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GRAND CANYON SUPERGROUP, NORTHERN ARIZONA: STRATIGRAPHIC SUMMARY AND PRELIMINARY PALEOMAGNETIC CORRELATIONS WITH PARTS OF OTHER NORTH AMERICAN PROTEROZOIC SUCCESSIONS

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ABSTRACT

The Grand Canyon Supergroup consists of the Middle Proterozoic Unkar Group (~2 km thick) and Nankoweap Formation (~100 m) and the Late Proterozoic Chuar Group (~1.6 km) and Sixtymile Formation (~60 m). These strata accumulated, with one major break and a few minor breaks, in the interval ~1250 Ma to ~825 Ma. Strata of the Unkar Group, Nankoweap Formation, and Sixtymile Formation consist dominantly of red beds. Igneous rocks consist of a mafic volcanic unit at the top of the Unkar Group and mafic sills that intrude the group. Strata of the Chuar Group consist dominantly of gray shale and subordinate carbonate and red beds. Correlations with parts of other North American Proterozoic successions have emerged as a result of magnetostratigraphic studies. Paleomagnetic correlations employing paleomagnetic poles, apparent polar wandering paths, and polarities indicate correlations with parts of the Apache Group and Troy Quartzite of central Arizona, the Uinta Mountain Group of Utah and Colorado, the Keweenawan Supergroup of the Lake Superior region, and the Mackenzie Mountains Supergroup and other rocks of northwest Canada. The Belt Supergroup of western Montana and Idaho appears to be entirely, or nearly entirely, older than the Unkar Group. The paleomagnetic correlations for Late Proterozoic strata are supported by correlations from the study of planktonic microbiota in marine or lacustrine strata of the Chuar Group and the Red Pine Shale of the upper part of the Uinta Mountain Group. The correlations lead to an improved understanding of the Proterozoic depositional, igneous, and structural history of the western and central parts of the North American craton, including events related to the Keweenawan disturbance of Lake Superior.

INTRODUCTION

The Middle and Late Proterozoic Grand Canyon Supergroup is known only from exposures in the eastern and central parts of the Grand Canyon of the Colorado Plateau, northern Arizona. The general distribution of strata and intrusions of the supergroup is shown on figure 1. Most strata of the supergroup, tilted about 10 degrees to the northeast, are cut by throughgoing north- and northeast-trending faults and by a relatively large number of subordinate northwest-trending faults. Strata stratigraphically low in the supergroup are preserved in the west-central part of the Grand Canyon, where the rocks commonly display the effects of thermal alterations caused by the intrusion of thick mafic sills. A full section of the supergroup is preserved only in the eastern Grand Canyon. Here, the strata contain only minor mafic intrusions and appear nearly as unmodified by burial metamorphism as overlying Paleozoic strata. The northeasterly tilting allows the Proterozoic succession to be readily distinguished from the nearly horizontal Paleozoic rocks that form the continuous walls of the Grand Canyon. The Paleozoic section, about 1,650 m thick, accumulated during a 300-Ma interval, from about 570 to 270 Ma. In contrast, the Grand Canyon Supergroup, ranging from about 3,500 to 4,000 m in thickness, accumulated during an approximately 425-Ma interval of time, from about 1250 to 825 Ma. The stratigraphic framework and the approximate and estimated ages are given in figure 2 and table 1.

Far from being a homogeneous and monotonous sequence, the Grand Canyon Supergroup is characterized by lithologic diversity. Various studies during the past dozen and more years have provided new information on the depositional history and on structural and intrusive events that gave rise to a regional structural fabric inherited by the overlying Paleozoic section. Studies involving paleobiology, isotopic geochronology, and paleomagnetism (magnetostratigraphy) are continuing. Developing information indicates that the Grand Canyon Supergroup is one of the most complete and longest ranging records of Middle and early Late Proterozoic age preserved on the North American continent.

