the J1 set, no obvious pattern to their distribution as yet has been recognized.

Coexistence of J2 joints with the sporadically distributed J1 joints is sufficiently uncommon at the outcrop scale that determination of their relative ages was difficult. The problem was compounded by the fact that many joint-bounded blocks near the canyon rim, where exposures are best and soil cover least, are slightly out-of-place due to movement of the blocks near the unsupported cliff face. Abutting relations of one joint against another in some such areas are suspect. Nevertheless, apparently clear terminations of J2 joints against J1 surfaces were seen in several places, suggesting that J2 is the younger set. Plumose structure observed on numerous J2 faces confirms the extensional origin of the set, but J2 surfaces in many of the weakly cemented sandstone beds are far too weathered to preserve such delicate features.

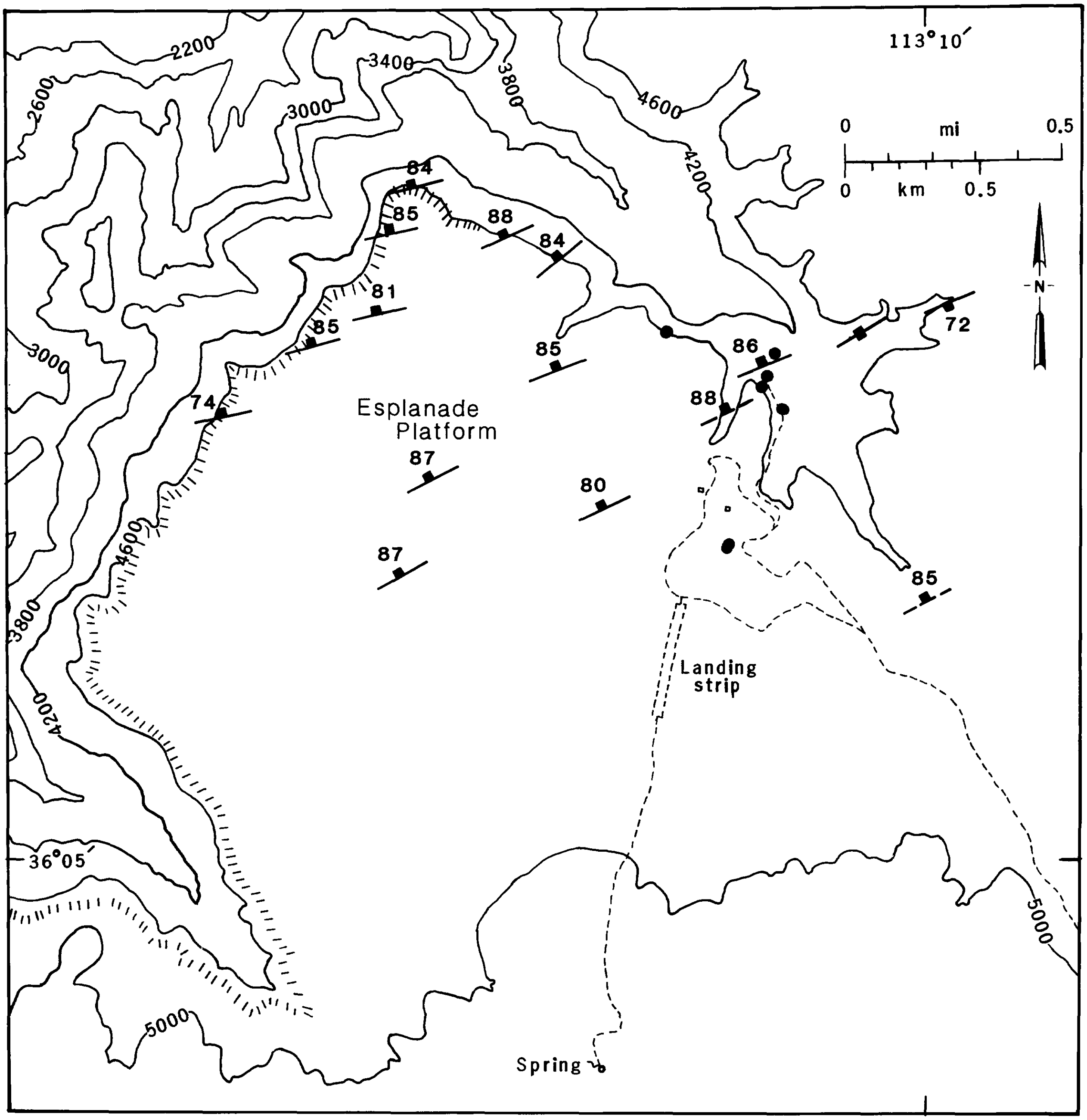


Figure 8. Orientations of J2 joints in Esplanade Sandstone around Ridenour mine. Most symbols represent the median of 12-20 readings; dashed symbols indicate sparse data. Overall median for entire area is N68E.

Episode 3: N60W joints

The J3 joints, of N49W-N63W strike and nearly vertical dip, comprise by far the most prominent joint set of the Esplanade Sandstone near the Ridenour mine (fig. 9). Few outcrops lack a definable J3 set (they are present at 21 of the 23 stations studied), and in many of these the J3 joints dominate the local fracture pattern. Joints of this set, as mentioned previously, also are prominent on aerial photographs of the region. Distances between adjacent J3 joints locally are as little as 3 inches (8 cm) and elsewhere as great as 15 ft (5 m), but spacings of 1.5-6.0 ft (0.5-2 m) are most common. The J3 joints generally are planar where they comprise the only well-expressed set, but their surfaces are noticeably more irregular wherever older joints are abundant. The typical appearance of the J3 set is shown in Figure 10.

A notable aspect of J3 joints is their relatively small size, much smaller on average than the joints of the preceding two sets. J3 joints at most stations are only 2-6 ft (0.6-2 m) long, and at only two stations were lengths of 10-20 ft (3-6 m) common. In addition, the J3 joints, more so than either the J1 or J2 joints, tend to terminate against prominent bedding surfaces between adjacent ledges of sandstone. Many J3 joints are thus confined to single beds and have heights equal to the thickness of those beds, typically 3-12 ft (about 1-4 m). Other but less common J3 joints cut multiple beds and have heights fully equal to the largest J1 and J2 joints, from 20 to 50 ft (6 to 15 m). Some of these are single fractures, but others, on close inspection, are seen to be vertically extensive zones of smaller, overlapping J3 joints rather than single fracture surfaces. The tendency for J3 joints to congregate in zones, within which individual fractures are spaced only fractions of an inch apart, is a property most pronounced in this set.

Abundant plumose structure, twist hackle, and local arrest lines show that the J3 joints are extension fractures. The configuration of plumose structure on some J3 joints shows that they propagated outward from a point on a preexisting J1 or J2 surface and establishes J3 as the younger set. So too does the fact that many other J3 joints curve toward and terminate against members of the J1 and J2 sets at all stations where these sets coexist. At only one station were large numbers of J3 joints observed to cut across the earlier fractures, implying local cementation of those earlier fractures prior to formation of the J3 set.

Episode 4: Horizontal, bed-parallel joints

Fractures more-or-less parallel to bedding, and analogous to sheeting (exfoliation) joints formed by erosional unloading of crystalline rocks, are common in the Esplanade Sandstone. Many such fractures, here termed J4 joints, occur along the bedding-plane interface between beds of slightly different lithology. Others occur within single beds and are of variable form, depending in large part on lithology. Where the rock is plane-parallel laminated, as is common in the siltstones but less so in the sandstones, the joints too are planar and follow the depositional surfaces (fig. 11, bed A). Such joints in the finer-grained beds are in part responsible for the fissile appearance of those beds. Within thick, massive, visually structureless sandstones, however, the J4 joints are irregular, curving fractures only crudely parallel to the top and bottom surfaces of the bed (fig. 11, bed C). Still other J4 joints in crossbedded, weakly to moderately cemented sandstones formed along the interface between adjacent cross strata and thus are inclined at various low angles to the other types (fig. 11, bed B). And finally, J4 joints in some well-cemented beds of crossbedded sandstone cut through the cross beds and maintain a subhorizontal attitude (fig. 11, bed D). All four types are widespread and gradational to one another.

In many exposures of the Esplanade Sandstone the J4 joints terminate against the walls of J3 joints. The J4 joints thus are relatively young members of the total fracture system.

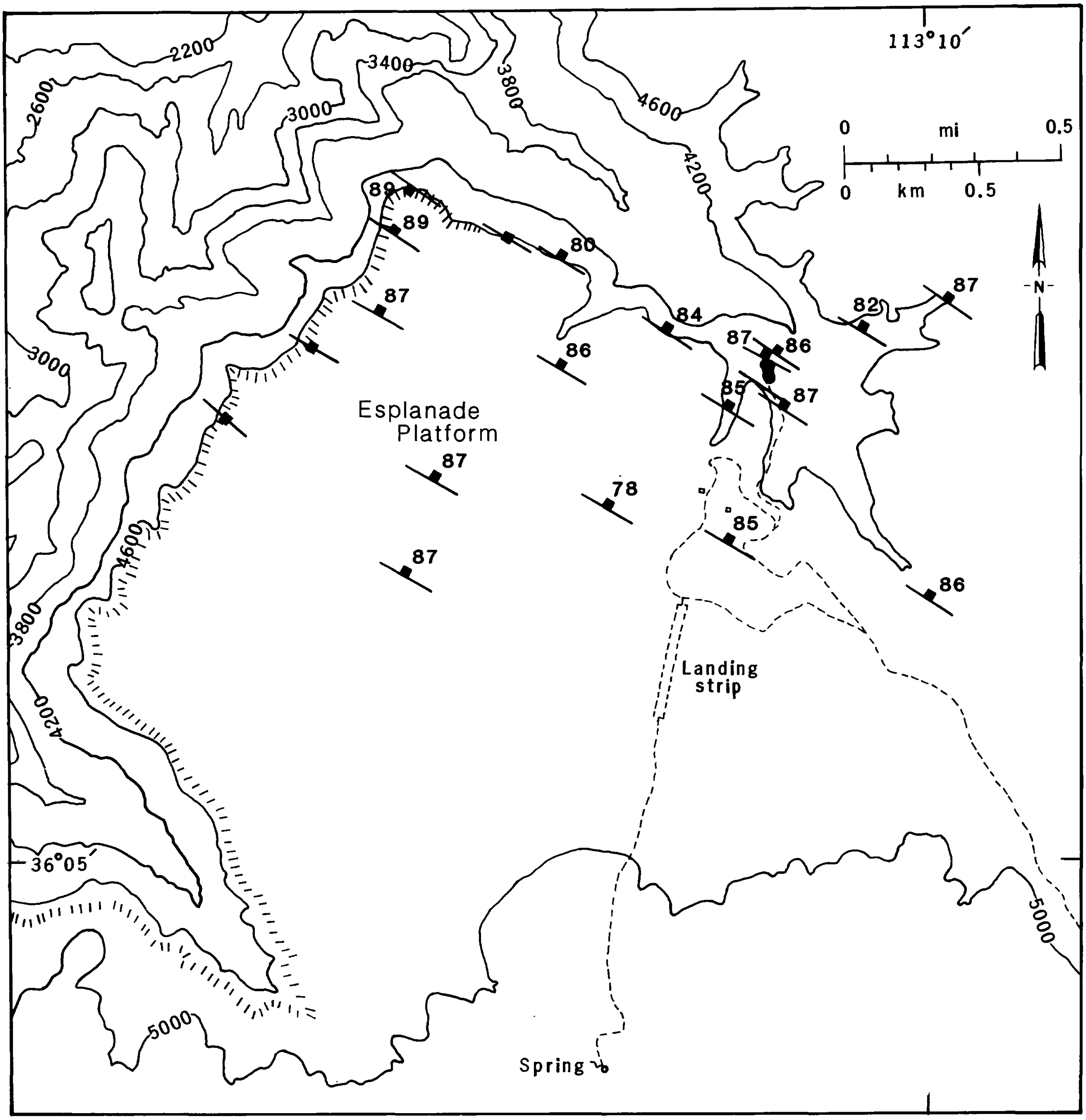


Figure 9. Orientations of J3 joints in Esplanade Sandstone around Ridenour mine. Most symbols represent the median of 12-20 readings. Overall median for entire area is N59W.

Figure 10. Photograph of well-developed J3 joints (parallel to line of sight of observer) in Esplanade Sandstone near station RM-9. Small, flat joints facing observer are members of J5 set.

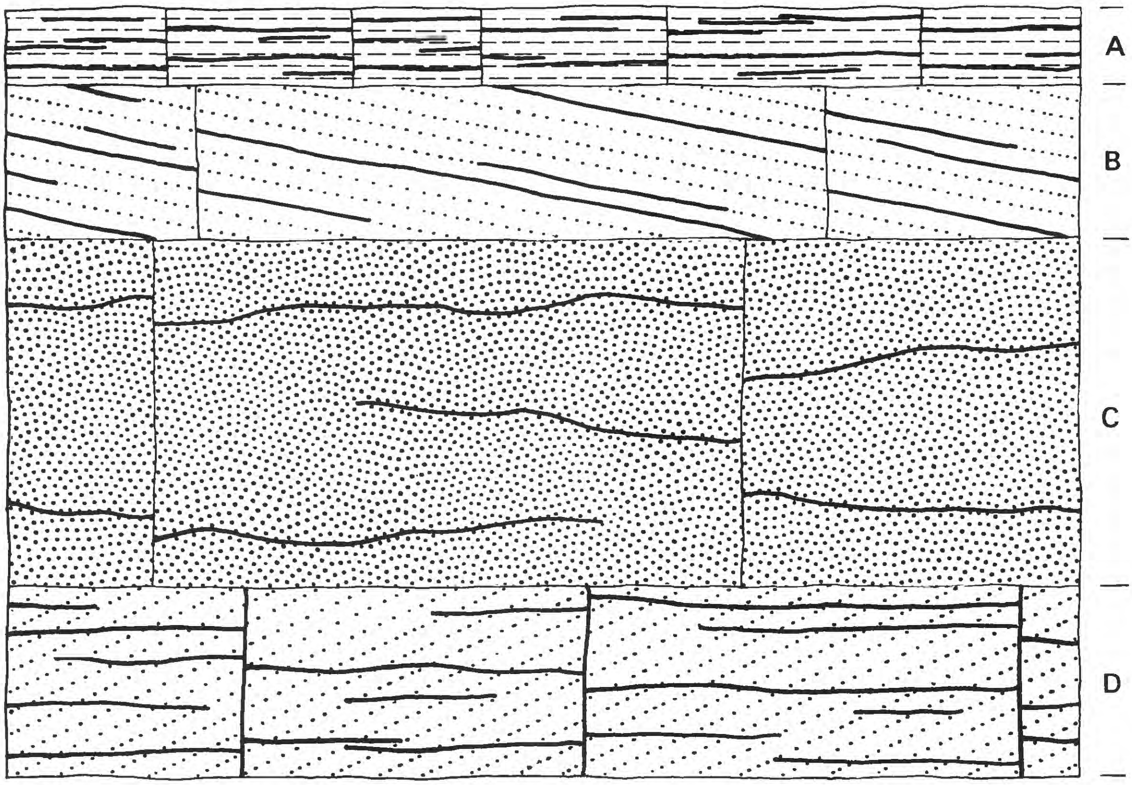


Figure 11. Sketch showing influence of lithology on character of J4 parting joints in the Esplanade Sandstone.

Episode 5: N35E joints

Small, crudely formed J5 joints of N25E-N50E strike and subvertical dip form a widespread but generally weakly expressed set near the mine (fig. 12). These joints are everywhere nearly perpendicular to the earlier J3 set (horizontal angles between them, as measured clockwise from J3 to J5, range from 82^o to 101^o) and have a similar distribution: they are present at most (14 of 21) sites where the J3 set was documented, but are missing from all studied outcrops that lack the J3 set. Despite the seeming connection, however, the two sets are of much different age, appearance, and genesis. Nearly all J5 joints terminate against whatever J3 (or older) joints are present and thus have lengths equal to or less than the spacings between those joints. Those lengths, 1-5 ft (0.3-1.5 m) in most places, are far shorter than typical lengths of J1, J2, and many J3 fractures. The heights, too, of J5 joints are small because few cut the entire thickness of any given sandstone bed; instead they are confined to individual slabs of rock bounded top and bottom by adjacent parting joints of the J4 set. Most J5 joints range in height from 1 to 4 ft (0.3 to 1.2 m), again significantly less than typical heights for the joints of all older sets. The small size and subplanar to nonplanar surfaces of J5 joints are properties shared consistently by no other set.

Although widespread, only rarely are J5 joints so closely spaced as to constitute a major element of the local fracture network. Spacings from 1-3 ft (0.3-1 m) were documented at only a single locality; in most other places the J5 joints are spaced 5-25 ft (1.5-7.5 m) apart. Arrest lines, twist hackle, and plumose structure are commonly found on J5 joint walls and show that they, like the members of the other sets, originated as extension joints.

COMPARISON OF FIELD AND PHOTOGEOLOGIC STUDIES

The traces of thousands of individual fractures are visible on true-color aerial photographs (about 1:27,000 scale) of the Esplanade Platform near the Ridenour mine (fig. 5). Nearly all are joints, although a few of the longest traces on the map represent minor faults. Most of the joints are visible directly as solution-widened clefts--narrow lines of shadow across a sunlit rock surface--and thus present no difficulty to a photo-interpreter interested in fracture networks. Others, hidden beneath a thin veneer of silty soil, are disclosed by rectilinear alignments of closely spaced desert shrubs. Although such alignments cannot unequivocally be proved to represent fractures, their similar orientations and lengths to nearby joints in bare rock leave little doubt as to their identity. Their numbers, in any event, are few compared to joints visible directly.

The fracture-trace map of Figure 5 is compounded almost entirely of three major fracture trends that correspond to the J1, J2, and J3 joint sets. The following characteristics of these joints as seen on the photographs were confirmed during field studies.

(1) J1 joints, of approximately due N strike, are large, only modestly abundant, and are irregularly distributed across the Esplanade surface.

(2) J2 joints, of approximate N70E strike, are also large, modestly abundant, and irregularly distributed.

(3) J3 joints, of approximate N60W strike, comprise by far the most abundantly visible joints and the most uniformly widespread set. Far more J3 joints were seen on the photographs than could be mapped at the scale of Figure 5. Their traces are notably shorter, on average, than those of either of the previous two sets, in keeping with their smaller size as observed in the field. Many J3 traces as seen on the photographs probably represent narrow zones of aligned J3 joints rather than individual fractures, most of which are significantly shorter than the traces on Figure 5 might imply. Thousands of J3 joints are visible in stream valleys where much bare rock is exposed, but their traces are less abundant on the adjacent plateau surfaces where thin veneers of unconsolidated sediment tend to obscure most joints.