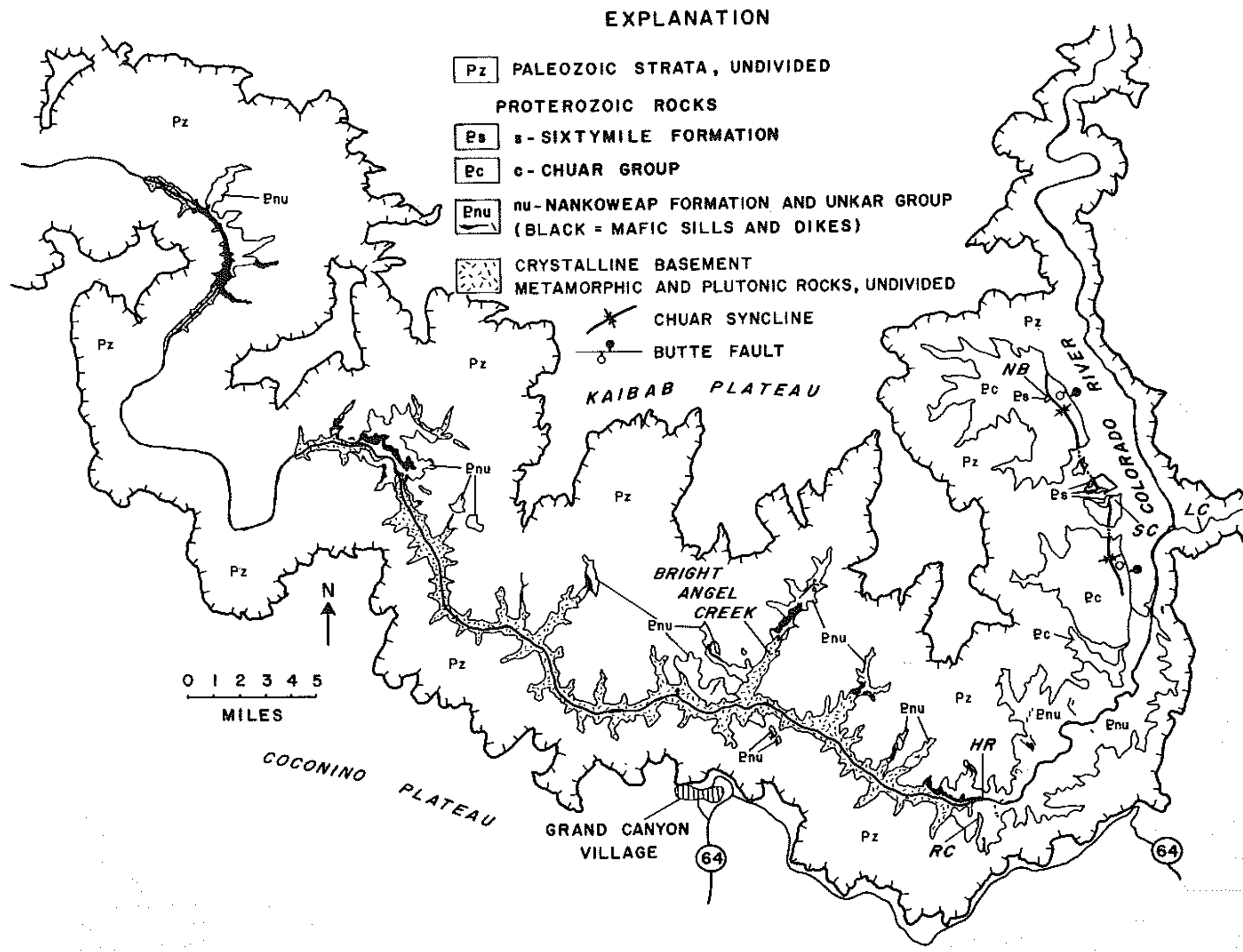


Figure 1. Generalized geologic map of eastern and central Grand Canyon showing distribution of units of the Middle and Late Proterozoic Grand Canyon Supergroup. The north-south-trending eastern margin of the Chuar Group in the eastern canyon marks the trace of the Butte fault (bar with ball indicating downthrown side; open ball, Proterozoic displacement; closed ball, Phanerozoic displacement). Adapted from Huntoon and others, 1976 (ed. 1980). (LC, Little Colorado River; NB, Nankoweap Butte; SC, Sixtymile Canyon; HR, Hance Rapids; RC, Red Canyon).

STRATIGRAPHIC AND STRUCTURAL FRAMEWORK

The Grand Canyon Supergroup is currently subdivided into four units (fig. 2 and table 1). In ascending order, they are the Unkar Group, Nankoweap Formation, Chuar Group, and Sixtymile Formation. Several unconformities are present that mark times when structural adjustments occurred on throughgoing faults, presumably in response to regional if not continentwide tectonic events. Unconformities are found at the top of the Hakatai Shale, at the top of the Unkar Group (Cardenas Basalt), within and at the top of the Nankoweap Formation, and as multiple unconformities in the lower and middle members of the Sixtymile Formation. Appreciable regional tilting occurred only as a consequence of the youngest of the Proterozoic structural adjustments, called the Grand Canyon-Mackenzie Mountains disturbance (Elston and McKee, 1982).

Nomenclature

The reader is referred to Spamer (1983) for an extensive annotated bibliography of Grand Canyon geology and paleontology. Spamer has summarized the history of development of geologic knowledge of the canyon and also provided a summary of the stratigraphic nomenclature that is adequate for most uses. Space is devoted here to stratigraphic nomenclature of the Proterozoic section because inconsistencies have arisen during the past decade, and some unnecessary revisions to well-established formation names for the Unkar Group have been proposed. The well-established names for formations of the Unkar group have been retained in this report, as well as an informal, descriptive nomenclature for members of formations of the Unkar Group, the Nankoweap Formation, and the Sixtymile Formation (fig. 2, table 1).

The earliest geologic studies in the Grand Canyon were by Powell (1876), whose first expedition was in 1869. In

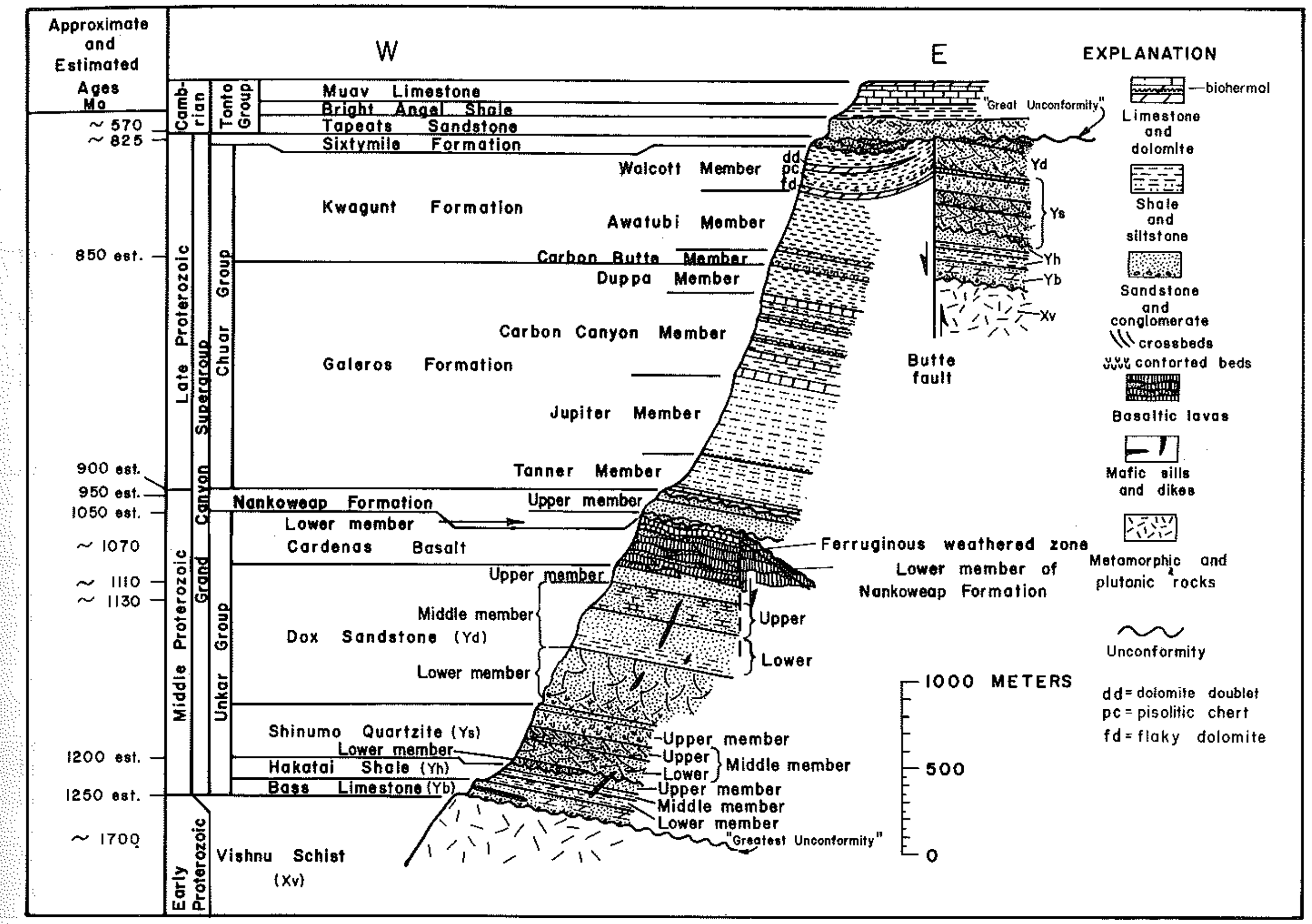


Figure 2. Stratigraphic outline of Grand Canyon Supergroup showing structural relations between Proterozoic and basal Cambrian strata, eastern Grand Canyon, Arizona. Structural offset on Butte fault is portrayed as it existed during early Paleozoic time. Approximate and estimated ages are in part from radiometric ages derived from igneous rocks of the Grand Canyon and in part from paleomagnetic correlations with other Middle Proterozoic successions dated by U-Pb (zircon) and Rb-Sr isochron methods on igneous rocks.

1882-83, Charles D. Walcott conducted pioneer work in the eastern Grand Canyon. His studies identified all of the units that were formally subdivided by later workers and that are now included in the Grand Canyon Supergroup. For an account of Walcott's work, see Yochelson (1979). Walcott named the Chuar (1883) and the Unkar (1894). He gave the Chuar group status, but he referred to both of these units in his 1890, 1894, and 1895 reports as terranes. His 1894 report contains a geologic map of the Proterozoic rocks in the eastern Grand Canyon that remains fundamentally correct to this day. In his 1894 report, Walcott redesignated the Grand Canyon Group of Powell (1876) as the Grand Canyon Series, consisting of two terranes of stratified rocks (the Unkar and Chuar) overlying a crystalline basement that he called the Vishnu terrane.

Strata of the Unkar terrane were subdivided into formations by Levi Noble (1914), who carried out detailed mapping and stratigraphic studies in and near the Shinumo Quadrangle of the central Grand Canyon. Noble used the terms the "Unkar Group" and "Chuar Group" at that time, but the Chuar had not yet been subdivided into formations. Noble's mapping and stratigraphic studies set the standard for subsequent geologic studies in the canyon, and names given to formations of the Unkar Group by Noble are retained in this report. However, the section of the Unkar studied by Noble is incomplete because pre-Paleozoic erosion in the area of the central Grand Canyon had removed strata above the level of the middle part of the Dox Sandstone. The missing strata, preserved in the eastern Grand Canyon, had been included by Walcott in his Unkar terrane, as were strata later called Nankoweap by Van Gundy (1934, 1951). It was not until recently that Ford and others (1972) formally named the basaltic flows in the eastern Grand Canyon the Cardenas Lavas, employing a name that had been used without documentation by Keyes (1938) (see discussion of Keyes' publications in Spamer, 1983). Because lava is hot fluid and the term basalt applies to solidified rock, the Cardenas Lavas are here formally redesignated the Cardenas Basalt.

The stratigraphy of the Unkar Group has been summarized by Beus and others (1974), whose stratigraphic framework is nearly identical with the framework shown in figure 2 and

TABLE 1. Summary of Middle and Late Proterozoic Grand Canyon Supergroup, northern Arizona[1]

	Thickness (Meters)
Cambrian	
Tonto Group	180-395
Unconformity	
Late Proterozoic	
Grand Canyon Supergroup	3,585+
Sixtymile Formation	59-64(+)
Upper member	12
Unconformity	
Middle member	25
Unconformity	
Lower member	22-27
Chuar Group	1,676[2]
Kwagunt Formation	632
Walcott Member	281
Awatubi Member	301
Carbon Butte Member	50
Galeros Formation	1,044
Duppa Member	104
Carbon Canyon Member	350
Jupiter Member	434[3]
Tanner Member	156
Unconformity	
Middle Proterozoic	
Nankoweap Formation	113-250+(?)
Upper member	100(+)
Unconformity	
Lower (ferruginous) member	13(+)
Unconformity	
Unkar Group	1,775[4]
Cardenas Basalt	224-450 (300)
Dox Sandstone	920
Upper member	93
Upper middle member	167
Lower middle member	270
Lower member	390
Shinumo Quartzite	350
Upper member	118
Upper middle member	80
Lower middle member	130
Lower member	0.15-187.5(18)
Unconformity	
Hakatai Shale	125
Upper member	40
Middle member	22
Lower member	62
Bass Limestone	80
Hotauta Conglomerate Member	0-2
Unconformity	
Early Proterozoic	
Vishnu Schist	

[1]Tonto Group from McKee and Resser (1945); Grand Canyon Supergroup (Elston and Scott, 1976; Elston, 1979, and this report); Sixtymile Formation from Elston (1979), and Elston and McKee (1982); Chuar Group from Ford and Breed (1972a, 1973); Nankoweap Formation and Unkar Group from Elston and Scott (1976); Unkar Group from Beus and others (1974).
[2]Thicknesses for Chuar Group are from Reynolds and Elston (1986; M. Reynolds, written communication, 1988).
[3]Thickness in part calculated from structure section.
[4]Nominal thicknesses for units of Unkar Group are principally from exposures in eastern Grand Canyon.

table 1. However, at about that time and since then, reports have appeared in which modifications to Noble's nomenclature have been proposed. Some of the proposed modifications are shown in Spamer (1983), implying that their use has been generally accepted, whereas other proposed modifications are not shown in Spamer. The Bass Limestone (Noble, 1914) was called the Bass Formation by Dalton (1972), but later Dalton and Rawson (1974) called it the Bass Limestone. Somehow, the name Bass Formation was attributed to Noble by Spamer (1983, p. 67). I favor retaining the original name, Bass Limestone, because the Bass is the only formation in the Unkar Group in which appreciable beds of carbonate are found, even though such beds are not dominant or even conspicuous in the eastern exposures. Daneker (1974) referred to the Shinumo as the Shinumo Quartzite (Noble, 1914), but he subsequently called this formation the Shinumo Sandstone (Daneker, 1975). Spamer has retained the term "Quartzite" in his compilation. The Shinumo is a quartzite, mostly being firmly if not extremely well cemented by silica. The Dox Sandstone (Noble, 1914) was redesignated the Dox Formation by Stevenson (1973) and Stevenson and Beus (1982), and its four informal members (lower, lower middle, upper middle, and upper) were given formal names derived from local features and drainages. These names are listed by Spamer (1983, p. 67). Redesignation of the Dox as a formation, and the formal naming of its four members, serves no useful purpose. The Dox consists dominantly of sandstone, ranging from very fine grained and silty to medium to coarse grained and pebbly. Argillite and mudstone are subordinate, and carbonate is very rare.

Van Gundy (1934, 1951) recognized that a thin sequence of red beds, separated from underlying basaltic flows of the Unkar Group and overlying marine or lacustrine strata of the Chuar Group by unconformities, belonged to neither the Unkar nor the Chuar. Although called the Nankoweap Group by Van Gundy, the unit later was reduced to formational rank by Maxson (1967) on his geologic map, because the Nankoweap had not been subdivided into formations. Elston and Scott (1976), corroborating the conclusions of Van Gundy, recognized three unconformities separating two informal (lower and upper) members in the Nankoweap. A major hiatus separates the lower and upper members. At this time, the Grand Canyon Series also was redesignated as the Grand Canyon Supergroup (Elston and Scott, 1976), following current practice that allows a supergroup to be established if it consists of some combination of groups and formations totaling at least three.

Stratigraphic studies and mapping by Ford and Breed (1972a, 1972b, 1973) led to the establishment of three formations in the Chuar Group. The lower two formations, the Galeros and Kwagunt, were subdivided into several formal members, as shown in figure 2 and table 1, and these were adopted by Elston (1979). The Sixtymile Formation at the top of the Proterozoic section was removed from the

Chuar Group and established as a separate unit for reasons given by Elston (1979) and Elston and McKee (1982), resulting in the present fourfold subdivision for the Grand Canyon Supergroup.