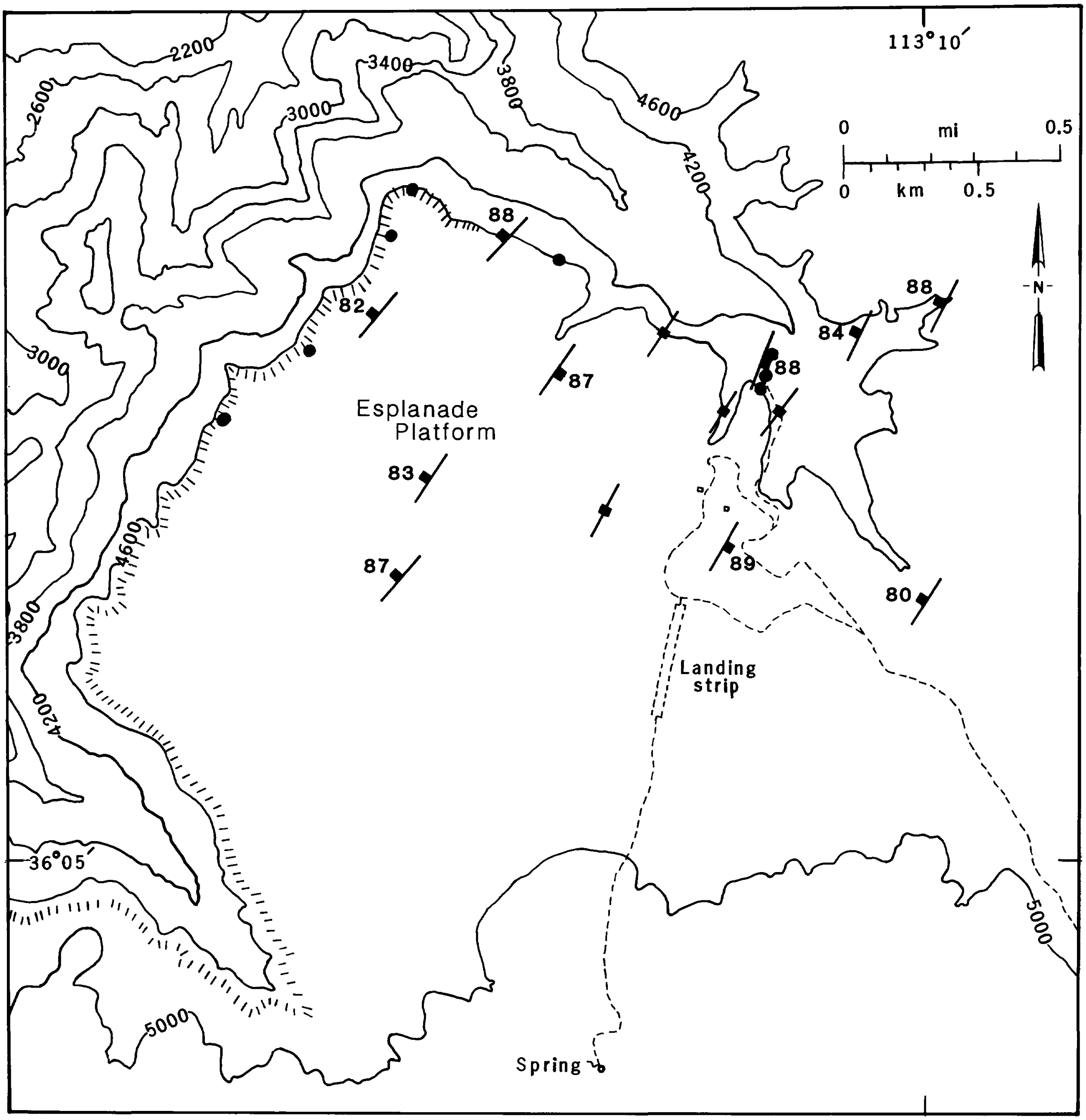


Figure 12. Orientations of J5 joints in Esplanade Sandstone around Ridenour mine. Most symbols represent the median of 12-20 readings. Overall median for entire area is N33E.

Overall, the aerial photographs provide an accurate view of the orientation and relative prominence of three major joint sets in the Esplanade Sandstone, and provide some evidence of their distribution as well. Moreover, had one endeavored to guess the relative age of the J1 through J3 sets from photographic evidence alone, the guess probably would have been correct. Such deductions rest on the assumption that the oldest joints are the longest--because no older fractures existed to impede their lateral growth--and that fractures of successively younger sets are progressively shorter. The average trace length of the joints of any particular set can then be taken as a crude guide to its relative age. The traces of J1 joints tend to be of uniformly substantial length wherever they are found and thus, by that criterion, the J1 joints probably comprise an early set. Some J2 joints, too, are of impressive length, but others are shorter, particularly in areas of abundant J1. In such areas it is rare to observe a J2 trace cutting across a J1 joint, and so the J2 joints appear to be the younger set. Finally, the myriad short traces of the J3 joints and the rarity with which they appear to cross other fractures suggest they are the youngest of the three prominent sets visible on the photographs. The relative ages of the three sets as documented on the ground are in good accord with properties of the individual joints as seen from the air.

Although it would certainly appear that photogeologic work in the Ridenour mine area could have provided a useful shortcut to structural studies, it must be emphasized that fracture histories as read from aerial photographs alone should neither be assumed to be true nor claimed to be complete. Demonstration that one joint set predates another necessarily rests on direct observation of abutting relations in outcrop, and sometimes with a hand lens. The distant view provided by aerial photographs should never be assumed to provide reliable information on such small-scale effects. Then, too, bed-parallel joints such as those of the J4 set are not visible on vertical photographs of horizontal beds, and so the photographs contain no evidence of at least one critical element of the fracture and uplift history of the area. Finally, the photographs used for this study were insufficient to reveal the widespread distribution or even the certain existence of the J5 joint set, due to the small size of those fractures. Our experience in other parts of the Grand Canyon region leads us to a similar conclusion: aerial photographs are a valuable tool to be used in structure studies, but considerable field work is mandatory to any believable interpretation of fracture history.

TIMES AND DEPTHS OF JOINTING

J4 and J5 sets

As in many other areas of horizontally bedded sedimentary rock, the presence of bed-parallel parting joints--in this case, the J4 set--provides a key for distinguishing old, pre-uplift joints from those formed later, during or after regional uplift and unloading. The pre-uplift joints presumably formed at deeper crustal levels, higher confining pressures, higher temperatures, and perhaps under conditions of higher fluid pressures than did their younger counterparts.

Bed-parallel parting joints in sedimentary rocks are analogous to sheeting joints in crystalline rocks but have been comparatively little studied. Recent work has shown that they can form within the upper 1,600 ft (500 m) or so of section (Hickman and others, 1985) and that, with local exceptions due to favorable lithology, their numbers decrease with depth. In one underground mine in Colorado, for example, bed-parallel joints in oil shales at the 490-ft (150-m) level are four times as abundant as their counterparts at the bottom of the mine, 340 ft (100 m) lower (E.R. Verbeek and M.A. Grout, unpub. data, 1986). Such studies suggest that, as in crystalline rocks, the presence of abundant subhorizontal extension fractures in little-deformed sedimentary rocks is indicative of fracture under relatively near-surface conditions. If such conditions were approached only once during the burial and uplift history of a given rock unit, such that the maximum age of the bed-parallel partings within that unit can be stated with some degree of certainty, then the maximum age of some joint sets and the minimum age of others can also be estimated.

Wenrich, Billingsley, and Huntoon (1986) suggest that regional uplift of the Hualapai and western Coconino Plateaus began during the compressive movements of the Laramide Orogeny, which they define in a broad sense to include Late Cretaceous through Eocene events. Uplift continued at intervals through the whole of Cenozoic time, ultimately elevating the region by 2-3 miles (3.2-4.8 km) and resulting in the stripping of thousands of feet of rock from the plateau surfaces since the close of the Cretaceous Period some 65 Ma (Wenrich, Billingsley, and Huntoon, 1986). Exactly when during this extended cycle of uplift the J4 joints formed in the Esplanade Sandstone is conjectural. Two facts, however, suggest that they are geologically quite young. First, knowledge that unloading joints form only at shallow depths implies that most of the overlying rock had already been stripped from the Esplanade Sandstone by the time the J4 joints formed. Second, Lucchitta (1979) presented evidence that more than 3,000 ft (900 m) of uplift along the Grand Wash cliffs, 40 mi (64 km) west of the Ridenour mine, has occurred only in the last five million years. That 20-30% of the total uplift occurred during the latest 7-8% of Cenozoic time suggested to Wenrich, Billingsley, and Huntoon (1986) that rates of uplift (and thus erosion) have accelerated in the recent geologic past. These two facts, taken together, suggest a late Cenozoic age for the J4 and J5 joint sets.

Additional evidence refines the probable age of the J4 and J5 sets still further. The relatively uniform orientations of the J5 joints across the Esplanade surface (fig. 12) imply the former existence, during J5 time, of uniformly oriented stresses within that unit, and hence the absence of steep local topographic gradients. Put another way, had erosional dissection of the Esplanade Sandstone already begun by J5 time, the J5 joints near the sites of incision--that is, near the present-day edges of the Esplanade Platform--could not have formed in the orientations they did. We thus conclude that the J5 joints formed before the Grand Canyon reached less than about half of its present depth. Canyon cutting at higher levels must nevertheless have already been in progress, for the presence of the J4 unloading joints shows that most of the Permian and Triassic strata, still preserved on nearby plateaus flanking the Grand Canyon, had been removed from the Ridenour mine area. Both the J4 and J5 sets, then, must date from the early stages of cutting of the western Grand Canyon. Lucchitta (in press) recently summarized evidence that this section of the canyon was excavated "in, at most, the interval between 6 Ma . . . and 1 Ma. More likely, it began to be cut shortly before 5 Ma and was nearly as deep as it is today shortly after 4 Ma." If so, the most probable age of the J4 and slightly younger J5 joints is around 5 Ma, or early Pliocene.

A postulated early Pliocene age for the J5 joint set is consistent with evidence that crustal stresses at that time were favorably oriented for the formation of a set of NE-striking joints. Crustal extension, beginning in Miocene time and continuing into the Pliocene, resulted in extensive normal faulting of the Grand Canyon region (Lucchitta, 1974; Huntoon, 1974), first along N-trending faults and somewhat later along those of NE trend. These movements were related by Huntoon (1974) to the onset of the Basin and Range Orogeny in areas to the west.

J1 through J3 sets

Nearly 270 million years elapsed between deposition of the Esplanade Sandstone in early Permian (Wolfcampian) time (McKee, 1982) and formation of the J4 and J5 sets in Paleocene time. Three sets of joints formed in the sandstones during this long interval, but determination of their absolute ages is difficult at present. Evidence to be presented in a later section, however, will show that all three sets are of post-late Triassic age, and thus younger--perhaps much younger--than 200 Ma. The general absence from the region of strata younger than Triassic frustrates attempts to date the fracture events more closely through conventional means. The J2 set in the Esplanade Sandstone possibly is Laramide in age because its joints strike about N70E, parallel to the direction of crustal compression during monocline development (Reches, 1978), but this is a tenuous suggestion at best.

Inasmuch as the J1 through J3 sets almost certainly predate canyon cutting, the vertical distance from the Ridenour mine to the top of the Kaibab Limestone, which caps the nearby plateaus, provides a minimum estimate of overburden loads at the times of jointing. That distance is 1,900-2,000 ft (560-590 m). If one or more of the J1-J3 sets formed before regional denudation had stripped the area to the Kaibab surface--that is, if some of the sets are pre-Laramide--then the thickness of the overlying Moenkopi Formation must be added. About 1,200 ft (360 m) of Moenkopi is preserved at Mt. Trumbull 21 mi (34 km) to the north and also probably covered the Ridenour mine area (G.H. Billingsley, oral commun., 1988). The minimum thickness of rock that once overlay the Ridenour strata, then, is about 3,100-3,200 ft (945-975 m). Whether any younger sediments of the Chinle and overlying formations were once deposited in this area is conjectural. Regardless of the uncertainties involved, it is clear from these simple arguments that the J1-J3 sets represent fracturing of the rock under conditions quite unlike those of the shallowly formed, and younger, J4 and J5 sets.

A COMMENT ABOUT JOINT STYLES

The relation between environmental conditions during fracture and the physical characteristics of the fractures produced is a complex one, understood only in general terms for most geologic applications. Several properties of the joint network near the Ridenour mine nevertheless seem worth noting, inasmuch as they clearly reflect changing conditions of fracture through time.

Fractures of the early J1 and J2 sets, which formed in moderately to deeply buried strata below the level at which unloading joints can form, commonly are of large vertical size. Many grew to heights of 5 m or more and cut multiple beds of sandstone, terminating vertically only against intervening beds of mudstone. Joints of these two sets are of such closely similar size and appearance that conditions during fracture probably were much alike. A change in conditions was signalled by the appearance of the J3 set, whose joints show a greater tendency to terminate against bedding surfaces than do their predecessors. This suggests as one possibility that fracture was now occurring at a shallower depth. Finally, the most shallowly formed joints, those of the J5 set, are almost uniformly of small vertical extent because their growth in that direction was restricted by the then-common subhorizontal joints of the J4 set. Decreasing joint age and decreasing depth of fracture, then, were accompanied in this area by a general decrease in joint height.

Studies by two of us (Verbeek and Grout, 1983, 1984; Grout and Verbeek, 1985) in several other areas of the western U.S. have disclosed broadly similar results. In areas where the geologic history is not clouded by multiple episodes of uplift and reburial, the earliest (and thus most deeply formed) joints commonly terminate only against contacts between strata of dissimilar lithology. Where the beds are thick or where multiple beds of similar lithology are in contact, these joints are of large vertical extent. Joints of later sets known or inferred to have formed at somewhat shallower depth often show a tendency to terminate against more minor lithologic contacts, and are thus smaller. Post-uplift joints that formed in near-surface rocks already pervaded by unloading joints generally are the smallest of all. It is often possible, then, to distinguish at a glance which among several sets of coexisting fractures formed early and at an appreciable depth, and which formed later and nearer the surface. We stress, however, that this is a general tendency only, with known exceptions, and that joint size should not by itself be considered a reliable criterion of either relative age or depth of formation.

MINERALIZATION AND ALTERATION ALONG JOINTS

J1 through J3 joints

Alteration of the sandstone wall rock adjacent to J1 through J3 joints was noted at many localities. The most common effect is bleaching of the normally pink or brick-red sandstone to pale shades of orange-gray or tan, rendering many joints highly visible as prominent stripes across pavement outcrops. The degree to which the walls of individual joints are altered shows obvious correlation with joint age: where joints of two different sets coexist in the same bed, bleached zones along joints of the older set are invariably wider than those along joints of the younger set. Near station RM-22, for example, wall rock adjacent to J2 joints is bleached for distances of 0.2-0.3 inch (5-8 mm) from the joint planes, whereas for J3 joints the corresponding distances are only 0.08-0.16 inch (2-4 mm) (fig. 13). In another outcrop nearby the bleached zones extend 0.04-0.12 inch (1-3 mm) to either side of J3 joints, but J5 surfaces are not bleached at all. Observation that the oldest joints are consistently the most altered suggests that the joints of each set, once formed, generally remained open to ground-water flow thereafter rather than being quickly sealed by precipitation of secondary minerals within them.

The comparative rarity in the area of joint intersections, as opposed to simple terminations, shows that complete closure of the joints of any one set by cementation prior to formation of the subsequent set was only locally achieved. This, too, suggests that the joints of any given set generally remained open to ground-water flow long after their formation. However, partial closure by precipitation of secondary minerals as thin films on joints was rather common. Careful examination with a hand lens of horizontal pavement exposures reveals in many places the presence of thin coatings of colorless to white, coarsely crystalline calcite on the walls of J1 through J3 joints. In most joints the calcite grew upon walls already discolored (bleached) by ground-water flow, but in some the calcite was deposited upon a pristine joint wall, implying precipitation shortly after joint opening. In a few areas a hair-thin film of a nearly black mineral (goethite?) intervenes between the joint wall and the white calcite. The wall rock itself commonly is impregnated with calcite for distances of 0.1-0.4 inch (3-10 mm) outward from the joint planes and thus is both more firmly cemented and less porous than the adjacent, unaffected sandstone more distant from the joints. Even where prolonged weathering has stripped all trace of mineral coatings from the J1 through J3 joint walls, as it has in much of the area, the tendency for the adjacent well-cemented rock to protrude as thin ribs from weathered outcrop surfaces attests to carbonate mineralization along the fractures at some time in the past.

J4 and J5 joints

Opportunity to document the effects of alteration and mineralization along J4 joints was limited because the sandstones, upon exposure, flake readily parallel to bedding. Nevertheless, probable remnants of thin calcite coatings, now highly weathered, were noted in a few places. Thin infillings of translucent white calcite were likewise noted within J5 joints in several places where these joints were best protected from weathering. Bleaching of the wall rock adjacent to J4 or J5 joints, however, was not observed at any locality.

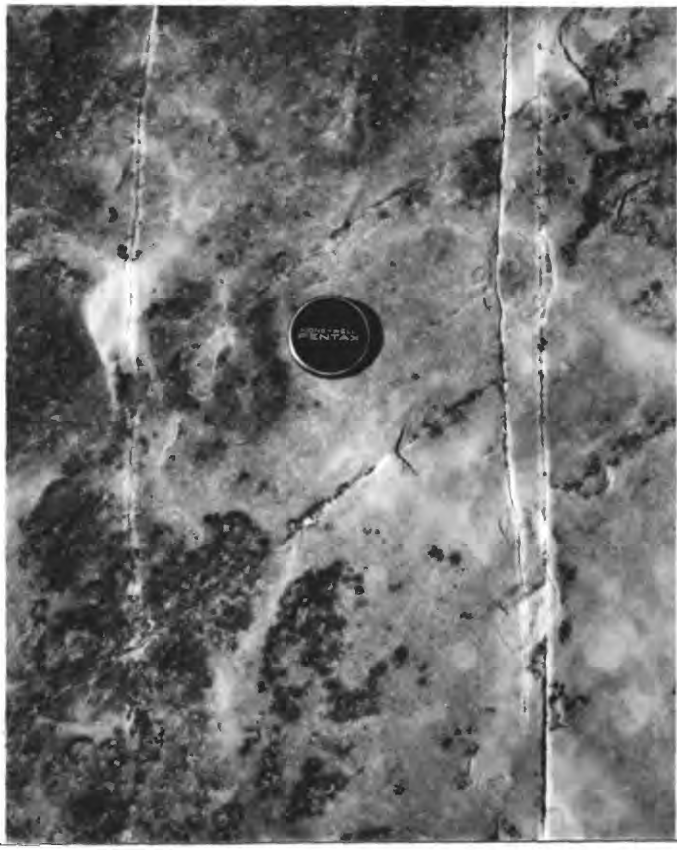


Figure 13. Bleached (reduced) rock adjacent to J2 and J3 joints near station RM-22. Photograph of horizontal surface. Note that widths of bleached zones are wider for the older J2 joints (parallel to long edge of photograph).

Discussion

The overall picture that emerges from the evidence available is one of prolonged ground-water flow through a well-interconnected network of J1 through J3 joints, with only incidental (and geologically late) contribution to the flow network by the younger and generally tighter J4-J5 joints. Detailed study of the mineralogic and chemical effects accompanying alteration of joint walls and deposition of secondary minerals upon them is beyond the scope of this study, but a few general conclusions are evident from field observations:

(1) Fluids circulating through J1-J3 joints were capable of removing finely divided hematite pigment from the original rock to leave narrow bleached zones adjacent to the joint walls. The reducing agent presumed responsible for this process remains unidentified. The absence of visible pyrite and rarity of goethite within the bleached rock or coating the joints suggests that most of the iron was removed in solution rather than being redeposited locally in some other form. (The limonite commonly seen on exposed joint walls along the canyon rim is a much younger product of weathering.)

(2) The absence along J4 and J5 joints of bleached zones comparable to those along J1-J3 joints shows that the reducing fluids migrated through the Esplanade Sandstone before uplift, while that unit was still deeply buried. Upon subsequent uplift and erosional unloading, when the J4 and J5 joints formed in the shallow subsurface, the Esplanade Sandstone was subject only to the influences of shallowly circulating, oxidizing, meteoric

ground waters. The joint network shows clearly the effects of changing fluid chemistry with time.
(3) None of the fluids circulating through J1-J5 joints were at any time capable of removing carbonate from the host rocks to widen the joints by solution. As shown later, this stands in sharp contrast to the extreme effects of solution-widening along ring fractures within the same rocks adjacent to the Ridenour pipe. Evidence for the lack of solution along joints is seen throughout the area and takes several forms: (a) The opposing walls of many joints are irregular in detail but almost perfectly matched, such that the fracture could be closed completely if pressed together. Dissolution of wall rock adjacent to joint surfaces would destroy this relationship. (b) The preservation on many joints of delicate surface features that formed during fracture propagation shows that the joint faces, though altered in many examples, have retained their original form. Plumose structure on most joints, for example, cannot survive removal of material more than one or two grain diameters inward from the original joint walls, yet joint plumes are magnificently preserved on many joints and have been modified only by weathering upon exposure. (c) The calcite fill in all joints is clean and lacks inclusions of quartz grains decemented from the adjacent wall rock.
(4) Calcite was deposited from both reducing and oxidizing solutions as a stable phase during nearly the entire fracture history of the Esplanade Sandstone. Evidence for this stems from the manner in which the joints of various sets abut and crosscut one another. Although fracture intersections are relatively uncommon, implying a fairly open fracture network as noted previously, their local presence is instructive as to timing of mineralization within joints. Intersections of the following types have been recorded: J2 joints across J1, J3 across J1 and J2, and J4 and J5 across joints of all previous sets. The only common phase within all these fractures is calcite. These observations imply that deposition of calcite within the joints of any one set had already begun by the time the succeeding set formed, thereby enabling those joints already bonded together in stress-transmitting contact to be crosscut by members of the younger set. The picture that emerges is one of slow deposition of calcite over a protracted period of time, during which multiple fracture sets were created in the Esplanade Sandstone. Rates of deposition were such that most joints were slowly plated with calcite, but not sealed completely, thus remaining open to fluid flow. In a few places, however--and particularly among small joints of narrow original aperture--mineralization was complete and younger fractures cut across older, sealed joints.