"Great" and "Greatest Angular" Unconformities

Two major unconformities bound the Grand Canyon Supergroup, the lower separating stratified Proterozoic rocks from the crystalline basement, and the upper separating Proterozoic strata from overlying Paleozoic strata (fig. 2). The older unconformity was called the "greatest angular unconformity" by Noble (1914, p. 31), whereas both Walcott (1894, p. 506, and 1895, p. 317) and Noble (1914, p. 31 and Plate IX) referred to the upper unconformity as the "great unconformity." Where Proterozoic strata were removed by the younger episode of erosion and Paleozoic strata directly overlie the crystalline basement, the two unconformities are merged into a single, truly great unconformity. We now know that the upper unconformity marks an approximately 230-Ma hiatus (between ~800 Ma and 570 Ma), whereas the lower unconformity marks an approximately 425-Ma loss of record (between ~1675 Ma and ~1250 Ma).

STRATIGRAPHY

Crystalline Basement

Rocks of the crystalline basement, called the Vishnu Schist by Noble (1914), consist of considerably more than schist. Noble and Hunter (1917) identified eight geographically segregated groups of rocks consisting variously of gneisses, amphibolites, granites, granite gneisses, massive mafic intrusive rocks, and metadiorite. The metamorphic rocks may represent a stratified assemblage of interbedded mafic flows and clastic rocks. At a number of places, vertically dipping metamorphic rocks have been invaded from below by plutonic rocks. The distribution of various intrusive and metamorphic rocks has been depicted by Maxson (1961, 1967, 1969) and by Babcock and others (1974, 1979). The results of the mapping by Babcock and others also is shown on the geologic map of Huntoon and others (1976).

The age of the basement rocks is known from U-Pb ages determined on cogenetic zircon from plutonic rocks in the Vishnu Schist. Determinations for two individual plutons range from about 1695 Ma to 1725 Ma (Pasteels and Silver, 1965). Recalculation employing new constants would give ages about 30 Ma younger, indicating that the plutonism occurred in the interval 1665 to 1695 Ma.

Unkar Group

Strata of the Unkar Group consist dominantly of fine- to coarse-grained red beds, variously of marine, nearshore marine, tidal-flat, and continental origin. Four episodes of marine deposition, followed by times of emergence and subaerial accumulation, are recognized in the Unkar Group. Conspicuous carbonate beds are found only in the Bass Limestone, but even in this formation clastic deposits predominate at places. Rare stromatolite-bearing carbonate beds, a few centimeters to a few decimeters thick, are found locally in the upper middle member of the Dox Sandstone.

Marine clastic and carbonate deposits of the Unkar Group are mostly dark to light purple. Exceptions include the lower half of the lower member of the Dox Sandstone, which is dominantly gray and greenish gray. In the lower part of the Unkar Group in the central Grand Canyon, beds that have been altered by the intrusion of sills are brownish. In contrast to purplish marine strata, beds that are considered to have accumulated subaerially are red-brown, and in two units (middle member of the Hakatai Shale and parts of the upper middle member of the Dox Sandstone) the strata are bright red-orange. Hematite associated with secondary alteration of a part of the upper member of the Shinumo Quartzite also is red-brown. Such altered rock lacks disseminated bleached spots (freckling) found in unaltered purple (mainly marine) and red-brown (mainly continental) strata.

Four depositional cycles are recognized in the Unkar Group, each recording a cycle of marine and subaerial deposition. The cycles include: (1) the Bass Limestone and lower member of the Hakatai Shale (marine), overlain by the middle (subaerial) member of the Hakatai; (2) the upper member of the Hakatai Shale (marine), overlain by the lower (subaerial) and lower middle and upper middle members of the Shinumo Quartzite (nearshore marine and possibly subaerial in part); (3) the upper member of the Shinumo Quartzite and lower member of the Dox Sandstone (marine), overlain by the lower middle member of the Dox Sandstone (subaerial); and (4) the upper middle member of the Dox (tidal-flat), overlain by the upper member of the Dox (subaerial?).

Bass Limestone. The Bass consists of interbedded sandstone and silty sandstone, prominent interbeds of conglomerate and dolomite (some stromatolite-bearing), and subordinate interbeds of argillite. The formation becomes generally finer grained toward the top. Carbonate rock is abundant, particularly in western exposures of the central Grand Canyon. Clastic rocks predominate on the east, in the area of Hance Rapids. The upper boundary is arbitrarily drawn at the highest, more or less laterally continuous sandstone that resembles sandstone of the Bass. The stratigraphically highest carbonate beds commonly lie some distance below this contact. A basal conglomerate, present only locally, was called the Hotauta Conglomerate by Noble (1914) and was considered by him to be a separate formation. Because the Hotauta where named by Noble (1914) differs in no fundamental way from conglomerates found higher in the Bass, it was treated as a member of the Bass by Dalton (1972) and Beus and others (1974). That rank is accepted here.

Hakatai Shale. The Hakatai Shale is a generally fine grained, slope-forming unit that is subdivided into three informal members. The lower member consists of purplish to reddish-purple mudstone, interbedded sandy siltstone, and rare thin beds of sandstone. These strata accumulated under quiet conditions, apparently during the waning phases of marine deposition that began during accumulation of the Bass.

Beds of the lower member of the Hakatai Shale grade upward to mudstone, siltstone, and subordinate sandy siltstone of the middle member, which has a strikingly red-orange color. The middle member is one of the most distinctive red-bed units in the Grand Canyon Supergroup. Beds of the middle member locally display large reduction spots (large "freckles"), which commonly contain dark-gray to greenish-gray centers that in turn enclose very dark gray to black central cores of possibly organic (stromatolitic?) origin. The cores, enclosed by halos of non-reddened rock, appear identical to vanadium-rich reduction spots seen in strata of the lower middle and upper members of the Dox Sandstone that are considered to have accumulated in subaerial environments. On the basis of widely divergent paleomagnetic poles from strata of the enclosing lower and upper members of the Hakatai Shale, the subaerial exposure of the thin middle member that led to development of the pervasive red-orange pigmentation is inferred to have occurred over a geologically appreciable span of time.

The upper member of the Hakatai Shale consists of lavender, fine- to coarse-grained, cross-bedded sandstone of probably marine deltaic origin. This unit forms ledges and even sheer cliffs where protected by strata of the overlying Shinumo Quartzite. Sears (1973), from a detailed structural study along the Bright Angel monocline, has shown that deposition of the upper member of the Hakatai Shale ended as a consequence of high-angle reverse faulting, southeast side up, on the northeast-trending Bright Angel fault. Sears (1973) also reported similar movements on other faults in the area arising from a general northwest-directed compression.

Shinumo Quartzite. Four members are recognized here in the Shinumo Quartzite, one less than reported by Daneker (1975). They are: (1) the lower member (an arkosic, conglomeratic sandstone); (2) the lower middle (purple quartzite) member, composed of cross-bedded quartzite, which Daneker (1975) subdivided into two units that he considered to be members; (3) the upper middle (rusty-red quartzite) member, a unit lithologically similar to unit 2; and (4) the upper member, a sandstone exhibiting highly disrupted bedding that is capped by an extremely well cemented gray quartzite. The lower member is of possibly fluviatile and tidal-flat origin, whereas the lower middle and upper middle members variably are of nearshore marine, tidal-flat, and supratidal-flat origin (Daneker, 1975). The upper member was considered by Daneker (1975) to have accumulated as part of a mouth-bar system in the lower deltaic plain and delta-front facies of a tidal complex.

The lower (conglomeratic sandstone) member of the Shinumo Quartzite accumulated on the downthrown side of the northeast-trending Bright Angel fault, overlapping a faulted northwest-facing monoclinal fold (Sears, 1973). The member wedges out on the upthrown side, as seen in exposures farther southeast along the Colorado River. Multiple sets of beds disrupted by fluid evulsion are present locally in the upper part of the lower member and across most of the upper member of the Shinumo.

In view of crisp reduction spots ("freckling"), the undeformed cross-bedded lower middle (purple quartzite) member of the Shinumo Quartzite probably has remained unaltered since its time of accumulation. This member passes upward into "rusty-red" quartzite of the upper middle member through a transition interval of several meters that exhibits both purple and red-brown colors. In this interval, the purple beds contain a paleomagnetic direction identical to underlying beds of purple quartzite, whereas the rusty-red beds contain an anomalous paleomagnetic direction reflecting secondary components of magnetization. The differences in color are not related to differences in lithology, and the rusty-red member lacks the freckling seen in the purple sandstone. In view of the lack of freckles and the anomalous paleomagnetic direction, the rusty-red color is inferred to have resulted from a secondary hematization that occurred some appreciable time after deposition and lithification. Some parts of the rusty-red upper middle member are extremely well cemented by silica, whereas other parts are much less well cemented, suggestive that movement of ground or connate waters was responsible for the silicification as well as secondary hematization.

The upper member of the Shinumo is a quartzite characterized by a series of fluid evulsion structures that are present across all but the uppermost part of the member. They occur in sets that are separated by several planar diastems, indicating that their formation occurred episodically. Prior to a rather extensive, but incomplete bleaching in Cenozoic(?) time, deformed sandstone of the upper member originally was a purple, freckled sandstone. The purple rock was altered to a red-brown rock, an event inferred to have taken place at the end of deposition of the upper member. Two discrete, anomalous paleomagnetic directions of opposite polarity have been obtained, one from the purple rock (reversed polarity), and the other from the red-brown rock (normal polarity). The origin of the fluid evulsion structures and the episode of secondary hematization are inferred to have been related to movements on the Bright Angel and other throughgoing faults in the region.

Dox Sandstone. The Dox Sandstone is the thickest formation of the Unkar Group (more than 900 m). Four distinctive members are recognized, and they accumulated in alternating shallow-marine, tidal-flat, and continental environments of deposition. The thicknesses of the individual members become progressively less upward (approximately 387 m, 263 m, 161 m, and 93 m, respectively). The Dox has been described by Stevenson and Beus (1982),

who also have discussed the sedimentology and depositional environments. The lower member, in part a nearshore marine deposit and possibly also of supratidal origin, is sandstone that is dominantly gray in its lower half. The upper few tens of meters of the lower half of the lower member contain pale purple interbeds, marking a transition to dark purple, marine or supratidal beds of the upper 194 meters. The color transition, from gray to purple, takes place within unit 3 of the lower member of Stevenson and Beus (1982). Although argillaceous beds are present in the lower member, sandstone and silty sandstone are common through the section. Two intervals of contorted bedding, reflecting the stratigraphically highest fluid evulsion structures in the Unkar Group, are present in unit 1 of the lower member, within 30 m of the base of the Dox (Stevenson and Beus, 1982, fig. 2).

The lower middle member of the Dox Sandstone consists of interbedded red-brown mudstone, siltstone, silty sandstone, and sandstone. The lower one-third is comparatively fine grained, consisting of interbedded mudstone and sandstone. The upper two-thirds consists dominantly of fine- to medium-grained sandstone that contains subordinate siltstone and rare interbeds of claystone. The slope-forming lower part, which accumulated in a mud flat probably close to the sea, contains channel-like, ledge-forming interbeds of sandstone. The overlying strata form cliffs, ledges, and subordinate steep slopes, and channellike festoon cross-beds suggest that fluviatile conditions dominated.

Deposition of the upper middle member of the Dox Sandstone marked a return to marginal-marine and tidal-flat conditions. Fine-grained and mostly slope-forming, the deposits consist of interbedded argillaceous sandstone and sandy argillite, subordinate claystone, and rare carbonate. Variegated colors abound. Intimately associated, they variously are purplish-red and red-brown and presumably reflect accumulation under alternately shallow-water marine and subaerial conditions. Salt casts are common to locally abundant, as are ripple marks and desiccation cracks. A few thin, widely spaced sequences of pale-green beds, which contain discontinuous stromatolitic dolomite beds, mark marine incursions.

The upper member of the Dox Sandstone seems to record sedimentation under upper tidal-flat to coastal-plain conditions. Bedding types, and the presence of salt casts, indicate deposition in alternating sand and mudflats marginal to the sea. Clear evidence for marine incursion, present in the underlying upper middle member, is lacking.

Sills and dikes. Intrusive and extrusive igneous activity in the Middle Proterozoic section of the Grand Canyon Supergroup is restricted to rocks of the Unkar Group (diagrammed in fig. 2). Although eruption of the Cardenas Basalt was the final event in the accumulation of deposits of the Unkar Group, important igneous activity preceded eruption of the Cardenas. From paleomagnetic directions and poles, intrusion of thick mafic sills found in the lower part of the Unkar Group in the area of the central Grand Canyon appears to have occurred during deposition of the lower part of the upper middle member of the Dox Sandstone. A dike and a thin sill that intrude the Dox in the eastern Grand Canyon also contain this "middle" Dox paleomagnetic direction, which is distinct from the direction obtained from the Cardenas Basalt. In contrast, a thin sill that intrudes the Bass Limestone at Hance Rapids has a paleomagnetic direction that, although similar to the Cardenas direction, may be relatable to intrusion during deposition of the upper part of the lower middle member of the Dox Sandstone. Lastly, dikes exposed at the head of Hance Rapids and in nearby Red Canyon (fig. 1), which cannot be connected with the thin sill, have a Cardenas paleomagnetic direction. This correspondence suggests that the dikes were emplaced at the time of eruption of the Cardenas Basalt and that they may have been feeder dikes for the volcanic complex.