Post-exposure effects

A very late stage of mineralization is recorded by the presence of a highly calcareous, fine-grained, porous material that filled all remaining fracture space in many outcrops in the study area. This material is variously white, pale gray, or tan, has a low specific gravity due to its great porosity, and has a chalky appearance resembling travertine or caliche. Observations in the Ridenour mine confirm the latter origin, for the chalky fracture fillings exist only within the shallowest mine workings and fail to persist to depth. Fillings of caliche within J1 through J3 joints commonly are 0.1 to 0.8 inch (0.3-2.0 cm) thick but in some places attain thicknesses of 1-2 inches (2.5-5 cm); analogous fillings in J4 and J5 joints, in contrast, rarely exceed 0.3 inch (0.7 cm). Grains of fine quartz sand, weathered from the Esplanade Sandstone and blown or washed into open fractures, are embedded in caliche at many sites. Locally these are accompanied by angular fragments of wall rock to form a sandy, calcareous, matrix-supported "breccia" bearing a superficial resemblance to concrete. The young age of the caliche is reflected by its presence in joints of every set in the area as well as by its form--as continuous, unbroken fillings extending from one weathered fracture into others of different orientation (fig. 14).

Figure 14. Continuous filling of caliche within open, weathered J3 and J5 joints. Photograph of horizontal pavement surface. J3 joints are parallel to tape.

REACTIVATION OF JOINTS

The joints of all five sets of the Esplanade Sandstone around the Ridenour mine formed as extension fractures, but evidence of reactivation of several sets was seen at many localities. Although detailed study of the directions and sequence of such movements could add much new information to the structural history of the region, especially as regards stress directions and movements on nearby faults, such study was beyond the scope of our work. Below we record only a few observations, together with brief comments on their possible tectonic significance.

The realization that some joints were sheared laterally subsequent to being opened, whereas others of different orientation were simply opened further without shear, has proved intriguing. Although many joints in the area are too highly weathered to permit easy recognition and measurement of small amounts of lateral slip, such slip did occur and probably was common. Between stations RM-5 and RM-8, for example, the evidence for horizontal shear along some joints was especially clear. In this area, within a complex zone of interaction between J2 and J3 joints, oblique right-lateral reopening of numerous J2 joints was documented by matching points along one irregular joint wall to their offset counterparts on the opposing wall. The measured strains ranged from 0.08 to 0.3 inch (2-8 mm) in a N20E-N45E direction, roughly perpendicular to the J3 joints. The movements thus probably date from the time of formation of the J3 set.

Continuation of the same strain whose initial increments gave rise to the J3 joint set could well explain a variety of observed structures in the Ridenour mine area. The following events, from oldest to youngest, are possibly all related to a single, protracted period of NNE- to NE-directed, horizontal crustal extension: (1) Formation of abundant J3 joints and concomitant shear along preexisting J2 joints. (2) Widening of some J3 joints to form extensional fissures as strain continued. (3) Local inception of vertical movement along J3 surfaces as the strata were gradually pulled apart. At station RM-2, for example, stratigraphic separations of 1-4 inches (about 3-10 cm) occurred along J3 joints and resulted in segmentation and offset of previously mineralized ring fractures near the Ridenour pipe (fig. 15). (4) Map-scale faulting as offset along J3 joints increased with continuing extension. The series of WNW-striking faults that offset the Esplanade Sandstone northeast of the Ridenour mine (Wenrich, Billingsley, and Huntoon, 1986) may be structures of this type--they are mapped as having vertical rather than inclined dips and likely represent reactivation within a linear zone of previously formed J3 joints. Though such structures are common on the Colorado Plateau and invariably are portrayed as faults on geologic maps (see McGill and Stromquist, 1979, for spectacular photographs), it is important to realize that they did not originate through shear failure of the affected strata.

The above scenario implies that some normal faulting in the Ridenour mine area—and particularly along WNW- to NW-trending faults parallel to the J3 set—occurred prior to formation of the bed-parallel J4 set, and thus before the main phase of regional uplift. If so, movement on those faults predated movements along the much more numerous faults that strike NNW to NNE and that were either created or reactivated in late Cenozoic time during E-W, horizontal crustal extension (Wenrich, Billingsley, and Huntoon, 1986).

As already mentioned, secondary opening of scattered joints to create prominent fissures was noted at many places. Amounts of opening of 0.5-3.0 inches (1.3-8 cm) are common among J1-J3 joints, but openings of more than 0.2 inch (0.5 cm) are rare among the much younger J5 joints, most of which retain their original narrow apertures. The probable manner and time of opening of the J2 and J3 joints was mentioned above, but the time of opening of the earlier J1 joints is only speculative. If they too were reactivated during J3 time, as seems likely, then a component of left-lateral shear should have occurred along the affected joints during reopening. Additional reopening almost certainly took place during the late Cenozoic E-W crustal extension of the region, as the J1 joints are ideally oriented for such to have occurred. Regardless, it is clear from field evidence that the large wall separations observed along some J1 joints represent not their original apertures, but rather some later event that postdates formation of the J1 set. Widths of the translucent, white calcite that filled some J1 joints show that their apertures at the time of filling were modest, about 0.04-0.08 inch (1-2 mm). Some of those filled joints were later cracked open, so that bits of the calcite layer now cling to one joint face and the remaining bits to the other. The intervening space, locally as much as 3 inches (8 cm) wide, commonly is filled with caliche of quite different appearance from the earlier calcite.

STRESSES INFERRED FROM JOINT SETS

Regional stress histories in the Grand Canyon region most commonly are inferred from the movement histories of various sets of faults, but joints offer a supplemental and likely more sensitive source of information about more subtle aspects of paleostress fields. The reasons are that extension joints in most rocks form at much lower stresses than those necessary to induce shear failure in the same materials, and the amount of strain necessary to produce even a prominent set of joints commonly is only a fraction of one percent. A set of joints, then, often is the ONLY structural record of a given period in a region's geologic history. The main disadvantages of joints are that their absolute ages can only rarely be determined with certainty, and the causes of the minor strains and low stresses that produced them are frequently obscure. Nevertheless, used in conjunction with other, more conventional evidence, joints provide a much more thorough view of regional stress histories than could otherwise be obtained. As in the preceding section, we offer here only a few observations with brief interpretation of the results.

Figure 15. Minor normal offsets along reactivated J3 joints near station RM-2, Ridenour mine. Faulted dark layer is a mineralized ring fracture. View to WNW.

For extension fractures such as those of the J1 through J5 sets, the orientation of some components of the stress field at the time of failure can be confidently inferred from the orientations of the joints themselves. Experimental evidence bearing on the propagation paths of actively growing extension fractures in rock relative to applied macroscopic stresses were summarized recently by Barton (1983). The results show consistently that extension fractures propagate perpendicular to the direction of least compression (or greatest tension if one or more of the principal stresses are tensile). The orientation of σ_3, then, can be uniquely defined for each joint set in the Esplanade Sandstone as the perpendicular to the joint planes. Where a given set exists over a wide geographic area as a common element of the total fracture network, the σ_3 orientation of the regional stress field during the time of formation of that set can be regarded as comfortably established. Knowledge of the relative ages of the various sets then provides some impression of how the stress field evolved through time. The orientations of σ_1 and σ_2 are more troublesome, for generally it is known only that they must lie within the plane of the joint. In the absence of extreme topographic relief, an often-made and frequently valid assumption is that one of the principal stresses must be vertical and due to superincumbent load, and the other horizontal. This cannot always be demonstrated, however, and thus it is generally more wise to speak of σ_v, the vertical stress, and σ_{hmax}, the maximum horizontal compressive stress. The latter is parallel to joint strike and is equivalent, in tectonic parlance, to the "direction of crustal (or tectonic) compression" or (both vaguely and incorrectly) the "direction of tectonic stress". For both, of course, the stress magnitudes are such that $\sigma_2 \leq \sigma_v, \sigma_{hmax} \leq \sigma_1$.

J1 through J3 sets

The existence within the Esplanade Sandstone of at least five sets of extension fractures, every one of very different orientation from the rest, shows at a glance that the regional stresses changed markedly in direction with time. The first three sets of joints, all of which formed under considerable overburden load before canyon-cutting commenced, are vertical. The orientation of σ_3, then, during the (presumably) long time interval spanning these three periods of fracture, remained horizontal throughout but rotated to different directions with time. With reference to Figures 6, 8, and 9, those directions were about N85W (J1), N20W (J2), and N30E (J3). The corresponding directions of "tectonic compression", or σ_{hmax}, during these same periods were about N5E (J1), N70E (J2), and N60W (J3). All three sets at present can be dated only as post-late Triassic and pre-Pliocene, but future work along nearby monoclines and the many faults of the region could do much to establish the ages of these larger structures relative to the various sets of joints.

Crude estimates of overburden stress during the J1 through J3 fracture episodes can be derived from available data. An estimated average specific gravity of 2.49 for the section between the Esplanade Sandstone and the top of the Kaibab Limestone can be obtained from the lithologic descriptions and thickness data of Wenrich, Billingsley, and Huntoon (1986) and the physical properties of different rock types compiled by Balmer (1953). Inclusion of the overlying Moenkopi Formation reduces this average to 2.43. Using the estimates of overburden thicknesses at the times of fracture from p. 26, formation of the J1 through J3 sets occurred under minimum total vertical loads (S_v) of about 140 bars (14 MPa). Maximum likely vertical loads were about 230 bars (23 MPa) but could have been greater if any post-Moenkopi strata once covered the area and one or more of the sets formed during maximum burial. These values, 140-230 bars, are total vertical stresses and make no assumptions about fluid pressures during fracture. Assuming fluid-saturated rock and no overpressure during fracture, the effective vertical stress ($\bar{\sigma}_v = S_v - p_f$) would reduce to 85-134 bar (8.5-13.4 MPa). Fluid overpressures during any fracture event would, of course, have reduced the vertical load still further.

J4 and J5 sets

Late Cenozoic regional uplift initiated a still-continuing cycle of erosion that ultimately stripped thousands of feet of overburden from the Esplanade Sandstone. Toward the latter part of this period, probably in early Pliocene time, sufficient rock had been removed that the vertical was now the σ_3 direction, and the subhorizontal unloading joints of the J4 set developed. Concerning horizontal stresses during this period we know only that a σ_{hmax} direction of roughly N-S is compatible with the tectonics of the time as recounted by Huntoon (1974) for the nearby eastern Grand Canyon region. The Ridenour mine strata during formation of the J4 set almost certainly were within 1,500 ft (450 m) of the surface, and probably much less. This corresponds to overburden loads of less than about 35 bars (3.5 MPa)--a considerably different environment from that postulated above for the J1-J3 sets. Despite the fact that the strata were already near the surface and that incision of the Esplanade Sandstone by the rapidly deepening Grand Canyon probably occurred less than a million years later, an additional and final set of vertical joints--J5--developed. The J5 set shows that σ_3 was once again horizontal and probably reflects active tension associated with post-Laramide Basin-and-Range crustal stretching in areas to the west.

SUMMARY AND CONCLUSIONS

The joint network of the Esplanade Sandstone near the Ridenour pipe is the combined product of five separate episodes of extension fracture. Evidence to be presented later, from geologic relations in the Ridenour mine, suggests that all five sets are of post-Late Triassic age. The first three sets, with average strikes of about due N (J1), N70E (J2), and N60W (J3), formed before bed-parallel parting joints (J4), due to erosional unloading in late Cenozoic time, had split the thick sandstone beds into thinner slabs. The J1 through J3 joints thus probably predate the main phase of regional uplift and erosion or occurred during its early stages, and formed under conditions of considerable overburden load. Estimates of overburden thickness during J1-J3 joint formation range from 1,900-3,200 ft (530-950 m), and possibly more. These joints probably remained well below the local water table for much of their history and served as effective conduits for the movement of fluids, at least some of them reducing. Rock immediately adjacent to the joint walls was altered by prolonged fluid flow and commonly became further indurated by the precipitation of calcite in available pore space. Additional calcite formed coatings on J1 through J3 joint walls, but the comparative rarity of joint intersections, as opposed to simple terminations, shows that complete closure of joints by cementation was only locally achieved. The fracture network is well interconnected and probably remained open to fluid flow for most or all of its existence.

Regional uplift of between 2 and 3 miles (3.2-4.8 km) during much of Cenozoic time resulted in erosional unloading and the attendant formation of bed-parallel parting joints of the J4 set, analogous to "sheeting joints" in many plutonic and some metamorphic rocks. Additional vertical joints of the J5 set, of average N35E strike, then formed within the overlapping slabs of rock bounded by the horizontal J4 joints. Both sets are of young geologic age--probably early Pliocene--and most likely are present only within near-surface rocks. Rock adjacent to J4 and J5 joint walls is unaltered and only locally coated with thin films of calcite, showing that these young, shallow joints played only a minor role in the hydrologic history of the region.

GEOLOGY OF THE RIDENOUR MINE

GENERAL CONFIGURATION OF PIPE AND MINE

The Ridenour pipe crops out within an east-facing, semicircular embayment high on the southwest wall of an unnamed, northwest-trending tributary canyon south of the Colorado River (fig. 16). Erosion has cut obliquely through the pipe such that the ring-fracture zone along its north, west, and south edges is splendidly exposed in outcrop at mine level, and also along the canyon wall below it, but much of the eastern third of the pipe has been removed. Ring fractures bordering the east edge of the pipe, however, are exposed along the rock-floored stream valley below the mine, and a small outcrop of the core breccia occurs on the west side of the same valley, just above stream level, at the base of the mine dumps. The rest of the pipe core and the innermost portions of the ring-fracture zone are covered by dump material and the access road to the mine, but good exposures occur underground.

The pipe in map view is nearly circular (fig. 17). From edge to edge of the ring-fracture zone it measures slightly more than 500 ft (150 m) across. The diameter of the pipe core, in the only place where this could be measured, is 290 ft (83 m). The latter measurement, however, is approximate only, for pipes are known to vary in diameter with depth, and the measurement was made of necessity between two points 140 ft (42 m) apart vertically. The pipe is conspicuous on aerial photographs and is visible from afar because the normally red Esplanade Sandstone is strongly bleached to ivory and buff colors in and near the pipe.

Figure 16. Aerial view, looking SSW, of Ridenour mine. Prominent joints in sandstones above the mine are members of the J3 set. Photograph by Karen J. Wenrich, 1982.

The mine workings, most of which are underground, are almost wholly confined to, and closely follow, the curving ring-fracture zone within country rock along the western edge of the pipe (fig. 17). The main, and lowest, level of the mine, an arcuate drift several hundred feet long and about 50 ft (15 m) below the surface, provided access to a series of narrow overhand stopes along heavily mineralized portions of the ring-fracture zone. Some waste rock was removed through a haulage adit whose portal opened to the canyon to the east, and the remainder was used as backfill in several of the stopes, rendering them inaccessible. Shallower stopes, also along the ring-fracture zone, were worked either downward from access holes at the surface or laterally from adits driven into the hillside at road level. A few short prospect adits driven across the ring-fracture zone complete the surface workings. Waste rock from the surface excavations was dumped into the canyon to the east, nearly covering the portal of the haulage adit from the deeper levels.

Within the canyon below the Ridenour mine are four prospect adits, two of them driven into the southern part of the ring-fracture zone, one into the northern part, and one into the core breccia. The southern adits were both sited along conspicuously mineralized portions of the ring-fracture zone, where Cu- and V-mineralized fractures, green and charcoal gray in outcrop, cut bleached Esplanade Sandstone. The upper adit extends inward only about 10 ft (3 m) to a point where it is clogged by rubble, but the lower adit is about 105 ft (32 m) long as measured by pacing. The small adit in the core breccia farther north, near stream level, is only about 20 ft (6 m) long and reveals no trace of ore minerals. The fourth adit, an oblique cut through the northern edge of the ring-fracture zone, is about 60 ft (18 m) long but shows only sparse signs of mineralization in the form of small and dispersed spots of malachite. Radioactivity counts in all four adits are low, and it is doubtful that any of them produced anything but small amounts of copper ore.

The map of Figure 17, adapted from Miller (1954) but with considerable additions, shows most of the workings of the Ridenour mine. Although some ore was produced during the early 1960's, the mined area today is not much changed from the time of Miller's visit.

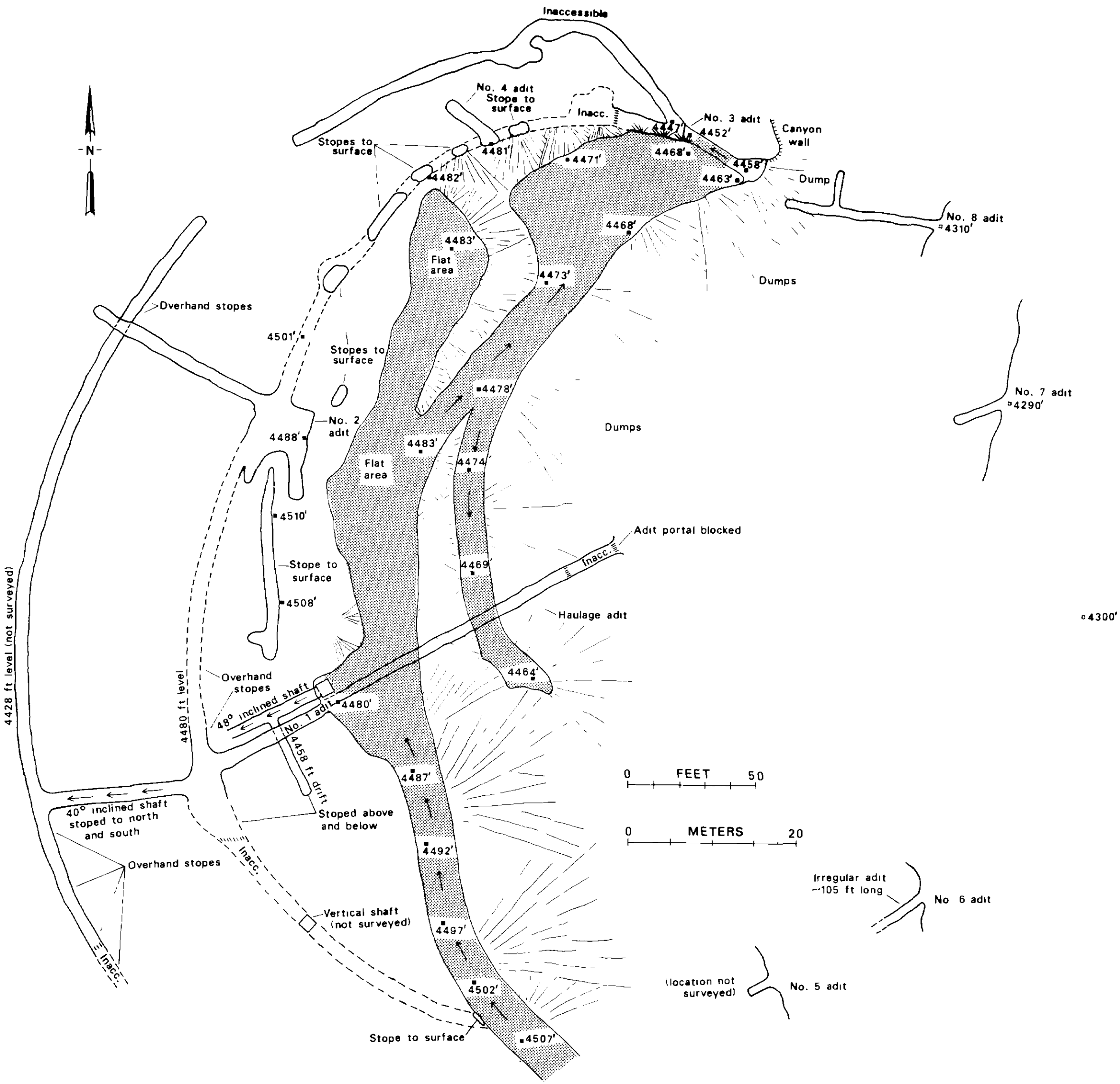


Figure 17. Plan-view map of Ridenour mine, showing surface and underground workings. Adapted from Miller (1954) but with considerable additions. Elevations shown as solid squares are based on assumed elevation of 4,480 ft at no. 1 adit. Open squares denote approximate elevations determined from topographic map.

PRODUCTION HISTORY

Broadly curved ring-fracture surfaces coated with malachite and azurite are still preserved in the canyon below the Ridenour mine and doubtless attracted the attention of early prospectors, who reportedly discovered the deposit sometime during the 1870's (Miller, 1954). Records of early production are scant, but mining for copper probably began as early as 1887 (Chenoweth, in press) and continued intermittently until about 1916. Toward the latter part of this period, during World War I, about 1,000 tons of hand-sorted ore was transported by burro and freight wagon to a railhead near Peach Springs (Miller, 1954). Thereafter, for more than forty years, the mine lay idle.

The Ridenour mine attracted attention once more in the 1950's as a potential source for uranium. R.D. Miller, then with the Atomic Energy Commission, confirmed in his 1954 report the presence of high-grade uranium ore and was guardedly optimistic about reserves, stating that uranium ore occurs "in significant quantities" but that the uranium-vanadium zone had not yet been exposed sufficiently by the mine workings to reliably estimate reserves. Mining records show that only a single shipment of uranium ore, totaling 14 tons and averaging 0.15% U_3O_8 and 2.36% V_2O_5, was made from the Ridenour mine in early 1961 (Chenoweth, in press). A small (10 ton) shipment of copper ore was also made from the mine about this time. From then on, apparently, the mine lay idle once again.

The Ridenour pipe was drilled in 1976 to assess its potential for uranium at depths below those exposed by past mining operations. Three holes drilled by Western Nuclear, Inc., to depths ranging from 324 to 990 ft (99 to 302 m), disclosed little mineralized rock, and in 1978 the company's lease on the property was dropped (Wenrich, Billingsley, and Huntoon, 1986). Copper-, vanadium-, and uranium-mineralized rock is nevertheless abundant both in the surface and underground workings of the mine, and the site offers a splendidly exposed view into the ring-fracture zone of a mineralized breccia pipe.

A detailed review of the historical development of the Ridenour mine is given by Chenoweth (in press).

HOST ROCKS NEAR MINE

Beds of the Esplanade Sandstone near the mine commonly are 6-20 ft (2-6 m) thick and crop out as a stepped sequence of elongate ledges and low cliffs (fig. 16). The local section is 90-95% sandstone, interlayered in places with thin and generally poorly exposed layers of siltstone and silty shale. Individual sandstone beds are lenticular in cross section, and though most can be traced laterally along canyon walls for hundreds of feet or more, many can be seen to pinch out gradually to zero thickness. Nearly all contain prominent sets of planar cross strata. Most of the sandstone beds are quartz-rich, porous, and only moderately indurated, with variable but generally small amounts of calcite as the most obvious cementing agent. Their normal color on both fresh and weathered surfaces is pale to medium brick red, except in and near the mine where the rock is bleached. A partial stratigraphic section, measured in unaltered strata along the east-facing canyon wall just north of the mine, is shown in Figure 18 and described in Appendix A. The section includes all units exposed at the surface and in shallow workings of the mine.

STRUCTURE OF THE PIPE CORE

The central, brecciated core of the Ridenour pipe is best visible along a haulage adit once used to convey waste rock from subsurface workings of the mine eastward to the canyon into which the rock was dumped. The adit portal has been blocked and is now almost buried by additional waste rock dumped from the higher, surface workings of the mine. Present access to the core is via an inclined shaft, partly choked with rubble, adjacent to the main entry adit to the mine at road level (fig. 17).

Within the haulage adit the contact between country rock and collapse breccia of the pipe core is abrupt and of steep dip. The breccia is polylithologic and consists mainly of sandstone and subordinate siltstone derived from the upper half of the Esplanade Sandstone and overlying Hermit Shale. Bedding is visible in many clasts and shows that they are diversely oriented within the breccia. The breccia is clast-supported and poorly sorted, with clast sizes ranging from small pebbles barely an inch (2.5 cm) across to large

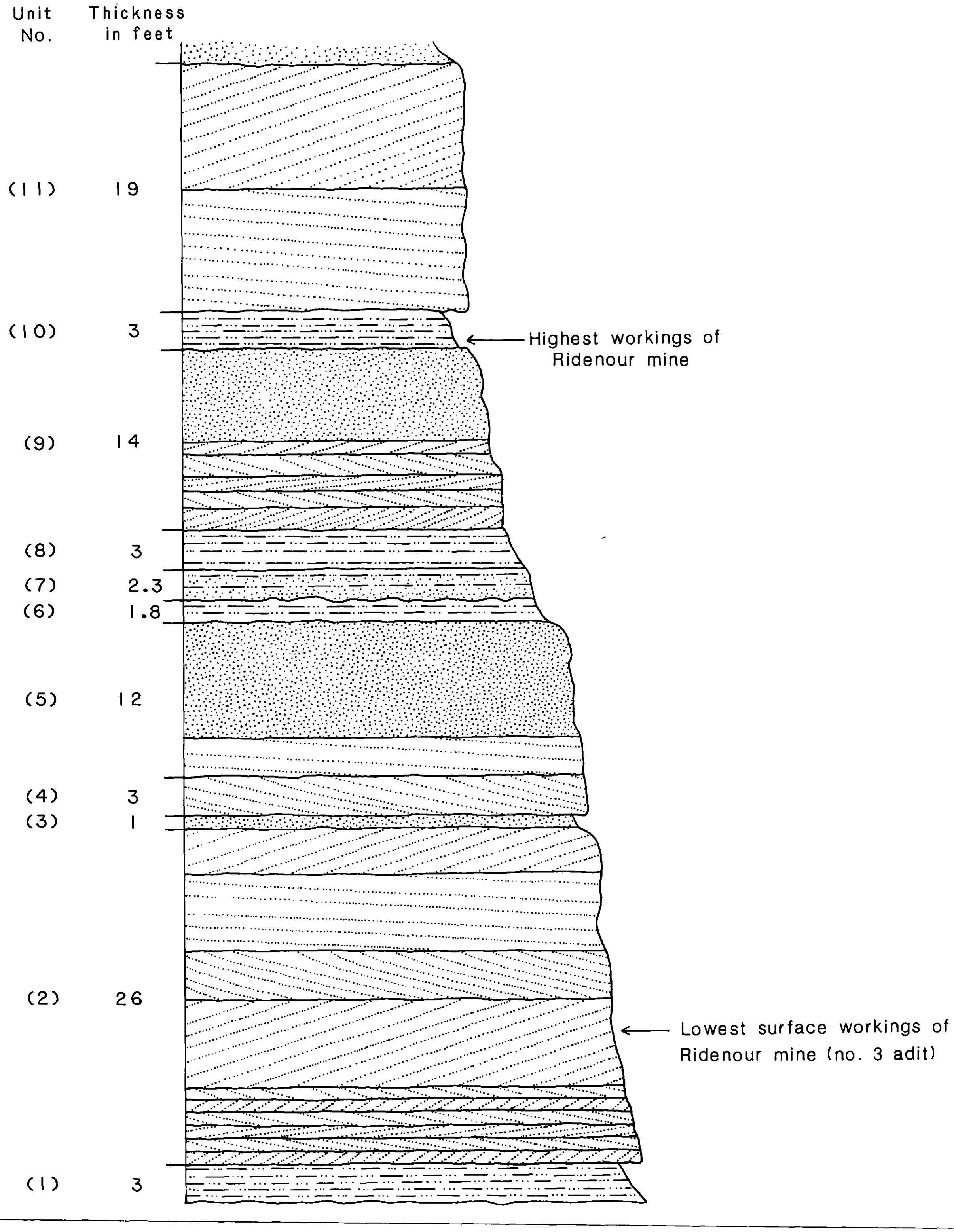


Figure 18. Partial stratigraphic section along west wall of canyon immediately north of Ridenour mine. Description in Appendix A.

slabs more than 10 ft (3 m) in length. Some of the smaller fragments are equant to subequant, but the larger clasts occur mostly as plates and slabs with broad upper and lower surfaces defined by bedding. Spaces between clasts are filled with loose, white sand so that few macroscopic voids remain. The sandy matrix probably was derived in large part from disaggregation of sandstone clasts originally cemented by calcite. The breccia is unstable and the clasts poorly lithified due to this same process of decementation.

Two aspects of the core breccia are worthy of special note. First, the presence of clasts derived from the Hermit Shale shows that downward movement of at least some clasts in the Ridenour pipe was in excess of 500 ft (150 m), the approximate vertical distance between the haulage adit and the base of the Hermit Shale in nearby exposures. This amount of downdrop is well within the range of clast displacements reported for other pipes. Second, the character of the core breccia is in full accord with a derivation by collapse. Inequant clasts, especially large plates and slabs of thinly bedded sandstone and siltstone, tend to lie with their broad, flat surfaces at only shallow angles to the horizontal. Only among the smaller and more equidimensional clasts are steep as well as shallow dips common. This correlation of dip with clast shape and size is exactly what should result from free-fall of debris detached from the walls and roof of an open chamber onto a rubble-strewn floor below.

STRUCTURE OF THE RING-FRACTURE ZONE

Ring fractures

Large, arcuate, outward-dipping ring fractures form a well-defined zone within bleached country rock around the core of the Ridenour pipe. The structure of this zone along a hypothetical radial section from the edge of the pipe core outward is shown in Figure 19, and Figure 20 shows some of its properties in map view. The total width of

Figure 19 (next page). Composite sketch showing idealized cross-sectional geometry of a ring-fracture zone bordering a breccia pipe in the Esplanade Sandstone, based on exposures in the Ridenour mine. Note that the width of the ring-fracture zone varies from bed to bed as a function of lithology. The width of the zone of bleached rock varies accordingly. Large pockets of mineralized breccia are relatively abundant in permeable sandstones cemented primarily by calcite (middle of figure) but become less abundant and smaller in less permeable, more firmly lithified beds, especially those cemented by quartz (top of figure). Solution cavities along the ring fractures locally end abruptly along bedding-plane contacts with less-permeable beds, as at (A). Breccia within the solution cavities generally is monolithologic and derived from the adjacent wall rock, but a few cavities close to the pipe core contain mixed clasts (B). These clasts, once part of the core breccia, apparently tumbled or were washed into large voids along ring fractures that opened directly to the pipe core. The core/country-rock contact is steep in most places but locally has a more shallow dip where the country rock fell away along a ring fracture, as at (C).

Individual ring fractures in sandstone terminate against major lithologic discontinuities such as the thin shale bed at (D), but commonly extend through the contact of one sandstone bed with another (E) of similar lithology. Average dips of ring fractures range from 45^{o}-55^{o} for most beds observed, but dips along portions of some irregular fractures locally are as shallow as 20^{o} (F) or as steep as vertical (G). Within any one bed the ring fractures generally become both smaller and less abundant as the outer edge of the ring-fracture zone is approached.

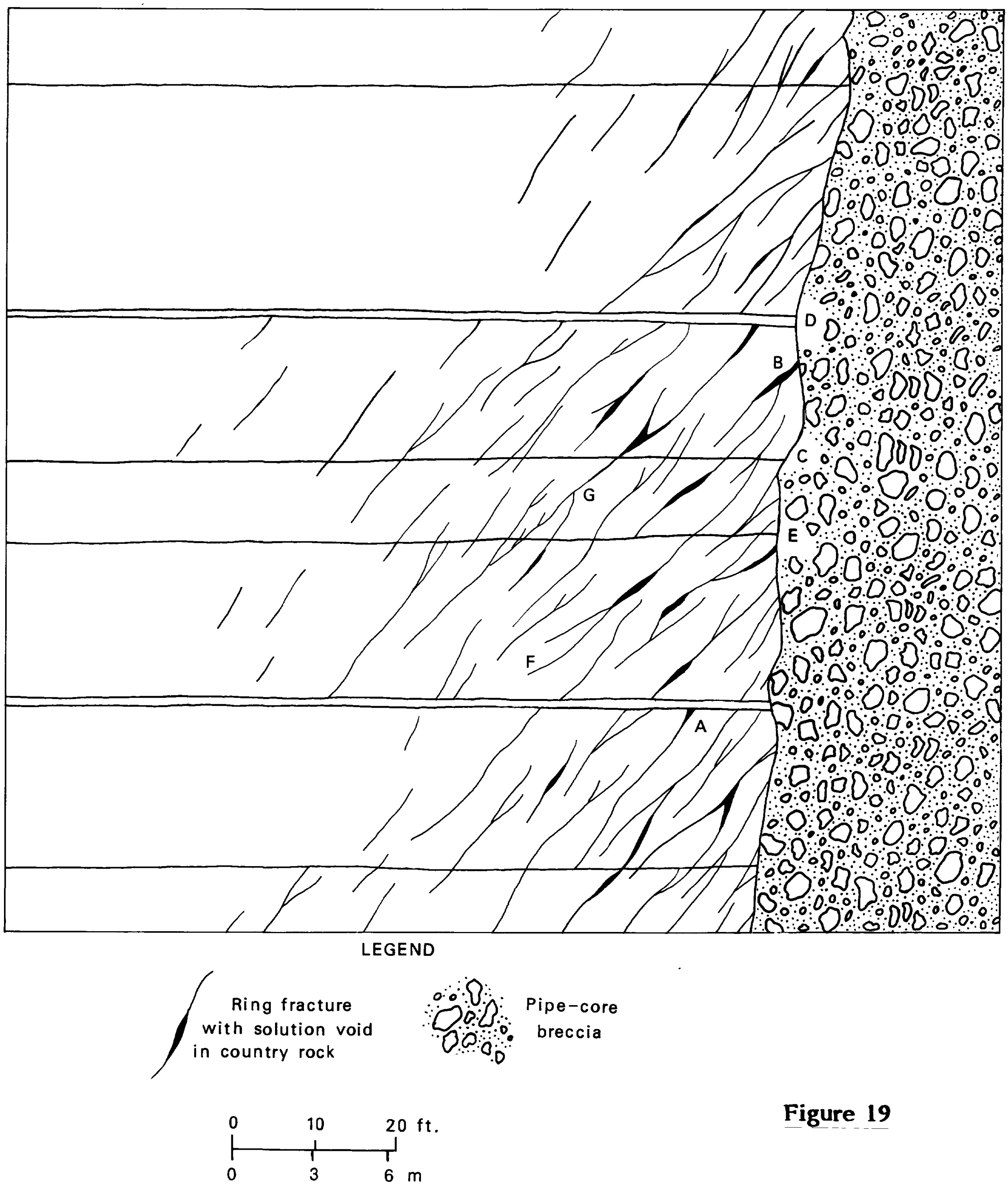

D
B
C
G
E
F
A
LEGEND
Ring fracture with solution void in country rock
Pipe-core breccia
0
10
20 ft.
0
3
6 m

Figure 19

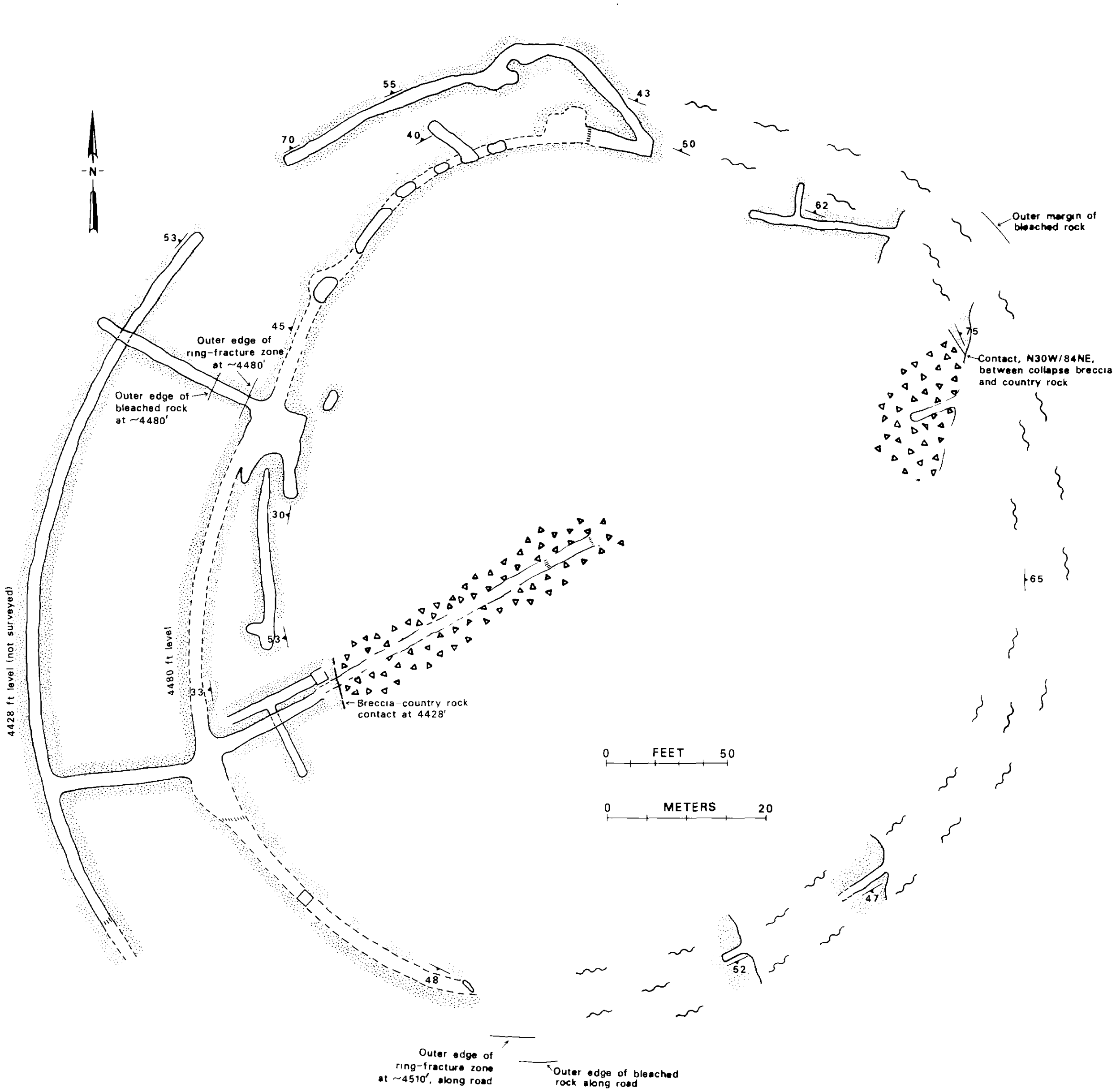


Figure 20. Map showing orientations of ring fractures, pipe-core boundary, and outer limit of bleached rock in the Ridenour mine. Triangle symbols = pipe-core breccia; stipple = Esplanade Sandstone in ring-fracture zone around pipe. Wavy lines show approximate position of ring-fracture zone in canyon below main mine workings.

the ring-fracture zone at any point is difficult to estimate because little of the pipe core is exposed at the surface, but a partial width of about 70 ft (21 m) was measured along the south end of the pipe. Within this zone are more than 60 subparallel ring fractures. A partial width of 130 ft (39 m) was measured on the 4,428-ft level of the mine, from the edge of the pipe core to the outer rib of the large arcuate drift to the west. In some other places, however, as along the stream valley below the mine and north of adit no. 7, the ring-fracture zone probably totals no more than 40 ft (12 m) in width. The mine workings for the most part exploit only the most heavily mineralized portions of the ring-fracture zone and hence are of limited use in defining its extent, but minimum widths of

50-60 ft (15-18 m) appear characteristic of most of the pipe. These widths are to some extent controlled by lithology, as it is apparent from observations along both the north and south edges of the pipe that the ring fractures within different beds extend outward for different distances from pipe center.

Excepting variations in width, the geometry of the ring-fracture zone shows little change from the highest surface exposures to the deepest levels of the mine, a vertical span of about 80 ft (24 m). Ring fractures are present in abundance along the entire preserved extent of the pipe boundary and curve markedly over short distances to strike everywhere nearly parallel to the pipe core (fig. 20). Their dips range from about 25° to nearly vertical, but these extremes are rare; most of the ring fractures dip between 40° and 60°, and the averages for all four stations where these features were measured lie between 45° and 53°. Individual ring fractures are large, irregular, and arcuate. Many can be followed in continuity for distances of 35-70 ft (10-20 m) along strike and 15-30 ft (5-9 m) along dip. Their irregular surfaces, some of which split and merge in complex fashion where the ring fractures are closely spaced, contrast markedly with the generally smooth, planar to subplanar, and mutually parallel surfaces of nearby sets of tectonic joints (figs. 21 and 22).

Spacings of ring fractures vary widely (fig. 23). Most fractures within the main part of the ring-fracture zone are spaced less than 20 inches (50 cm) apart, and in some places as many as seven of them are present within a band only 8 inches (20 cm) wide. Toward the periphery of the ring-fracture zone, however, the spacings generally increase and the sizes of individual fractures decrease.