Cardenas Basalt. This formation, 300 m and more in thickness, records an abrupt outpouring of potassium-rich mafic lavas (basalt and basaltic andesite) that brought deposition of the Dox Sandstone to an end. A single flow a few meters thick, precursor to the main eruption, is found locally within the Dox, a few meters below the top of the formation (Elston and Scott, 1973, 1976). The single flow is coherent, lacks any vestige of pillowing, and is vesiculated at the top, indicating extrusion in a subaerial environment. The surface on which this flow was extruded and the surface underlying the basal flow of the main pile of lavas were firm. Hematitic alteration resulting from baking at the contact was minimal, commonly amounting to only few centimeters or less. Basalt above the basal flow commonly forms steep slopes rather than cliffs and ledges and is characterized by a bottle-green color (Walcott, 1894). The slope-forming interval, about 100 m thick, consists of multiple flows, many of which are laterally traceable for only short distances. Several of the flows are separated by thin discontinuous beds of sandstone. The flows regain the appearance of a more normal mafic extrusive sequence above the bottle-green interval. Descriptions of the various parts of the Cardenas Basalt were presented by Hendricks and Lucchitta (1974) and Lucchitta and Hendricks (1974, 1983).

The depositional environment of the Cardenas has been the subject of some discussion. Pillow lavas, implying submarine eruption and emplacement, were reported in the Cardenas more than a decade ago (Hendricks and Lucchitta, 1974). A shallow-marine origin was inferred for the puzzling bottle-green unit because of spilitic alteration and the presence of secondary chlorite, epidote, talc, and other minerals (Lucchitta and Hendricks, 1974, 1983). Water must have played an important role in development of the bottle-green, slope-forming unit during its eruption, although field relations do not support a submarine environment of accumulation. The Cardenas paleomagnetic direction in dikes in Red Canyon (fig. 1) suggests that an eruptive center for the Cardenas may have been located a short distance west of the area of exposure and preservation of the Cardenas Basalt.

Nankoweap Formation

The Nankoweap Formation consists of two informal members that total about 100 m in thickness. The strata accumulated over a considerable span of time, but only a fragmentary record remains because of two discrete episodes of erosion. Key relations are diagrammed in figure 2.

Faulting on and near the Butte fault followed eruption of the Cardenas Basalt. South of the Colorado River, the basalt was tilted and an erosional escarpment was developed across the 330-m-thick section of flows, on which a 10-m-thick ferruginous weathered zone was developed. Iron-rich beds of the lower (ferruginous) member of the Nankoweap then accumulated unconformably on the Cardenas here and in the eastern part of the graben at Tanner rapids. Only remnants of the lower member remain, but from a reconstruction (Elston and Scott, 1976) this member once may have been much thicker. In response to an episode of uplift that was accompanied by faulting, the lower member and ferruginous weathered zone were nearly everywhere stripped from the Cardenas as a consequence of a long interval of erosion that resulted in planation. This surface of low relief is best seen west of the Butte fault where it underlies the upper member of the Nankoweap and truncates the Cardenas at a low angle. Faulting in the area south of the Colorado River served to juxtapose unaltered flows near the top of the Cardenas against the ferruginous weathered zone prior to planation, following which the lower member and ferruginous weathered zone were eroded from the upthrown block.

Following development of a surface of low relief, marked locally by lag deposits of gravelly chert, red-bed deposits of the upper member of the Nankoweap Formation accumulated to a thickness of about 100 m. Deposition appears to have occurred in sand and mud flats near the sea. The upper unit of the upper member of the Nankoweap is a cross-bedded sandstone of probably beach origin, the upper part of which is bleached. This unit is sharply and unconformably overlain by coarse dolomite of the lower part of the Tanner Member of the Galeros Formation (Chuar Group). The sandstone and dolomite form a continuous cliff in the graben at Tanner Canyon rapids, and the contact between the Nankoweap and Chuar is in the cliff face. There is no evidence to suggest a large hiatus at this contact. Temporal extents of the three hiatuses bounding and separating members of the Nankoweap Formation (see fig. 2) have been estimated on the basis of paleomagnetic correlations.

Chuar Group

Accumulation of the Late Proterozoic Chuar Group marked a major change from the preceding red-bed environments of deposition. Strata of the Chuar Group were described by Ford and Breed (1972a, 1972b, and 1973). The strata are generally finely laminated. Environments are consistent with an interpretation of sedimentation in a shallow lacustrine environment (Reynolds and Elston, 1986). Dark shale predominates, recording accumulation under generally reducing conditions apparently produced and maintained by an abundant planktonic microbiota. Widely spaced beds of dolomite and a few beds marked by distinctive structures and textures are found in the shales. Chuar strata also contain stromatolites of tidal-flat origin. Intervals of red beds are also present in the Chuar; they contain structures of subaerial and intermittently flooded shallow-water environments of deposition. Other diverse studies are continuing (Vidal, 1986; Horodyski, 1986; Feng and others, 1986; Elston, 1986).

The Chuar is subdivided into two formations, the Galeros below and the Kwagunt above (fig. 2). Because black shales of the Chuar all appear much alike, subdivision of the Chuar has been based on the presence of distinctive beds of other lithologies. The lower part of the Tanner Member of the Galeros Formation is a coarsely crystalline dolomite. The Jupiter Member is almost entirely dark shale. The Carbon Canyon Member contains several beds of carbonate, some stromatolite bearing, and some red-bed intervals. The Duppa Member, the upper member of the Galeros Formation, is almost entirely dark greenish-gray and grayish-red shale.

The base of the Kwagunt Formation is marked by cliff-forming red sandstone at the base of the Carbon Butte Member. A ledge-forming biohermal (stromatolite) reef marks the base of the overlying Awatubi Member, which is dominantly shale. The overlying Walcott Member, also dominantly black shale, contains several distinctive beds. A bed of flaky dolomite is found at the base, and about 17 m above this is a thin bed of black pisolitic chert. Vase-shaped microfossils, suggestive of heterotrophic protists (G. Vidal, 1986, written communication), have been obtained from shale underlying this pisolite bed and from the pisolite bed itself, from which diverse microfossils also have been reported (Bloeser and others, 1977). The highest marker beds in the Walcott Member are a pair of dolomite beds, in part disrupted. They are about 70 m below the top of the highest shale of the Walcott Member. This pair of dolomite beds thins and pinches out from the axis of the Chuar syncline in Sixtymile Canyon toward the Butte fault to the east, suggesting that minor movement on the fault occurred during deposition of the uppermost strata of the Chuar Group (Elston, 1979).

Paleontology. The relatively rich fossil record preserved in strata of the Chuar Group includes a variety of microfossils and stromatolites. Walcott (1899) was the first to study the Precambrian biota of the Grand Canyon. The fossil record in the Chuar Group can be divided into two categories: (1) the actual organisms preserved as microfossils in cherts and rarely in carbonates; and (2) organosedimentary structures produced by communities of microorganisms (in

particular, stromatolites). A brief review of the fossil record, ages, and inferred correlations, was given by Elston and McKee (1982, p. 693). Bloeser and others (1977, fig. 1) have summarized the stratigraphic distribution of microfossils and stromatolites across the Chuar Group. Included among the microfossils are vase-shaped microfossils, acritarchs (among them, *Chuaria circularis, Melanospherillia*), algal filaments, and unicells. The greatest abundance and diversity occurs in the Walcott Member of the Kwagunt Formation, the uppermost unit of the Chuar. Included among the stromatolites are *Boxonia, Baicalia, Inzeria,* and *Stratifera.* The first-mentioned form comes from the Kwagunt and the last three from the underlying Galeros Formation. The distribution of stromatolites and *Chuaria* from the Chuar Group has been discussed by Ford and Breed (1972a, 1972b, and 1973). Horodyski and Bloeser (1983) reported possible eukaryotic algal filaments from the Awatubi Member, the middle member of the Kwagunt.