Details of the original topography of ring-fracture surfaces have been obliterated in most places by solution of the fracture walls, pervasive mineralization, and subsequent oxidation of the minerals to new phases, thereby destroying most direct evidence of mode of failure. Although the rock still tends to split along the mineralized ring fractures during blasting and excavation, close inspection generally reveals that the induced fracture surfaces are not exactly coincident with those of the original ring fractures. The search for such delicate features as plumose structure--well preserved on many joint surfaces in the surrounding country rock--is futile in such areas. Nevertheless, two other aspects of ring fractures serve to confirm their identity as extension fractures. The first is the phenomenon of "hooking"--the tendency of an extension fracture during growth to curve toward a nearby free surface, such as another ring fracture, to terminate against it at a high angle (Kulander and others, 1979). Well-developed hooks of one ring fracture toward another are apparent at scattered points in the mine. The second, more telling (and related) feature is twist hackle, wherein a single fracture surface breaks during growth into a series of overlapping, en echelon segments, each of which twists during further growth to increasingly greater angles to the main fracture face. The mechanics of twist-hackle formation have been addressed by Kulander and others (1979), Pollard and others (1982), and Barton (1983), and will not be repeated here; the presence of this feature, however, is diagnostic of extensile failure. Fortunately for structural geologists, twist hackle is one of the most common and, by virtue of its coarse size, readily preserved of all fracture-surface features in rock. Prominent twist hackle was noted on ring fractures in several places, chiefly where these fractures were only lightly mineralized and the rock still separates along the original fracture planes. The presence of such features as hooks and twist hackle confirms expectations based upon theoretical considerations that the ring fractures are surfaces of extension failure.

Figure 21. View WNW along mineralized ring-fracture zone near station RM-1 and no. 3 adit (left background) of Ridenour mine. Ring fractures dip moderately to the right. Steeply dipping, unmineralized fractures along line of sight of observer are members of the later J3 joint set.

Figure 22. Close-up view of anastomosing, mineralized ring fractures (upper left to lower right) and later, unmineralized joints near station RM-1 of Ridenour mine. Late, supergene goethite unrelated to the primary phase of Cu-V-U mineralization coats some of the joints.

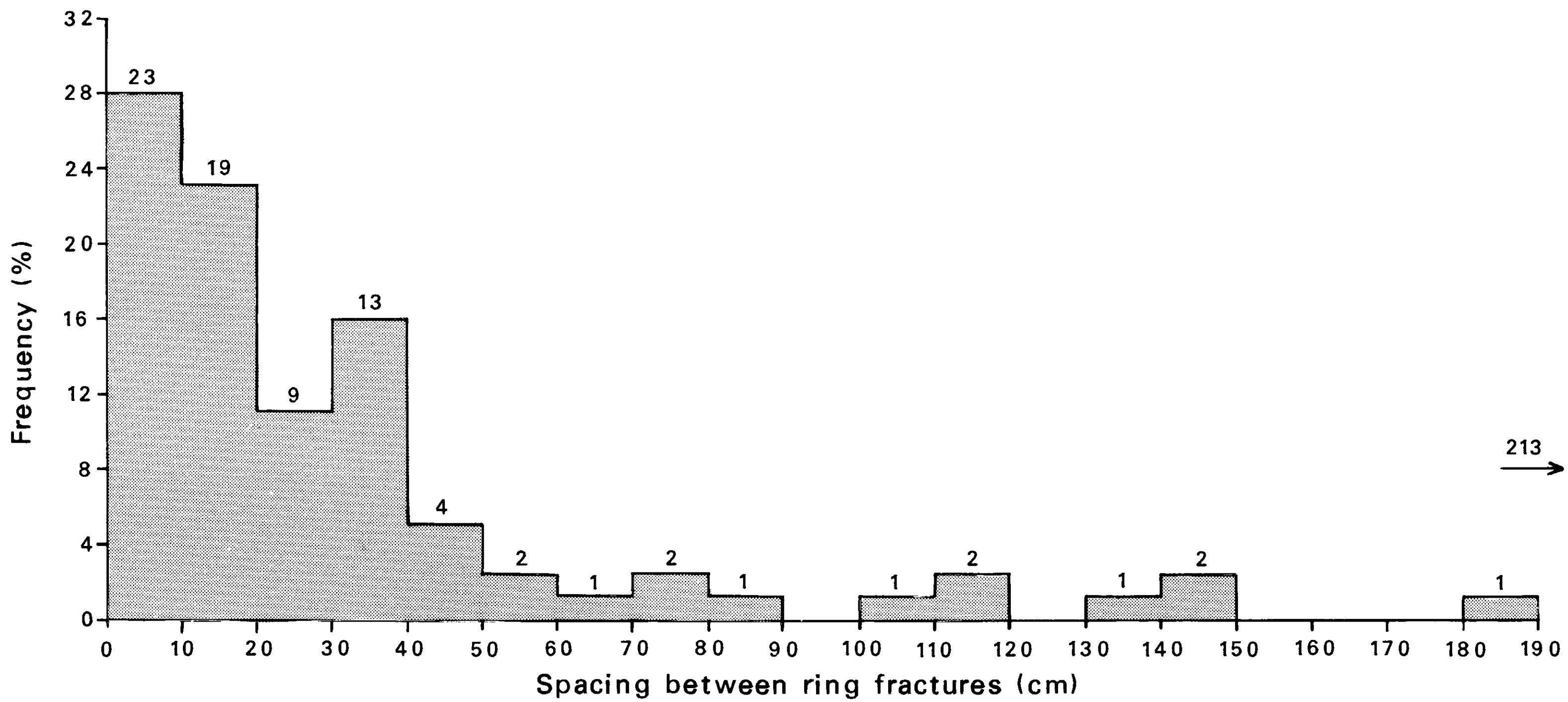


Figure 23. Frequency distribution of ring-fracture spacings in the Ridenour mine. Number of readings = 82.

Breccia bodies

Two types of breccia can be recognized in the ring-fracture zone. The first is volumetrically insignificant and occurs as small masses generally no larger than 1.5 ft (0.5 m) in any dimension. These breccias occur only where closely spaced ring fractures anastomose as described above, outlining lenticular fragments of rock that commonly are broken further along various subsidiary fractures (fig. 24). Although the rock within such areas is highly broken and thus has the fragmental appearance of a breccia, the various pieces have moved little from their original positions and have little void space or matrix between them. Clearly they are not the products of gravity collapse, in contrast to the breccia of the pipe core. All gradations exist between relatively intact country rock between widely spaced ring fractures and local breccias of the type shown in Figure 24.

The second, more common type of breccia probably comprised much of the copper ore once taken from the Ridenour mine. This breccia occurs as podiform masses in solution-widened pockets along individual ring fractures. The solution cavities range in dimension from small openings no more than a foot (0.3 m) across to large pockets more than 19 ft (6 m) long, 16 ft (5 m) wide, and nearly 3 ft (1 m) thick. These miniature, inclined caves, abundantly present in the Ridenour mine, constitute one of its more interesting features: whatever the chemistry of the early, pre-ore fluids that circulated through and around the Ridenour pipe, clearly they were capable of dissolving large amounts of carbonate cement from the host sandstone.

The geometry of a representative breccia-filled cavity is shown in Figure 25. Its walls are irregular and rounded by solution. The opposing walls would not match if pressed together, and bedding surfaces are offset only a fraction of an inch across the void, confirming that the wall separation is not due to mechanical dilation. When traced in any direction the openings pinch and swell, narrowing locally to zero width. The particular void shown in Figure 25 ends abruptly (at B) against a relatively insoluble bed, a fairly common occurrence. The breccia filling this and similar voids (fig. 26) clearly is of local derivation, with lithology identical to that of the enclosing host rock. The clasts, formed by collapse of solution-weakened rock from the walls of the growing voids, are diversely oriented within the breccia and are mostly of small size, less than 4 inches (10 cm) across. Clasts as much as 2 ft (0.6 m) in maximum dimension are seen locally in some of the larger breccia pods (fig. 27), but very large blocks and slabs analogous to those in the core breccia are lacking. The sandy matrix within which the clasts are embedded probably also is of local derivation and represents the insoluble residue, chiefly quartz, of decemented wall rock. Gradual decementation in place of the embedded rock fragments left many of them subrounded to rounded and was an additional source of matrix sand. Depending in part on the severity of solution, the relative proportion of rock fragments to sand is variable from place to place, so that parts of the breccia are clast-supported and other parts matrix-supported. The clasts in some of the lenticular openings are concentrated toward the footwall, where they apparently came to rest upon the rock surface and one another, and are both surrounded and overlain by fine sand that fills the remaining space.

Breccia within the ring-fracture zone differs markedly from that of the pipe core in that nearly all of it is monolithologic, with clasts derived wholly from the adjacent wall rock. Collapse of solution-weakened rock, where it occurred, was minimal, and nearly all of the breccia fragments are within a few feet of their original stratigraphic positions, in contrast to displacements of hundreds of feet in the pipe core. Only two instances of "foreign" clast types were seen in the ring-fracture zone, both in proximity to the pipe core. These particular cavities may have been open to the pipe itself (as at B on fig. 19), allowing rock fragments from the core breccia to tumble into them to form rare pockets of polylithologic breccia.

Figure 24. Minor brecciation of sandstone in highly fractured part of ring-fracture zone, station RM-1. Breccia clasts have moved little from their original positions.

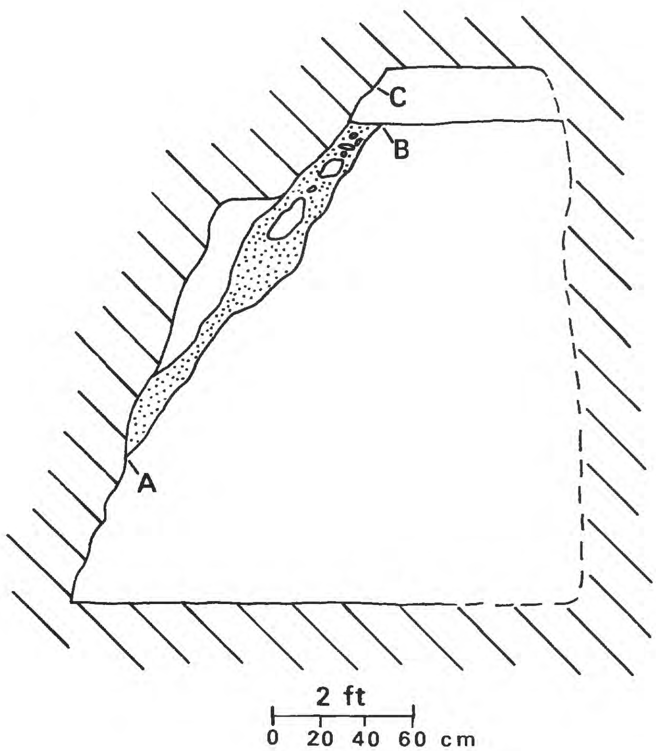


Figure 25. Geometry of breccia- and sand-filled solution pocket along ring fracture exposed in vertical section at NE end of arcuate drift on 4428-ft level, Ridenour mine. Abrupt end of solution pocket at point (B) occurs along contact between soluble (lower) and relatively insoluble (upper) beds.

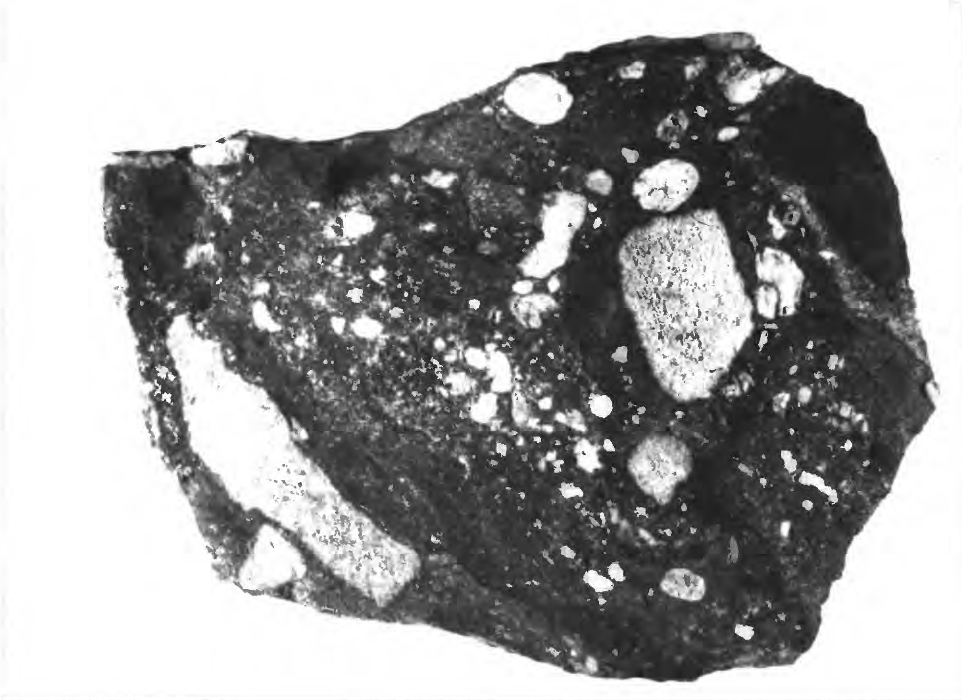


Figure 26. Mineralized solution breccia from ore pocket along ring fracture, 4428-ft level of Ridenour mine. Note rounding of clasts.

Figure 27. Local breccia filling solution-widened pocket within ring-fracture zone of Ridenour mine. This is the largest pod of breccia yet observed in the mine outside the pipe core. Location is in stope at SE end of 4458-ft drift below adit no. 1.

ALTERATION OF PIPE FILL AND SURROUNDING COUNTRY ROCK

As in other Grand Canyon breccia pipes, bleaching and decementation of the pipe-core breccia and adjacent country rock are the earliest mineralogic changes recognized in the Ridenour pipe. The bleaching was accompanied by considerable remobilization of iron, present originally as microscopic grains of hematite in the red beds of the Esplanade Sandstone and overlying Hermit Shale. Both processes were pervasive and affected nearly all of the rock in the pipe core and surrounding strata in contact with it, in contrast to the later and more localized effects of mineralization.

Pipe-core breccia

Most of the collapse breccia occupying the core of the Ridenour pipe is white, pale gray, or pale orange due to bleaching of the originally red clasts. The most prominent exceptions are found low on both ribs near the east end of the haulage adit, where clasts of nearly impermeable Hermit Shale retain their original, deep-red color. Some clasts of the Esplanade Sandstone in the same area retain vestiges of red color also, but elsewhere--along the entire remaining length of the haulage adit and in outcrop--they are strongly bleached. No attempt was made during this study to document the mineralogic changes accompanying bleaching of any of the Ridenour breccias, but Hoffman (1977), Sutphin (1986), and Wenrich (1986a) have shown for other pipes that similar bleaching involves the destruction by reducing fluids of original finely divided hematite pigment, and its removal in solution or local redeposition as another phase, such as pyrite or goethite. The chemistry and mineralogy of bleached versus unbleached rock are otherwise similar, except where overprinted by the later effects of mineralization.

The matrix sand of the core breccia and the outermost parts of some of the sandstone clasts are in places moderately to heavily pigmented by limonite and, less commonly, by secondary hematite. Both minerals locally are distributed in layers of varying richness, lending to the matrix a banded appearance and to individual clasts, when broken open, the impression of concentric structure. It seems reasonable to assume that these iron minerals were derived from the original hematite fraction of the rock, as suggested for other pipes, although direct proof is lacking. Whether any intermediate phase such as pyrite was involved is unknown. No pyrite was observed in the core breccia, although Miller (1954) found it in moderate abundance in the ring-fracture zone, and traces of pyrite were later found in drill core from depths of 715-990 ft (214-295 m) during a 1978 evaluation of the Ridenour pipe (Wenrich, Billingsley, and Huntoon, 1986). The occurrence of hematite as curving, diffuse layers resembling Liesegang bands through the Ridenour breccia suggests that it was derived by dehydration from earlier-deposited goethite.

Early dissolution of carbonate apparently was also widespread within the Ridenour pipe. Although unaltered strata of the Esplanade Sandstone are not notably rich in carbonate cement, the pipe breccia in some places is even less so. It is not uncommon to find, within the haulage adit, areas where the clasts and enclosing matrix show no reaction to dilute HCl. Removal of carbonate and resultant disaggregation of the sandstones, most of which were only weakly or moderately cemented to begin with, likely was the source of most or all of the sandy matrix of the core breccia. The same process of disaggregation resulted in partial rounding of some of the breccia clasts, a characteristic property of core breccias from other pipes in the Grand Canyon region (Watkins, 1975; Sutphin, 1986).

Ring-fracture zone

Sandstone and siltstone beds of the Esplanade Sandstone are bleached around the Ridenour pipe to an extent controlled by permeability. The bleached rocks are variously pale buff, ivory, pale pink, or grayish tan in color, as opposed to the predominant brick red of unaffected rock. The transition from highly bleached to apparently unaltered rock is relatively abrupt, taking place over distances of 6 ft (2 m) or less in most units. Beds that show bleaching for the greatest distances from pipe center are weakly cemented sandstones of such high permeability that a drop of water placed upon a freshly broken surface is almost immediately absorbed. With decreasing grain size and increasing degree of cementation, permeability and the effects of bleaching diminish. Some well-cemented siltstone beds (unit 7, for example) remain incompletely bleached everywhere within the mine area, even in places less than 30 ft (9 m) from the estimated outer margin of the (now-eroded) pipe core. In such areas it is not uncommon to see dark red to maroon, seemingly unaltered siltstones overlying completely bleached and nearly white sandstones.

At the outcrop scale, one can observe at many places in the mine that rock immediately adjacent to the ring fractures is more highly bleached than that further distant. Zones of completely bleached rock flanking the ring fractures in the sandstone beds commonly range in width from a fraction of an inch to 2.5 inches (6.5 cm). Analogous zones are notably thinner in the intervening siltstone layers. The bleaching fluids moved through the permeable sandstone beds by a combination of intergranular and fracture flow, resulting ultimately in bleaching of nearly their entire mass near the pipe, but with the most extreme effects bordering the avenues of greatest permeability--the ring fractures. Intergranular flow through the intervening mudstones, however, was impeded by their low permeability. Miller (1954) earlier had concluded that the fine-grained beds of the local section acted as partial barriers to fluid flow during alteration and mineralization of the Esplanade Sandstone.

The iron liberated from destruction of the original hematite in the ring-fracture zone was redeposited locally, within the bleached rock, as limonite. Large masses of prominently banded sandstone, where the bands are defined by alternating limonite-rich and limonite-poor rock--the so-called "zebra rock"--are widespread in the mine (figs. 28 and 29). The common parallelism of these bands to nearby ring fractures (fig. 30) reaffirms the importance of the ring fractures to fluid flow around the pipe.

As in the pipe core, early fluids moving through the ring-fracture zone removed much carbonate from the sandstone beds. Decementation of rock adjacent to the ring fractures resulted in formation of the lenticular solution openings previously described. Rock fragments and quartz grains freed by solution from the original rock accumulated in those openings to form lensoidal masses of breccia that subsequently became mineralized to form part of the copper ore of the Ridenour mine.

PRE-ORE DEPOSITION OF CARBONATE AND SULFATE MINERALS

Studies of ore samples from other pipes indicate that deposition of carbonate and sulfate minerals within the matrix of the core breccia followed bleaching and removal of carbonate from the same material, but preceded deposition of the metallic minerals comprising the Cu-U ores (Wenrich and Sutphin, in press). Little direct field evidence exists for this stage of mineralization in the Ridenour mine, and much of the core breccia remains depleted in carbonate. Locally, however--within the haulage adit--the sandy matrix of the core breccia is moderately to highly calcareous, whereas the embedded sandstone clasts are noncalcareous. Inasmuch as the matrix was derived from the clasts, calcite apparently was added locally to the matrix at some time following the widespread bleaching and early decementation of the rock. Careful examination in thin section of calcareous samples would be necessary to determine if this is a pre-ore or post-ore effect. However, an early stage of barite deposition in the Ridenour pipe has been inferred by H.B. Sutphin (written commun., 1988) from empty crystal molds in a sandstone sample from the ring-fracture zone.

Figure 28. Well-developed bands of limonite in bleached Esplanade Sandstone at Ridenour mine. Bands are parallel to ring fractures (not shown). Note that bands pass undisturbed across vertical J3 joints (left side of photo), showing the joints to be the later features.