The planktonic biota of the Chuar Group hold promise for the correlation of "late Riphean" and Vendian sections of Canada and the United States, Greenland, and Fennoscandia. Acritarch correlations, summarized later, indicate that the Chuar Group should be assigned to the Late Proterozoic.

Sixtymile Formation

The Sixtymile Formation is a 61-m-thick red-bed unit. Its accumulation records marine emergence resulting from uplift and faulting that brought deposition of Chuar Group rocks to an end (Grand Canyon disturbance). On Nankoweap Butte, one to two thin beds of tuff mark the contact between black shale of the Walcott Member of the Kwagunt Formation, below, and red beds of the Sixtymile Formation, above. The Sixtymile is subdivided into three members of approximately equal thickness, separated by unconformities. The lower member consists of breccia and landslide deposits that accumulated in a depression closely adjacent to and paralleling the Butte fault. At the type section in Sixtymile Canyon, landslide blocks and detritus were shed from an actively developing scarp into a developing Chuar syncline as a consequence of at least two increments of movement on the Butte fault (Elston, 1979). Much of the structural offset across the Butte fault, which eventually exceeded 3 km, occurred during accumulation of the lower member (offset is diagrammed in fig. 2). At Sixtymile Canyon, the middle member is a quartzite that appears to have accumulated in standing water (a lake?), following which the beds were folded and crenulated as a consequence of renewed deepening of the syncline. Breccia once again was shed into the syncline, accumulating above the unconformity that separates the middle and upper members. The upper member, above its basal breccia, is characterized by fluviatile sandstone. Only vestiges of this member are preserved at two places in the axial parts of the Chuar syncline (on Nankoweap Butte and in Sixtymile Canyon). Sandstone of the upper member probably formed the basal part of a thick section of basin fill that accumulated adjacent to a fault-block mountain produced during the Grand Canyon disturbance.

AGE AND CORRELATION

Radiometric Geochronology

Results of isotopic dating of igneous rocks of the Unkar Group were given by Elston and McKee (1982). These include virtually identical 1070-Ma Rb-Sr whole-rock isochrons of a sill that intrudes strata of the lower Unkar Group and flows of the Cardenas Basalt. Analytical errors of ±30 and ±70 Ma, respectively, were reported for these rocks. Whole-rock K-Ar dates from the flows of the Cardenas, from several sills, and from the crystalline basement, and a seven-step $^{40}Ar/^{39}Ar$ incremental heating diagram for a sill, have given ages that are markedly younger than the Rb-Sr isochron ages, indicating a loss of Ar that is inferred to have taken place with burial. Ar retention in the flows, intrusions, and basement is postulated to have begun as a consequence of cooling that attended faulting, uplift, and erosion accompanying the Grand Canyon disturbance. K-Ar ages from five Cardenas flows have provided an apparent age range for the time of cooling (855 to 790 Ma), from which a mean age of about 823 Ma has been calculated.

Paleontologic Correlations

The evidence for Proterozoic planktonic life has been reviewed by Vidal and Knoll (1983), who argued that Proterozoic plankters, as Phanerozoic microplankton, have environmental and stratigraphic distributions that are both delimitable and useful. Of equal importance, planktonic microfossils in Proterozoic rocks document evolutionary events, the record for which is damped or not observable in the restricted carbonate facies where silicification of stromatolitic microbiotas was most common. Acid-resistant, organic-walled microfossils occur in the Proterozoic siltstones and shales. Most of the fossils obtained from the Proterozoic rocks are morphologically and ecologically comparable to Paleozoic microfossils included in the group Acritarcha (Evitt, 1963), a nomenclaturally informal category established to serve as an "umbrella" for organic-walled microfossils of problematical biological affinities. Gross morphological features, and their problematical nature, allow the spheroidal remains from Proterozoic clastic (and in some cases, carbonate) facies to be placed among the acritarchs, but no clear phylogenetic lines of connection have been established between Proterozoic and Paleozoic acritarch taxa.

Vidal and Knoll (1983) also have reviewed the nature and distribution of Proterozoic acritarchs, including *Chuaria* and vase-shaped chitinizoanlike microfossils. The latter may be the earliest forms of primitive heterotrophic protists obtained from the geologic record. Vidal and Knoll (1983) noted that distinctive acritarch assemblages are found at several places in the northern hemisphere, and that the assemblages appear relatable to the assemblage obtained from parts of the Chuar Group. Microbiota from the Chuar and the Uinta Mountain Groups (Vidal and Ford, 1985) also have been reported to be demonstrably identical to form taxa previously reported from Late Proterozoic (upper "Riphean" and lower Vendian) rock sequences in the North Atlantic region (Sweden, Norway, Greenland, Svalbard), and the Russian Platform and southern Urals of the Soviet Union. The correlations indicate that deposition predated the Varangerian glacial event in the North Atlantic and that glacigenic units in North America thus may be of Vendian age. From paleontologic correlations in western North America, Chuar strata predate glacigenic deposits of the Windermere Supergroup in Canada, and the Chuar appears assignable to the "late Riphean" and Late Proterozoic.

Paleomagnetic Correlations

Paleomagnetic (magnetostratigraphic) studies in the Grand Canyon Supergroup and potentially correlative strata of the western United States have been in progress for more than 15 years. Work on developing a stratigraphically controlled apparent polar wandering path for the Middle and Late Proterozoic is nearing completion (Elston and Grommé, in review; Elston and Bressler, in review). Some information concerning the different studies in the western United States currently can be found in the reports of Elston and Grommé (1974, 1984), Elston and Bressler (1980), Bressler (1981), Elston and McKee (1982), Elston (1984), and Elston and Bressler (1984).

Many of the strata of the Grand Canyon Supergroup have proven amenable to paleomagnetic analysis. A series of stratigraphically controlled paleomagnetic field directions and intervals of differing polarity have been obtained across the ~4-km-thick section. Oriented samples were collected at approximately 1/3-1-m stratigraphic intervals in the Unkar Group, Nankoweap and Sixtymile Formations, and the red-bed parts of the Chuar Group. The paleomagnetic field directions have been used to calculate a series of paleomagnetic poles, with poles from reversely polarized rocks inverted to plot as if they were of normal polarity. Connected in stratigraphic order, these provide a high-resolution apparent polar wandering path for the Grand Canyon Supergroup (fig. 3; Elston and Grommé, 1984). It is a path that serves to anchor the North American polar path for a large part of Middle and Late Proterozoic time.