Figure 29. Discontinuous bands of limonite-pigmented sandstone in bleached Esplanade Sandstone from Ridenour mine. Dump specimen, 6 inches (15 cm) long.

Figure 30. Alternating bands of limonite-rich and limonite-poor rock around terminus of a single ring fracture in bleached sandstone near station RM-1, Ridenour mine.

ORE MINERALIZATION

Pipe-core breccia

Copper (and silver?) minerals– Most of the core breccia in the haulage adit and all of it in outcrop below the mine is devoid of visible copper minerals. Only two exceptions were noted, both within the haulage adit. The first consists of sparse disseminations of malachite within matrix sand of the core breccia, very near the outer edge of the pipe core. The second, located 35 ft (11 m) from the core boundary, consists of an arborescent coating 3 inches x 5 inches (8 x 13 cm) in area on the external surface of a sandstone clast. The coating is now goethite but preserves perfectly the minute crystal faces and herringbone habit of the original mineral, almost certainly native copper, but possibly silver. Small amounts of silver have been recovered from some of the Ridenour ores, and naumannite (a silver selenide) and bromargyrite (silver bromide) have been identified in samples from the mine (Chenoweth, in press). Although copper sulfides and sulfosalts are prominent components of the ore from mines in other Grand Canyon breccia pipes, and mineralized samples are consistently enriched in silver (Wenrich, 1986b), neither native copper nor silver have been reported previously.

Uranium and vanadium minerals– No uranium or vanadium minerals were noted anywhere within the core breccia, and extensive examination of the entire length of the haulage adit with a portable ultraviolet light (fitted with both longwave and shortwave tubes) failed to disclose the presence of any luminescent secondary uranium species. Radioactivity counts in the haulage adit (geoMetrics model GRS-101 scintillometer) are uniformly low, from 40 to 70 cps, as compared to background readings of 15 cps in the Esplanade Sandstone outside the mine area.

The near-total lack of mineralized rock in accessible portions of the Ridenour pipe core should not be viewed as abnormal for at least two reasons. First, little of the pipe core is exposed, and one cannot assume that those portions currently visible are representative of the whole. Mining in other pipes has confirmed that the distribution of ore minerals within the core breccia is irregular. In the Orphan pipe, for example, several pods of high-grade uranium ore in the pipe core were separated by large zones of low-grade to barren material (Magleby, 1961; Chenoweth, 1986). Second, the high permeability of the core breccia and the thorough oxidation of the near-surface portions of the Ridenour pipe provide conditions poorly suited to the preservation of the original ore minerals. Uraninite, for example, is highly soluble in oxidizing, carbonate-bearing ground waters over a wide range of pH (Garrels and Christ, 1965; Drever, 1982) and would readily be leached from a permeable rock such as the core breccia of the Ridenour pipe.

Ring-fracture zone

Mineralized rock in the Ridenour mine is almost wholly confined to the ring-fracture zone. Detailed study of the various ore and accessory minerals is underway by others, and comments here will be restricted mostly to the topic of structural control of mineral deposition.

Copper minerals- Throughout most of its history the Ridenour mine was worked for copper, contained chiefly in the minerals malachite, azurite, and chalcocite. These minerals occur together in three distinct but related environments. The first is along ring fractures, where the copper minerals occur both as open-space fillings and as impregnations and partial replacements of the adjacent wall rock. Many of the ring-fracture veins are 0.5-1.5 inch (1.3-3.8 cm) thick (fig. 31), and the observed extremes range from paper-thin seams to veins 6 inches (15 cm) across, but only a small fraction of each vein represents open-space filling. Examination of many veins with a hand lens, coupled with later study of mineralized ring fractures in polished section by H.B. Sutphin (written commun., 1988), confirms that original openings along most ring fractures were small--probably no more than 0.04-0.08 inch (1-2 mm), except where widened further by early (pre-ore) solution. Such modest openings nevertheless were huge relative to typical pore diameters in the adjacent fine- to very fine grained sandstones, and, moreover, fluid-flow paths within the fractures were continuous for many meters as compared to distances of only one to several grain diameters in the wall rock. Permeabilities along the ring fractures thus were orders of magnitude higher than that of the intact rock, and the ring fractures became the primary loci for fluid flow and mineralization in the mine area. Nearly all of the stoped-out areas in the Ridenour mine are narrow, inclined excavations that followed the most heavily mineralized portions of closely spaced ring fractures. The degree to which the remaining rock is mineralized shows no notable change from top to bottom of the mine, and much copper-mineralized rock remains in place.

The lenticular pockets of breccia previously described were a second source of copper ore during operation of the Ridenour mine. The sandy matrix of such breccias commonly is cemented by copper carbonates (fig. 26), and the same minerals locally have partially replaced and impregnated the outer portions of the breccia clasts or formed coatings around them. A notable property of such breccia masses is that the most densely mineralized rock commonly occurs within a zone 1-4 inches (2.5-10 cm) thick along the hanging-wall contact of the breccia with the enclosing rock. One possible explanation for this effect is that the reductant necessary for precipitation of the original ore minerals was a gas (H_2S?) that ponded against the hanging wall during its upward migration through the ring fractures (C.S. Spirakis, oral commun., 1988).

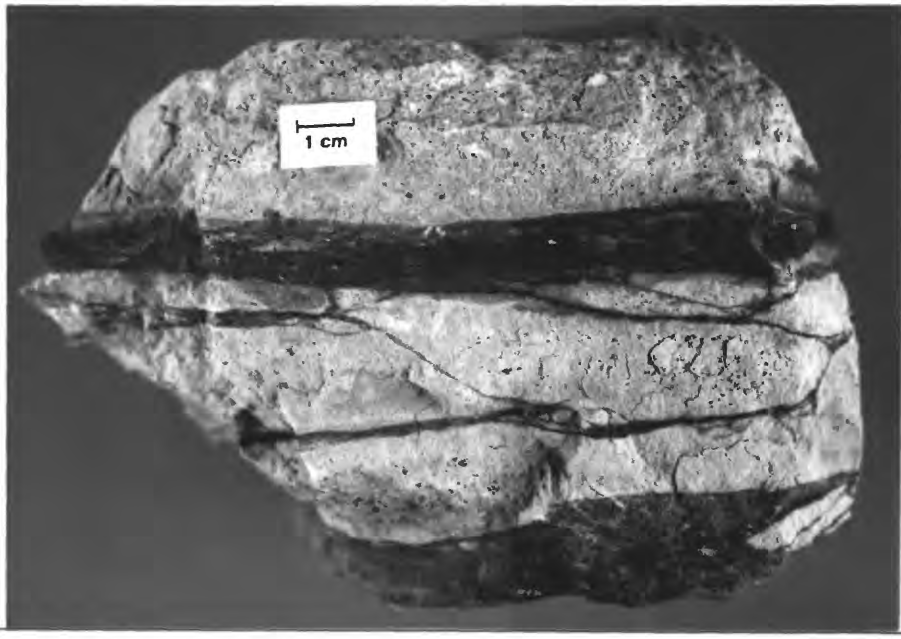


Figure 31. Photograph of mineralized ring fractures in bleached Esplanade Sandstone; sample from near no. 4 adit of Ridenour mine. Dominant minerals are chalcocite, malachite, and azurite.

The third and least significant environment for ore deposition was along bedding surfaces that had split open slightly during stoping of the pipe to allow penetration by the later mineralizing fluids, forming bed-parallel veins. Despite their orientation in common with J4 joints, these veins are much older and date from the time of formation of the associated ring fractures. They occur only within the immediate vicinity of the pipe and are common only in the fine-grained units--siltstones and shales--where fissility of the original rock presumably aided in their formation. Comparable veins are almost nonexistent in the more massive sandstones that comprise the bulk of the section.

Uranium and vanadium minerals- U-V minerals were exploited during the latest (1961) phase of mining in the Ridenour pipe, but these are of much more restricted and irregular occurrence than the copper minerals. Fine-grained, gray to black vanadium minerals, most as yet unidentified, line some ring fractures and impregnate the adjacent wall rock. Some veins can be traced as charcoal-gray bands in outcrop for distances of 30 ft (9 m) or more. Olive-green volborthite, a basic copper vanadate, forms conspicuous coatings on ring-fracture surfaces in widely scattered parts of the mine. That some ring fractures are mineralized predominantly by copper minerals, whereas others are rich in vanadium, constitutes one of the more curious aspects of the Ridenour-mine geology.

Visible uranium minerals are not abundant at present in most parts of the mine, but radioactivity counts of 100-400 cps in many of the copper-mineralized areas disclose their presence in modest amounts. Locally, as near station RM-2, small residual masses of dark, vanadium-rich rock encrusted with tyuyamunite and volborthite occur along stoped-out portions of the ring fractures and register 5,000-10,000 cps. Tyuyamunite and metatyuyamunite (the "carnotite" of Miller, 1954) occur variously as a cementing agent in sandstones; as tiny, scattered grains within V-mineralized rock adjacent to ring fractures; and in one stope as showy coatings on exposed ring-fracture surfaces. A host of other Cu-V-U minerals occur in small quantities in the Ridenour mine but will not be described here.

Summary

The distribution of ore minerals in the ring-fracture zone shows clearly that ore mineralization occurred wherever zones of secondary permeability existed--along ring fractures, within local masses of solution breccia, and along open bedding planes. Rock more than a few inches from such structures generally is bleached but not mineralized. Mineralization extended no further outward from the pipe than did the ring-fracture zone, and bleaching of the host rock generally extended only 10-20 ft (3-6 m) further.

The nearly complete absence of mineralized rock in the small portion of the pipe core currently visible is probably ascribable to thorough oxidation of the highly permeable collapse breccia.

JOINT NETWORK IN MINE

All five sets of joints previously described from intact country rock around the Ridenour pipe are also found in altered (bleached) and mineralized rock within the mine area (fig. 32). The character of the joint network within the ring-fracture zone and pipe core is described below and contrasted with that of the host strata. The various lines of evidence uniformly suggest that stoping of the Ridenour pipe, alteration (bleaching) of the host rock, and primary mineralization of the ring fractures all predated regional fracture of the surrounding Esplanade Sandstone.

Presence of J1-J5 joints within breccia

Most of the solution-collapse breccia of the pipe core, and much of that within solution-widened openings along ring fractures, is too poorly lithified to have responded brittlely to the same stresses that fractured the surrounding country rocks. Locally, however, the breccia is sufficiently cemented by calcite or copper carbonates that internal fractures are conspicuous. Those fractures, in all areas examined, can be identified as members of the J1 through J5 joint sets. A few examples follow.

(1) Within the haulage adit on the 4,428 ft level, in country rock immediately adjacent to the pipe-core breccia, the adit ribs are flat, vertical surfaces of about N70E strike--the walls of J2 joints. The J2 set here is so strongly expressed that the adit was purposely oriented along its strike to take advantage of the ease of excavation in that direction. Large, diversely oriented blocks and slabs of sandstone within the adjacent breccia also contain internal fractures of about N70E strike and vertical dip. Although fractures within the breccia at this locality are not great in number, those seen uniformly conform to members of the J2 set.

(2) The outcrop of pipe-core breccia in the stream valley below the mine is cut by joints of the J2 and J4 sets. The breccia here is rather firmly cemented, a fact that undoubtedly contributed to its preservation, and appears as a jagged mass of pebble- to cobble-sized fragments in a limonite-stained, sandy to silty matrix. Large, irregular J2 joints that cut uninterrupted through clasts and matrix alike occur in the most indurated parts of the breccia. Similar but smaller J2 joints that cut through fewer clasts or are confined to single, large blocks are characteristic of less-cemented parts of the same mass. The later J4 joints appear as irregular, subhorizontal fractures of 1.5-15 ft (0.5-5 m) trace length that divide the mass into crude, thick slabs.

(3) A fine example of a breccia pod filling a solution pocket along a ring fracture is exposed on the rear face of a stope extending S25E from a point halfway down the inclined shaft to the Ridenour mine, at an elevation of 4,458 ft (1,359 m). The breccia (fig. 27) is well-cemented by malachite and chalcocite in places and is cut by vertical joints of the J1 and J3 sets that extend through both the clasts and intervening matrix.

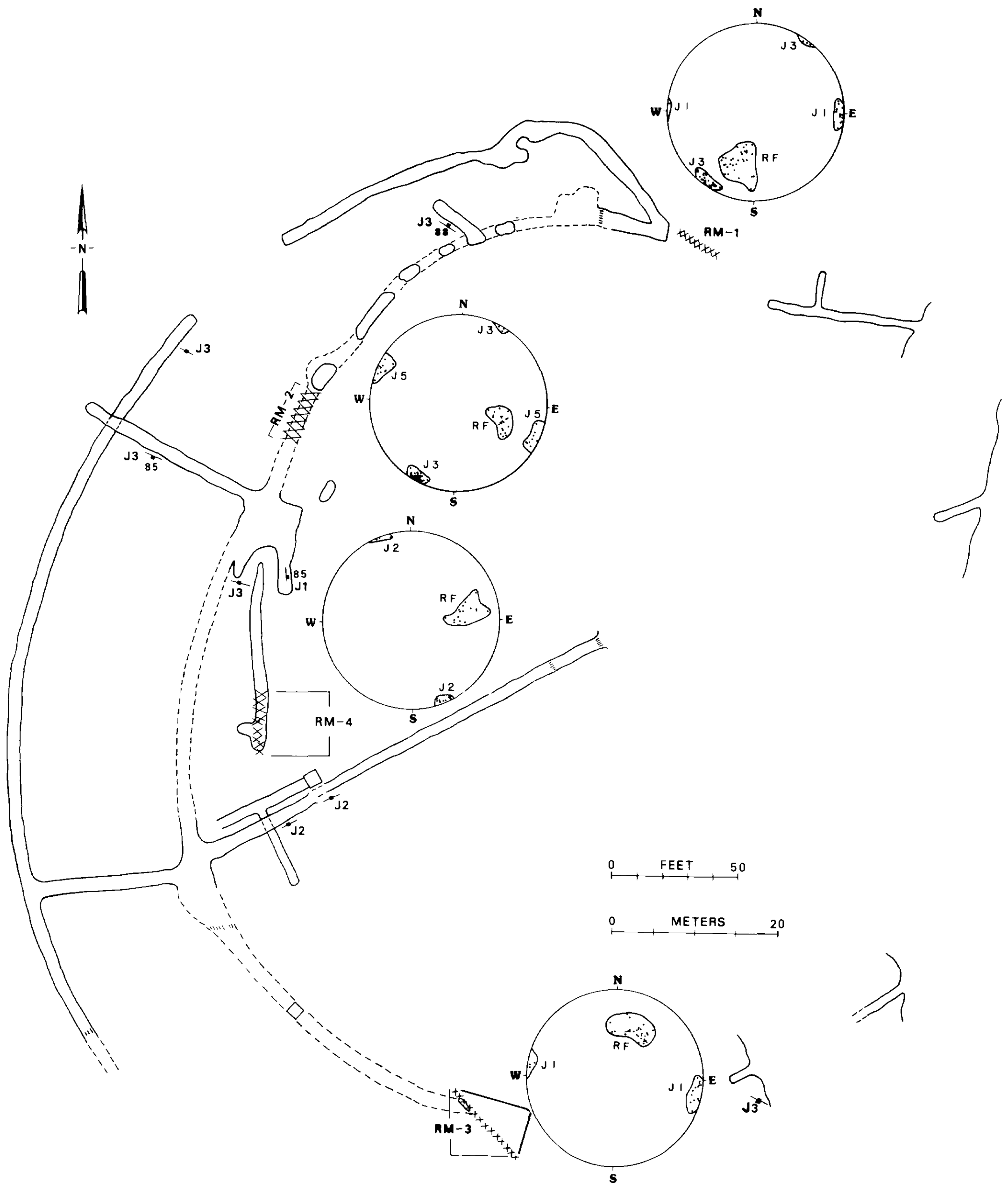


Figure 32. Map showing orientations of J1 through J5 joints in Ridenour mine. Stereonet diagrams are equal-area, lower-hemisphere projections. RF = ring fractures.

The evidence from these and similar places consistently suggests that solution-collapse breccias of the Ridenour pipe were formed and mineralized before jointing of the host strata took place, and that both the breccia and surrounding country rock were subsequently cut by the same five sets of joints.

Absence of joint-bounded clasts in breccia

If beds of the Esplanade Sandstone were jointed before the Ridenour pipe stoped through that formation, then some significant portion of the sandstone clasts in the core breccia should have shapes defined in part by those joints. Instead, the only consistently planar external surfaces of the breccia clasts are defined by bedding. Clasts approaching the shape of parallelipipeds, with opposite sides parallel and suggestive of joint-bounded blocks, are lacking. Similarly lacking are fractures within the clasts that maintain a constant angle to bedding regardless of clast orientation, as any set of pre-stoping joints must do.

Lack of solution widening along J1-J5 joints

Ring fractures within the Ridenour mine contain numerous lenticular caves due to solution-widening of the original narrow openings. All details of the original fracture surfaces were destroyed as quartz grains were progressively detached from the walls of the growing voids during decementation of the rock. Similar solution openings, however, are lacking along the J1-J5 joints. The joint walls, both within and outside the mine area, often retain delicate features of the original fracture surfaces such as plumose structure, except where these have been obliterated by recent weathering. The lack of solution effects along the well-preserved J1-J5 joints contrasts strongly with their abundant presence along the associated ring fractures.

Terminating relations among fractures

The joints of all five regional sets of the Esplanade Sandstone are extension fractures. The ring fractures also formed in extension. As mentioned previously, extension fractures generally terminate against older fractures unless those older fractures are cemented by some secondary mineral. In that event, the younger fractures will either cut across or terminate against the older ones, depending on the degree of cohesion between the mineral fill and the wall rock and on the mechanical properties of each. All of these effects are well illustrated in the ring-fracture zone.

Ring fractures in the Ridenour mine generally are quite heavily mineralized and thus "healed", but in some places, most notably along the south end of the pipe at station RM-3, some of the outermost ring fractures are nearly devoid of minerals. At this locality, joints of the J1 set terminate against various ring fractures, showing that the ring fractures predate even the oldest of the five regional sets of joints. J1 joints at several places in the mine broke into prominent twist hackle (fig. 33) and curved to terminate against a ring fracture at a high angle, both common effects of a younger fracture approaching an older one (Kulander and others, 1979). The relative ages of the ring fractures and the J1 joint set are especially clear at such places. Comparable observations can be made for joints of all other sets at various localities in the mine: for each set the component joints either cut across mineralized ring fractures or terminate against them, but the converse was not observed.

Size and shape of joints

Joints within the ring-fracture zone tend to be smaller--locally much smaller--than their counterparts outside the pipe because their growth was restricted by pre-existing ring fractures. The vertical joints shown in Figures 21 and 33, for example, are only 1.5-5 ft (0.5-1.5 m) in height, yet joints of the same sets immediately outside the mine area usually are at least several times larger. The ring fractures, in contrast, are of impressively large size, for they formed in previously unbroken rock.

The early presence of the ring fractures also affected the shapes of various joints within the ring-fracture zone by introducing irregular and closely spaced anisotropies that resulted in local stress perturbations. Whereas many J1 through J3 joints within the more homogeneous rock surrounding the pipe are nearly planar, their counterparts within the ring-fracture zone are noticeably more irregular.

Figure 33. J1 joint showing prominent zone of twist hackle along its termination against an older, mineralized ring fracture. The younger joint is unmineralized.

Differential mineralization of ring fractures and joints

Although much Cu-V ore in the Ridenour mine was deposited along ring fractures to form veins commonly an inch or two thick, joints of the J1-J5 sets in the mine area either are barren of ore minerals or contain only sparse, thin coatings of such late-formed supergene minerals as malachite, azurite, and volborthite. The earlier-formed sulfides and sulfosalts from the main phase of mineralization, some of which have been identified as residual phases in the ring-fracture zone, are lacking entirely in the later joints. Coatings of secondary Cu-V minerals on joint surfaces occur only within a meter or two (3-6 ft) of heavily mineralized ring fractures, the presumed source of the metals; the same joints more distant from the ring fractures remain uncoated. The evidence seems clear that primary ores were deposited only within the ring fractures, and that secondary minerals derived from them were deposited in small amounts in the later J1-J5 joints as oxidizing ground water flowed through the pipe.

Zonation of Cu-V minerals near fracture intersections

The simple observation that J1 through J5 joints tend to cut across ring fractures where these are heavily mineralized, but in many places terminate against them where mineralization was weak, strongly suggests that the main phase of Cu-V mineralization in the Ridenour pipe predated the formation of any regional joint set. Observations of mineral zonation near fracture intersections corroborate that conclusion.

Many ring fractures in the Ridenour mine are mineralogically zoned, the most common arrangement consisting of a thin central layer of chalcocite bordered by malachite or azurite, or both. The contrasting colors of these minerals lend to many ring fractures a pronounced banded appearance in outcrop. The thickness of each band commonly pinches and swells along the length of the ring fracture, but there exists no relation between such thickness changes and the positions at which the ring fractures are intersected by joints of the J1-J5 sets. Instead, the mineral zones match across each joint and show in their form no indication that fluid flow along the ring fractures at the time of mineralization was affected by vertical joints. A comparable situation exists for those ring fractures mineralized predominantly by vanadium minerals.

Limonite in bleached, jointed sandstone

Limonite, the most widespread noncarbonate gangue mineral of the Ridenour mine, occurs commonly in bleached sandstones as a pigmenting agent distributed in layers resembling Liesegang bands of exceptional length. The bands in many places are parallel to nearby ring fractures (fig. 30) and thus appear to have formed as fluids circulated through them. The uniformity and continuity of these bands in the many places where they are intersected by joints of the J1-J5 sets (fig. 28) show clearly that the joints were not yet in existence during deposition of the limonite. Much of this limonite likely was derived from finely divided hematite within the original rock, indicating that considerable remobilization of iron in and around the Ridenour pipe predated the formation of any joint set in the area.

Summary

The eight lines of evidence presented above individually and collectively lead to a single conclusion--that the Esplanade Sandstone was an unjointed unit, structurally intact, when the Ridenour pipe stoped through it. Bleaching of the sandstone around the pipe, leaching of carbonate from the pipe breccia and surrounding strata, redeposition of iron as bands of limonite pigment within massive sandstones, and deposition of primary copper, vanadium, and uranium minerals around and within the pipe all occurred before the first set of regional joints cut the host rocks.

SUPERGENE MINERALS IN J1-J5 JOINTS

Late Cenozoic oxidation of the Ridenour pipe resulted in such pervasive alteration of the primary mineral assemblage that only isolated remnants of the original phases can be identified in thin section (H.B. Sutphin, written commun., 1987). Various supergene minerals were deposited as patchy coatings on joint surfaces, within a few meters of mineralized ring fractures, as oxidizing ground waters leached metals from the ring fractures and locally reprecipitated them. Among these minerals are malachite, azurite, and volborthite. None of the primary ore minerals--the copper sulfides and sulfosalts, galena, and uraninite, among others--have been found on any joints of the J1 through J5 sets in the mine. All minerals identified to date from coatings on the joints are compatible with deposition under near-surface, oxidizing conditions.

Three of the minerals identified on J1-J5 joints in the mine area occur beyond it also and thus appear to be general to the study area rather than specific to the Ridenour pipe. They are described below in their order of deposition on the J1-J5 joints. Their presence on the J5 joints, the youngest and structurally most shallow set in the area, emphasizes the young geologic age and shallow depth of deposition of these minerals.

Goethite- Dense, black coatings of goethite are common on joints of all five sets throughout the Ridenour mine. The identity was confirmed by X-ray diffraction (P.J. Modreski, written commun., 1987). These coatings reflect minor redistribution of iron by meteoric ground water flowing through the pipe and are of much younger age than the widely dispersed, banded limonite referred to above. Goethite locally "bled" into the sandstone adjacent to joint walls to form an ochre-colored to brown border, overprinting the banded limonite of the earlier generation.

Black coatings similar to those in the mine, but of nearly microscopic thinness, were seen in various joints on the Esplanade Platform at places far removed from the mine. Their presence probably signifies minor hydration of original hematite in the rock bordering the joints, but such coatings, though widespread geographically, are not common. Too little material was available for a positive identification, and its correlation in manner and time of occurrence with the goethite in the mine area is only assumed.

Calcite- Thin coatings of translucent, cream-colored to white calcite were noted on numerous joints of all five sets at many places in the mine. This calcite encrusts the goethite deposited earlier on the walls of the same fractures and is visually similar to the calcite that fills joints elsewhere on the Esplanade Platform. Its deposition, then, is a regional phenomenon unrelated to the Ridenour pipe.

Caliche- As in much of the study area surrounding the Ridenour pipe, caliche in the mine area is common in J1-J5 joints and also occurs locally as chalky coatings on exposed rock surfaces. Fragments of mineralized rock commonly are embedded in this material where vertical joints transect ring fractures near the surface. Caliche also acts as a cementing agent of the core breccia, but only within a few meters of the surface, as in the northeasternmost portion of the haulage adit in the mine. The distinctive yellowish-orange to bluish-white fluorescence of the caliche is an aid to discerning its presence within parts of the breccia and in distinguishing it from the earlier, nonfluorescent calcite cement within the breccia matrix.

CHRONOLOGY OF PIPE DEVELOPMENT

A suggested chronology of the evolution of the Ridenour pipe, based on evidence presented in preceding pages and on general facts taken from the published literature, is given below and summarized in Table 1. Direct evidence for all but the first three events is present in the Ridenour mine.

1. Deposition and lithification of the Redwall Limestone in Late Mississippian time.

2. Minor uplift and emergence of the Redwall toward the close of the Mississippian Period. Streams cut valleys as deep as 400 ft (130 m) into the Redwall surface. A karst topography developed, and the limestone was pervaded by numerous large caverns 1,100-1,500 ft (300-450 m) below the future stratigraphic level of the Ridenour mine. Partial to complete filling of many of these caverns by fluvial sediments of the Surprise Canyon Formation, of Late Mississippian age, establishes their early age (Billingsley, 1986).

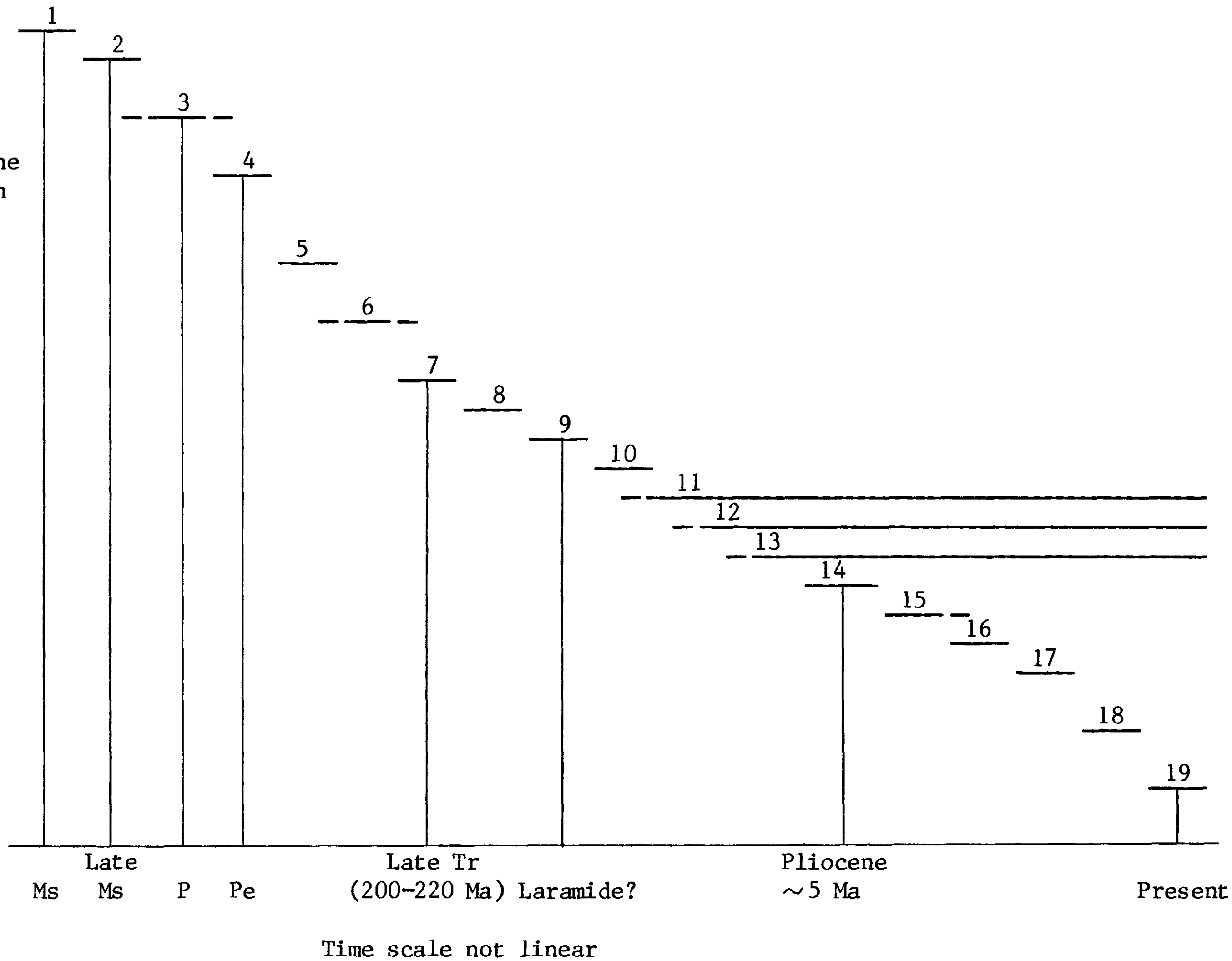
3. Possible initial stoping of the Ridenour pipe from Late Mississippian to Early Pennsylvanian time. Stoping during this time period of some pipes is inferred from observed thickening and sagging of the Surprise Canyon Formation (Late Mississippian) and overlying lower beds of the Supai Group (Watahomigi Formation of Pennsylvanian age) toward exposed pipes (Billingsley, 1986).

4. Deposition and lithification of the remainder of the Supai Group, including the lower Permian Esplanade Sandstone.

5. Renewed collapse and stoping of the Ridenour pipe through the Esplanade Sandstone. Resumption of collapse may have occurred in middle Triassic (Chinle) time in reponse to the fluctuating water tables of that period (Wenrich, 1986a). The form and large size of the ring fractures encircling the pipe core show that the Esplanade Sandstone at this time was lithified but unjointed: the pipe stoped through mechanically intact rock.

Table 1. Chronological development of Ridenour pipe

1 Deposition of Redwall Limestone
2 Uplift of Redwall; caves form
3 Initial stoping of pipes; deposition of lower Supai Grp.
4 Deposition, lithification, and diagenesis of Esplanade Sandstone
5 Stoping of Ridenour pipe through Esplanade Sandstone. Ring fractures form
6 Bleaching and decementation; reducing fluids
7 Cu-V-U mineralization; reducing fluids
8 J1 joint set develops
9 J2 joint set develops
10 J3 joint set develops
11 Regional uplift
12 Oxidation of primary ore
13 Canyon cutting
14 J4 unloading joints develop
15 J5 joints develop
16 Goethite dep. of joints
17 Calcite dep. on joints
18 Dissection of Esplanade Platform; drainage of pipe
19 Caliche in all fractures in zone of weathering



6. Bleaching and decementation of the core breccia and of strata immediately surrounding the Ridenour pipe. Mineralogic studies of other pipes suggest that iron from hematite in the originally red sandstones was redeposited locally by reducing fluids as pyrite in the bleached rock (Gornitz and others, 1988). Removal of carbonate from the host rocks, probably simultaneous with bleaching, produced numerous lenticular solution openings along ring fractures encircling the pipe. Quartz grains and small rock fragments freed by decementation of the host rock filled the solution openings and, in the pipe core, formed much or all of the matrix of the collapse breccia.

Diagenesis of the Esplanade Sandstone had already been completed by this time, because the distance from pipe center that individual beds are bleached correlates well with their present degrees of permeability in unaltered strata outside the pipe area.

7. Cu-V-U mineralization within bleached rock in and peripheral to the pipe. Conditions at this time were reducing and, by analogy to pipes where reduced ore is better preserved, led to the deposition of such phases as chalcopyrite, galena, pyrite, bornite, sphalerite, enargite, and uraninite, plus numerous less-common sulfides and sulfosalts (Wenrich and Sutphin, in press). Of these minerals, the first four have been identified as residual phases in ore from the Ridenour mine, and the abundant chalcocite probably was derived from original enargite or chalcopyrite (H.B. Sutphin, written commun., 1988). Ludwig and others (1986) have shown from U-Pb age determinations that the main phase of uranium mineralization in several other pipes occurred about 200-220 Ma (middle to late Triassic). These dates fix a probable upper limit for the Cu-V mineralization of the Ridenour pipe, because Wenrich (1986a) and Wenrich and Sutphin (in press) suggest from textural evidence of unoxidized ore samples from other pipes that deposition of uraninite postdated most of the other ore minerals.

8-10. Formation in succession of the three regional joint sets J1 (N), J2 (N70E), and J3 (N60W). The actual times of fracture and the intervals between them remain unknown, although the J2 set may be of Laramide age. Available evidence suggests that all three sets formed at depths of 1,900-3,200 ft (560-975 m), and possibly greater. Removal of hematite from rock bordering the joint walls formed narrow bleached zones with common widths of 0.1-0.4 inch (0.25-1.0 cm), and shows that fluids circulating through the joint system (and thus the Ridenour pipe) were still reducing. Their chemistry clearly had changed with time, however, for the joints--unlike the earlier ring fractures--were neither mineralized nor widened by dissolution of carbonate from their walls, which are largely intact. The correlation of increasing width of bleached zones with increasing joint age shows that all three sets remained open and served to channel ground-water flow for an extended period of time.

11-12. Regional uplift and supergene oxidation of the primary ore. Uplift may have begun during or shortly after Laramide (Late Cretaceous through Eocene) time and continued through much of the late Cenozoic (Wenrich, Billingsley, and Huntoon, 1986). Supergene oxidation of the primary ore commenced during uplift as the upper reaches of the Ridenour pipe were raised into the zone of oxidizing ground waters. Probable acceleration of uplift in late Cenozoic time (Lucchitta, 1979; Wenrich, Billingsley, and Huntoon, 1986) prompted Wenrich and Sutphin (in press) to suggest that much supergene alteration of the original phases occurred within the past five million years. Minerals formed during this time in the Ridenour mine include, in approximate order of abundance, malachite, azurite, volborthite, tyuyamunite and metatyuyamunite, conichalcite, and vesignieite. The same minerals were deposited in small amounts on nearby joints as metals leached from mineralized ring fractures were reprecipitated locally. Comparable coatings of Cu-V-U minerals were nowhere noted outside the mine area. Oxidation of primary ore was a protracted process that continues to the present day; it thus overlaps in time all of the events listed below.

13. Initial stages of excavation of the Grand Canyon. Lucchitta (in press) suggests that canyon cutting probably began shortly before 5 Ma but may have begun as much as a million years sooner.

14. Formation of bed-parallel parting joints (the J4 set) in response to continued regional uplift and erosional unloading. Such joints generally form only at shallow depths. The presence on nearby plateaus of some 2,000 ft (600 m) of strata above the level of the Ridenour mine shows that canyon cutting by J4 time must already have begun, in order to lower the local erosion surface to a level where unloading joints could develop in the Esplanade Sandstone. An age of about 5 Ma is likely for the J4 set in light of the abundant evidence that much of the lower Grand Canyon was excavated 4-5 Ma (Lucchitta, in press). The fresh, unaltered wall rock adjacent to J4 joints beyond the immediate mine area confirms that they have not long served as conduits for ground-water flow. J4 joints in the mine contain only sparse coatings of secondary Cu-V-U minerals derived from nearby ring fractures.

15. Formation of the J5 (N30E) joint set, the youngest set known from this area. Like the J4 joints, these joints formed at shallow depth and had little impact on paleohydrologic flow. Local coatings of coarse-grained, translucent calcite on joints of both sets, however, suggest that they formed below the local water table, before erosional dissection drained this part of the Esplanade Platform. So too does the uniform orientation of the J5 joints across the Esplanade Platform: the implied absence of topographic perturbations of the stress field during J5 time shows that canyon incision near the Ridenour mine had not yet reached the level of the Esplanade Sandstone.

16-17. Deposition of goethite, followed by calcite, in joints of all five sets. Goethite in the Ridenour mine appears as dense black coatings on joint surfaces and probably was derived locally, from previously deposited, iron-bearing minerals within the pipe and associated ring-fracture zone. Analogous coatings on joints beyond the mine are present but of microscopic thinness. White, sugary calcite, however, is common in joints throughout the area studied. Calcite of similar appearance in the Ridenour mine commonly constitutes the latest phase in residual vugs within breccia-filled solution cavities of the ring-fracture zone.

18. Drainage of ground water from the once-saturated Esplanade Sandstone due to erosional dissection (canyon cutting) of the Esplanade Platform. Since at least that time, flow within the upper portions of the Ridenour pipe has been vertically downward. Ground water saturated in carbonate is locally depositing calcite in small amounts as stalactites, stalagmites, curtains, and flowstone within the Ridenour mine.

19. Widespread deposition of caliche in joints of all sets, both within and beyond the area of the Ridenour pipe, in near-surface environments.

DISCUSSION

PALEOHYDROLOGIC IMPLICATIONS

Structural relations in the Ridenour mine show that the pipe itself is the oldest post-depositional structure known within the study area, and that rocks around the pipe were both altered and mineralized before any regional joint set had formed in the Esplanade Sandstone. If primary mineralization in the Ridenour pipe occurred about 200-220 Ma, as seems likely from U-Pb age determinations in other pipes (Ludwig and others, 1986), then at least 60 m.y. elapsed between deposition of the Esplanade Sandstone and the development of the first regional set of joints within it. For some unknown fraction of that time the Ridenour and kindred pipes nearby were the **ONLY** macroscopic conduits for vertical fluid movement across formation boundaries in the area.

Limited data from other parts of the Grand Canyon region suggest this situation was not unusual. The work of Sutphin (1986), for example, suggests that many pipes on the southern Marble Plateau (fig. 1) are old structures cut by predominantly younger sets of joints. Sutphin noted that many shallow sinkholes in the Kaibab Limestone on the plateau surface have rectangular outlines controlled by well-developed sets of joints, whereas the older breccia pipes are invariably almost circular. Alteration haloes of bleached rock around the pipes are circular also, implying the absence at the time of alteration of strong permeability gradients within the plane of bedding, and thus the probable absence of fractures.

Immediately south of the area mapped by Sutphin, on the Black Point monocline in the Little Colorado River valley 106 mi (170 km) ESE of the Ridenour mine, lies the Riverview pipe (fig. 1). This pipe was mined in the 1950's for uranium extracted from a mineralized collapse breccia (Chenoweth and Blakemore, 1961). A recent study of the structure of the mine and its immediate surroundings (E.R. Verbeek and M.A. Grout, unpub. data, 1986) suggests that the regional joint sets there postdate both the Riverview pipe and the monocline. The pipe is exposed within middle (?) and lower Triassic strata of the Moenkopi Formation and contains within its core several large, downdropped blocks of Shinarump Conglomerate (upper Triassic). Both the displaced blocks and the surrounding rock are cut by the same two sets of joints. Bed dips along the monocline in this area range from horizontal to about 25° NE, but the joints remain everywhere almost vertical, suggesting that the monocline is the older structure. With the exception of minor thrust faults and associated local fractures related to the development of the Black Point monocline in Laramide time, the Moenkopi Formation near the Riverview mine apparently remained unjointed for more than 150 m.y.

The recent study of joints on the western Hualapai Plateau by Roller (1987) also suggests that some, and perhaps most, of the joint sets there are geologically young. She described four sets of joints in the Supai Group (Pennsylvanian-Permian) that appear to correlate with similar sets observed within Tertiary basalts and conglomerates. Work within the Tertiary units was of limited scope and the suggested correlations thus are tentative, but the fact remains that multiple episodes of fracture in that area occurred in Tertiary time. New work by Roller (in press) extends similar conclusions to areas near the Ridenour mine.

Finally, recent work in the solution-collapse breccia pipe of the Apex mine near St. George, Utah, shows that stoping of the pipe, alteration of the wall rock, and mineralization of the breccia predate Late Mesozoic thrusting in the mine area (Verbeek and others, 1987). The Apex mine is in the Basin and Range Province and thus in a tectonic setting quite different from that of the Grand Canyon pipes, but Wenrich and others (1987) argue from geologic and geochemical evidence that the pipes themselves are kindred structures. Given that those Grand Canyon pipes studied in detail are known to considerably predate structural distinction of the Colorado Plateau from the Basin and Range Province, the discovery of a mineralized pipe west of the Plateau was to be expected. Again, in that area, the pipe itself is old relative to other nearby structures.

Although no attempt is made in this paper to interpret paleohydrologic flow directions and sources of ground water (but see Huntoon, 1970, 1986), the evolution through time of structural conduits for ground-water flow in the Grand Canyon region is deserving of comment. The combined evidence from the several studies noted above supports the tentative conclusion that many of the Grand Canyon breccia pipes were both formed and mineralized before pervasive fracture of their various host formations occurred. The "parent" formation of those pipes, the Redwall Limestone, was deposited in Mississippian time. By the close of that period an extensive system of caverns, some of them already filled to various levels by fluvial sediments of the Surprise Canyon

Formation, existed throughout the Redwall Limestone (Billingsley, 1986). In contrast to overlying formations, which had yet to be deposited, the Redwall Limestone at this time may already have been fractured (Roller, 1987, in press). The possibility that initial cavern development in the Redwall may have been controlled by joint sets of Mississippian age had been raised earlier by Sutphin and Wenrich (1986). If true, hydraulic connection via a fracture network between the Redwall and underlying strata, and with the highly faulted crystalline rocks beneath, existed before deposition of the overlying strata.

By late Triassic time hundreds, if not thousands, of breccia pipes had stoped upward in the Grand Canyon region to various levels within the Pennsylvanian through Triassic strata overlying the Redwall Limestone. The post-Redwall strata at this time apparently remained unjointed over much of the region, virtually precluding rapid vertical movement of ground water in any place other than through breccia pipes. The pipes were mineralized by Cu-V-U-bearing fluids of unknown provenance in middle to late Triassic time. The general absence of fault-controlled ore bodies derived from the same fluids is an additional indication that the post-Redwall strata were as yet little fractured.

The times at which various regional sets of joints formed within the post-Redwall strata generally are unknown, but the bulk of the evidence suggests that most of the sets are of Laramide age or younger. Regional integration of the ground-water flow network through a pervasive system of fractures is thus a rather young element of Grand Canyon geology. Flushing of breccia pipes by oxidizing meteoric water at this time led to alteration of the primary ore within the upper reaches of many pipes to form mineral assemblages such as that observed today at the Ridenour mine.

STRUCTURAL CONTROL OF BRECCIA PIPES

Apparent alignments of breccia pipes in many areas of the Hualapai, Coconino, and southern Marble Plateaus have led to the repeated suggestion that the locations of some, and perhaps many, pipes are structurally controlled. However, the nature of the controlling structures and the manner in which they influence pipe development have remained obscure. A few pipes--the Riverview, for example--lie along the tilted flanks of lengthy monoclines. Others lie within or sufficiently close to a major fault zone that some workers (Osterwald, 1965; Baillieul and Zollinger, 1980) feel a genetic link is implied, and still others, such as the Bat Cave pipe (Wenrich, 1985), rest squarely on faults of moderate throw. For many pipes, however, obvious evidence for structural control is lacking, at least at the surface. The Ridenour pipe is one of these. With respect to major structures, the mine lies 2.5 mi (4.0 km) east of the Hurricane fault zone and 4.0 mi (6.4 km) west of the Toroweap fault zone. The nearest "major" structure, the Lava fault, has a mapped offset of 400 ft (120 m) (Wenrich, Billingsley, and Huntoon, 1986) and lies 1.4 mi (2.3 km) northwest of the mine. Several minor normal faults with offsets of 10-25 ft (3-8 m) occur within a half mile of the mine on its northeast side, but none impinge on the pipe itself. The only fault within the mine has a mapped normal offset of 3 ft (1 m) and postdates both the pipe and the main phase of mineralization. There is little evidence at the Ridenour mine that any mapped fault influenced the pipe location or facilitated stoping, and all five joint sets that cut the host rock are now known to postdate creation of the pipe. Similar statements could be applied to the Riverview pipe and apparently to many other breccia pipes as well.

In retrospect, the general inability to relate locations of breccia pipes to specific structures in the surrounding rocks should not be surprising: the pipes were mineralized in early Mesozoic time, whereas the monoclines, faults, and most or all of the joint sets that deform the post-Redwall strata are far younger, of Laramide and later age. This, however, does not entirely negate the possibility of control by much older structures, evidence for which might exist only at deeper and generally unexposed stratigraphic levels where the pipes first started to develop. One possible explanation for structural control of breccia pipes is reviewed briefly below for the two areas where it has been most frequently invoked.

Marble Plateau

For the southern Marble Plateau (fig. 1), Sutphin and others (1983), Sutphin and Wenrich (1986, 1988), and Sutphin (1986) suggested that the lack of coincidence between trends of aligned breccia pipes and of prominent fracture sets at the surface was evidence for a deeper level of structural control. They hypothesized that the Redwall Limestone was cut by early sets of fractures that controlled initial cavern development but that have no expression in the Kaibab Limestone capping the plateau surface 2,000 ft (600 m) above. The similarity in trend between pipe alignments (Sutphin and Wenrich, 1986, 1988; Wheeler, 1986) and known and inferred fault zones in the crystalline basement rocks beneath the Marble Plateau led them to the further inference that minor reactivation of those basement fault zones in Paleozoic time was responsible for the development of the hypothesized fractures, in linear zones parallel to, and directly above, the faults.

Reactivation of Precambrian fault zones is well known from the Grand Canyon region and occurred in both normal and reverse senses at various times. Its effects are complex, particularly where structures from multiple episodes of movement are superimposed, but all are strongly dependent on the magnitude of slip. Where displacements were large, reactivation of Precambrian fault zones commonly resulted in faulting of the entire section of Paleozoic rocks above. Long, narrow zones of subparallel faults across the plateaus flanking the Grand Canyon are one expression of this process; the Hurricane and Toroweap fault zones are familiar examples. Lesser amounts of slip locally resulted in faulting of the lower parts of the sedimentary section but not of higher units because throw across many of the faults diminishes upward. Huntoon (1974) described such structures from the eastern Grand Canyon and attributed the decreasing throw with height to ductile deformation within thick sections of weak rock such as the Bright Angel Shale. The key point as it relates to the hypothesis of Sutphin and his colleagues is that minor reactivation in Paleozoic time of Precambrian faults beneath the Marble Plateau conceivably could have resulted in local fracture of the Redwall Limestone but not of overlying units, particularly if such reactivation occurred during the minor period of uplift and emergence of the Redwall in Late Mississippian time, before the overlying units were deposited. If so, lengthy belts of highly fractured Redwall above the basement faults would have been favored sites for initial cavern development and for subsequent stoping to form chains of breccia pipes as seen at the surface. The controlling structures, however, would remain "blind" and have no expression in exposed rocks. This hypothesis is plausible and fits known facts, but it remains incompletely tested, as nothing is known about the fracture network in the Redwall Limestone beneath the Marble Plateau. The nearest exposures, in the canyon of the Little Colorado River, are nearly inaccessible.

Hualapai and western Coconino Plateaus

A similar hypothesis of structural control has recently been propounded for the Hualapai lands, including the area of the Ridenour mine on the western edge of the Coconino Plateau, by Billingsley and others (1986), Wenrich, Billingsley, and Huntoon (1986), Sutphin and Wenrich (1987), and Wenrich and Sutphin (in press). Opportunity exists in this region to address the topic of structural control directly, for the "parent" formation of the pipes--the Redwall Limestone--is exposed and accessible to study in many places not far west of and below the Ridenour mine. One intriguing result from reconnaissance studies of the regional fracture network by Roller (1987, in press) is that the two earliest sets of prominent joints in the Redwall Limestone on the Hualapai and western Coconino Plateaus do not cut overlying strata of the lower Supai Group. Likewise, no counterpart to those early sets was found by us at the level of the Esplanade Sandstone around the Ridenour mine. Roller (1987) suggested as one possibility that the Redwall Limestone was lithified and then cut by the two early sets of joints prior to deposition of the overlying Supai Group. If so, the joints are of Late Mississippian to Early Pennsylvanian age and thus could have influenced both early cavern development in the Redwall Limestone and subsequent stoping of pipes through the rest of that formation.

Testing of this hypothesis should be relatively straightforward, for if it is true, the structure of breccia pipes within the Redwall Limestone should differ markedly from those in higher units in at least four ways: (1) Breccia pipes stoped through previously broken rock in the Redwall should lack a well-defined ring-fracture zone. Ring fractures, if they did form locally, should be small and should terminate against the earlier joints unless those joints had already been healed by precipitation of secondary minerals such as calcite. Roller (in press) recently addressed this topic and noted that ring fractures are absent around pipes that crop out in the Redwall. (2) Individual pipes stoped through jointed rock might well be elongated in plan view parallel to the most prominent set of fractures, whereas the same or other pipes at higher stratigraphic levels, cut only by post-pipe joints, should tend toward circular outlines. In this respect it is interesting to note that all but 2 of 93 pipes mapped in Permian and Triassic strata of the southern Marble Plateau are circular (Sutphin, 1986), whereas numerous pipes mapped by Billingsley and others (1986) in the Blue Mountain area of the Hualapai Reservation, immediately above the top of the Redwall, are elongated in a N40-60E direction. The direction of elongation is parallel to one of the two early sets of pre-Supai joints documented by Roller (1987) in the Redwall Limestone. (3) Pipes stoped through jointed rock should contain in their cores polyhedral blocks of collapse breccia. Roller (in press) noted exactly this in some pipes within the Redwall Limestone--some of the clasts had planar external faces, defined apparently by joints. (4) Wenrich (1985) and Sutphin (1986) noted that many breccia pipes are encircled by inward-dipping beds due to solution-thinning of nearby strata. Old, pre-pipe joints in dipping beds should have rotated with those beds to new and generally nonvertical orientations, whereas post-pipe joints would not be so affected. Close attention to the orientations of various joint sets as they are traced from horizontal beds outside pipes to dipping beds near them should provide one ready means to determine which, if any, among several or more sets of joints were present at the time of pipe formation.

Mapping of aligned pipes and statistical testing of suggested alignments for significance has not yet been accomplished for the Hualapai pipes, nor has it been determined if the early (pre-Supai Group) joints mapped by Roller (1987, in press) are related in trend and distribution to underlying basement fault zones. Those early joints have average strikes of N48E and N51W, almost exactly matching the preferred trends of breccia pipes on the Marble Plateau, but so much distance separates the two areas (85-100 mi, or 135-160 km) that no special significance should be attached.

IMPLICATIONS FOR MINING OF BRECCIA PIPES

The geometry of breccia pipes and the distribution and grade of Cu-V-U ores within them are complex functions of several factors, not all of them well understood at present. Factors often mentioned include lithology, structure of the ring-fracture zone, the source, chemistry, and temperature of the mineralizing fluids, whether these fluids moved upward or downward through the pipes, and the origin, nature, and possible migration through pipes of reductants that led to precipitation of the primary ores. Some of the geochemical factors are addressed in papers by Gornitz and Kerr (1970), Gornitz and others (1988), Rasmussen and others (1986), Sutphin (1986), Wenrich (1985, 1986b), and Wenrich and Sutphin (in press). Below we address only a few of the more obvious physical factors affecting ore deposition in mineralized pipes.

Structure of ring-fracture zone

The ring-fracture zone in mined Grand Canyon breccia pipes commonly is a site of rich concentrations of ore. The width of this zone, and thus the potential volume of mineralized rock, varies within relatively narrow limits at any particular stratigraphic level but shows marked variations vertically. At the Ridenour mine the width of the ring-fracture zone ranges from somewhat less than 40 ft (12 m) near the no. 7 adit to at least 130 ft (39 m) on the 4,428-ft level, about 140 ft (42 m) higher stratigraphically. Kofford (1969) noted for the Orphan pipe that the mineralized ring-fracture zone on the 365-ft level measures 500 ft (150 m) edge-to-edge around a pipe core of 380 ft (115 m) diameter, showing that the ring-fracture zone on that level averages about 60 ft (18 m) in width. The 365-ft level is about 230 ft (65 m) below the base of the Hermit Shale and thus probably is in the lower part of the Esplanade Sandstone, as is the Ridenour mine. The widths of the ring-fracture zone in the two areas are comparable. Within the Hermit Shale, however, the ring-fracture zone around the Orphan pipe narrows to 6-20 ft (2-6 m) (Kofford, 1969). It is likewise narrow in this unit around the EZ-2 pipe, about 40 mi (64 km) NNE of the Ridenour mine. Krewedl and Carisey (1986) state that bleaching of the Hermit Shale around the EZ-2 pipe extends no farther than 50 ft (15 m) from the pipe core; the width of the associated ring-fracture zone presumably is somewhat less.

It seems clear from this and additional published information that lithology exerts a strong influence on the dimensions and character of the ring-fracture zone. Similar effects are evident at the Ridenour mine on a bed-to-bed level. Maximum widths of the ring-fracture zone and the most strongly mineralized rock appear to correlate with beds of mechanically weak, highly permeable sandstone, whereas well-cemented sandstones of low permeability are distinctly less favorable environments for ore. The strongly cemented sandstone of unit 11 (fig. 18), for example, contains no ore, nor is it broken by ring fractures, despite the abundant presence of both directly below in the underground stopes. The lower contact of this bed marks the uppermost extent of the mine workings. Beds of mudstone and shale may be the most unfavorable lithology of all, as they are at other pipes (Kofford, 1969; Chenoweth, 1986). Ring fractures within shaly layers at the Ridenour mine are poorly developed, as the rock instead tended to split along discontinuous fractures parallel to the plane of fissility. Bed-parallel veinlets of copper minerals were noted in a few such places, but the veinlets are thin and ore grades low. In other places the shaly beds are barren.

Diameter of pipes

Diameters of individual pipes, like the widths of ring-fracture zones, vary from level to level, and for the same reasons. Again a rough correlation with lithology is evident, as pipe diameters seem greatest in thick units of relatively weak sandstone (e.g. the Supai Group) and least in formations dominated by shales and mudstones (e.g. the Hermit Shale) or by well-cemented sandstones of exceptional mechanical strength. The Orphan pipe, for example, flares from a minimum diameter of about 165 ft (50 m) near the base of the Hermit Shale to about 490 ft (150 m) within the underlying Esplanade Sandstone, an increase of 325 ft (100 m) over a comparable vertical distance (Gornitz and Kerr, 1970). Krewedl and Carisey (1986) likewise noted the dependence of pipe diameter on rock type and suggested also that the size of the original caverns in the Redwall Limestone may have played some role. The limited exposures of the core breccia at the Ridenour mine and the small vertical extent of the mine workings do not allow these factors to be directly addressed for that pipe, nor are drilling records sufficient to reconstruct its subsurface geometry.

Fracture history of host rocks

Knowledge that different stratigraphic units are cut by joints of different geologic age in the Grand Canyon area (Roller, 1987, in press) introduces additional potential for vertical variability in pipe geometry and mineralization. Nearly all of the Cu-V-U ore in the Ridenour mine occurred along large, arcuate ring fractures encircling the pipe because these were the only fractures in existence at the time of ore formation. The edge of the ring-fracture zone in this mine forms a sharp cutoff of mineralized rock. A similar situation likely prevailed at the Orphan mine, which also had a well-developed ring-fracture zone within the upper, mined portions of the pipe.

The pattern of mineralization (if any) at deeper levels in these and similar pipes, however, may be much different if older sets of joints predating ore formation are present in the older rocks. Such joints, if open, likely would have allowed migration of the ore fluids to much greater distances from the pipe than was characteristic of the higher strata, resulting in a more diffuse pattern of mineralization with no well-defined outer boundary. Strata cut by pre-pipe joints may contain only a weakly developed ring-fracture zone or be missing one entirely, as around some of the Redwall pipes recently examined by Roller (in press). In this regard it is perhaps significant that a series of holes drilled in 1961-62 from the lowest levels of the Orphan mine failed to locate evidence of a ring-fracture zone in strata much below the mine workings (Chenoweth, 1986). The age of various joint sets relative to the times of pipe formation and mineralization is an additional factor potentially influencing the character of ore bodies and their variation with depth, but one for which little information is available for most parts of the Grand Canyon region.

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APPENDIX A

Measured stratigraphic section near Ridenour mine
(described from top to bottom)

Unit 11

Noncalcareous to slightly calcareous, quartz-cemented, fine-grained sandstone. Color variable; medium pink to salmon pink where most firmly cemented, grading locally into brick red and weakly cemented sandstone resembling that of underlying beds. Prominently crossbedded in sets 6-10 ft (2-3 m) in height. Unit is 19 ft (5.8 m) thick.

This sandstone is of quite different character from all sandstone beds described below. Much of it is strongly cemented and nonporous, in contrast to the weakly cemented, locally friable, and highly porous sandstones of underlying beds. On broken surfaces this sandstone has a finely frosted appearance, and individual quartz grains are difficult to distinguish by eye because of pervasive quartz cement. Other sandstones below, when broken, show only dull, rough surfaces with individual quartz grains standing in relief.

Unit 10

Moderately to weakly cemented, generally noncalcareous, coarse siltstone. Medium to dark brownish red on both fresh and weathered surfaces. Poorly exposed; generally found as float or small outcrops below overhanging ledge of unit 11. 3 ft (0.9 m) thick.

Unit 9

Porous, weakly cemented, very fine grained sandstone. Generally noncalcareous but locally moderately calcareous. Color ranges from pale pink or nearly white to medium brownish red or brick red on both fresh and weathered surfaces. Mottled appearance is common. Locally friable and easily disaggregated by scratching with pick end of hammer. Lower third crossbedded in sets 1-1.5 ft (30-45 cm) thick; weathers to smooth, rounded forms. Upper two-thirds massive and weathers to irregular, knobby surfaces. 14 ft (4.3 m) thick.

Unit 8

Siltstone; dark brownish red on weathered surfaces. Forms covered slopes north of mine and is inaccessible in mine area, so was not inspected closely. Rock is considerably darker in color than underlying units, and thus presumably is finer grained. Fissile; weathers to thin plates and laminae. 3 ft (0.9 m) thick (estimated).

Unit 7

Massive, porous, slightly calcareous, medium brownish-red coarse siltstone to fine-grained sandstone. Sinuous base probably is an erosional contact. 2.3 ft (0.7 m) thick where measured north of mine. Relative thicknesses of units 6 and 7 changes somewhat laterally; within the mine area they are of nearly equal thickness.

Unit 6

Generally noncalcareous, moderately fissile, coarse- to medium-grained siltstone. Dark brownish red on both fresh and weathered surfaces. Parallel laminated; laminae are crudely planar to wavy. Weathers to thin plates 0.2-0.8 inch (0.5-2 cm) thick. Locally split into two nearly equal parts by a thin parting of fissile siltstone that wedges out laterally. 1.8 ft (0.6 m) thick.

Unit 5

Porous, noncalcareous to locally slightly calcareous, weakly to moderately cemented, very fine grained to fine-grained quartz sandstone. Brick red on both fresh and weathered surfaces. Locally friable; weathers to highly rounded forms. Prominently crossbedded in lower fourth of bed; remainder massive to crudely parallel-bedded. 12 ft (3.7 m) thick.

Unit 4

Porous, slightly to moderately calcareous, weakly to moderately cemented, fine-grained quartz sandstone. Slightly paler in color and better cemented than underlying unit. Appears massive from a distance but is internally crossbedded. 3 ft (0.9 m) thick.

Unit 3

Porous, slightly calcareous, weakly to moderately cemented, very fine grained quartz sandstone. Brick red on both fresh and weathered surfaces. Parallel bedded. Forms minor reentrant in canyon wall north of mine. 1 ft (0.3 m) thick.

Unit 2

Porous, weakly to moderately cemented, noncalcareous, very fine grained to fine-grained sandstone. Weathers to rounded forms with pitted surfaces. Brick red to pale brick red on weathered surfaces; similar or slightly darker when freshly broken. Prominently crossbedded in sets 8-12 inches (20-30 cm) in height in lower fourth of bed, increasing to 3-6 ft (1-2 m) in remainder of bed. Locally becomes coarser grained, better cemented, and slightly calcareous toward top of unit. 26 ft (7.9 m) thick.

The adit at the northeast end of the mine (No. 3 adit of Miller, 1954 and fig. 17 of this paper) was driven into this sandstone.

Unit 1

Deep brownish-red, fissile, noncalcareous quartz-rich siltstone. Nonresistant; forms reentrant in canyon wall northeast of mine, adjacent to the north edge of the dump material below the mine road. Weathers to thin plates. Consists of two fining-upward units; the base of each is massive to platy and passes upward into progressively more fissile, finer-grained rock. Not exposed in surface workings of mine, which are entirely above stratigraphic position of this unit. 3 ft (0.9 m) thick.