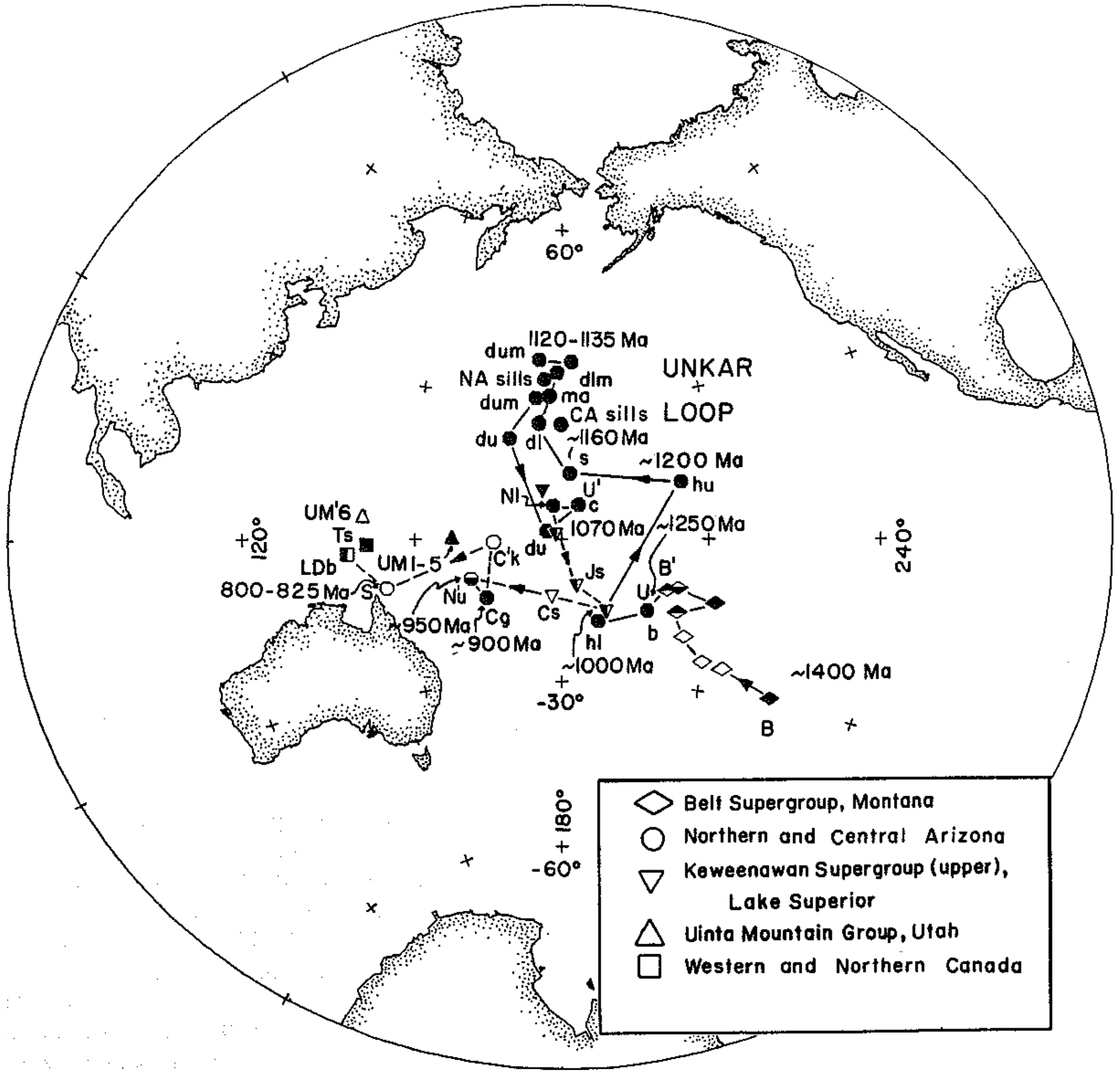
The wandering of the pole in such a path is apparent because it is not the spin pole that has moved (the spin and magnetic field directions coincide when viewed in the context of geologic time and the averaging-out of secular variation). The apparent polar motion thus must reflect rotations and changes in paleolatitude of the continental plate through time with respect to a fixed pole of rotation. Lastly, characteristics of the polar path and the distribution of polarities for the Grand Canyon Supergroup provide a framework for developing high-resolution correlations with Proterozoic rocks elsewhere on the craton.

Poles from the Grand Canyon Supergroup plot in the area of the present Pacific Ocean (fig. 3). Correlations have emerged where poles and polar paths obtained from different successions correspond or overlap, leading to a composite, magnetostratigraphically controlled polar path for the Middle and Late Proterozoic (fig. 3). The composite path is temporally controlled where U-Pb and Rb-Sr isochron ages from igneous rocks provide mutually supporting, nonconflicting ages.

A rather short apparent polar wandering path has been developed from the Middle Proterozoic Belt Supergroup of western Montana and Idaho (Elston and Bressler, 1980, and in review; Elston, 1984). The pole positions and polarity zonation are distinct from those of the Grand Canyon Supergroup (fig. 3). Deposition of the Grand Canyon Supergroup entirely (or almost entirely) postdated accumulation of the Belt Supergroup. The only permissible paleomagnetic correlation and temporal overlap is between the uppermost, normal-polarity part of the Pilcher Quartzite at the very top of the Belt Supergroup and the upper part of the Bass Limestone near the base of the Unkar Group (the lower part of the Bass has been thermally overprinted from the intrusion of sills). The north-south-trending polar path obtained from strata of the Unkar Group beginning with the Shinumo Quartzite correlates with a normal-polarity track from the Keweenawan Supergroup of Lake Superior. A normal-polarity pole from near-basal lower Keweenawan rocks appears to correlate at the level of the Shinumo Quartzite. Poles from middle Keweenawan rocks correlate with poles from the middle members of the Dox Sandstone, which plot at the apex of the "Unkar loop." In the Lake Superior region, correlative rocks are well dated by U-Pb age determinations on zircon. Poles from upper Keweenawan rocks correlate with the descending leg of the Unkar loop, derived from poles from the Nonesuch and Freda Formations and part of a track obtained from the Jacobsville Sandstone, all of northern Michigan.

Paleomagnetic evidence exists for the correlation of strata and intrusions of central Arizona (Shride, 1967; Wrucke, this volume) with rocks of the Grand Canyon Supergroup and other Proterozoic rocks of North America. A pole from reversely polarized rocks of the Pioneer Shale, the basal formation of the Apache Group, appears to correlate with reversely polarized poles from the Missoula Group of the Belt Supergroup of Montana. Additionally, poles from reversely and normally polarized rocks of the Missoula Group of the Belt Supergroup correlate with reverse- and normal-polarity poles from strata of the Sibley Series of the north shore of Lake Superior, a unit that underlies rocks of the Keweenawan Supergroup.

The foregoing correlations indicate a substantial hiatus at the unconformity that separates the Pioneer Shale from



B-B'—Belt Supergroup, Montana and Idaho
Grand Canyon Supergroup, northern Arizona:
U-U'—Unkar Group: b—upper member of Bass Limestone; h—Hakatai Shale, lower (hl) and upper (hu) members; s - Shinumo Quartzite; d—Dox Sandstone, lower member (dl), lower and middle member (dlm), upper middle member (dum; interval of asymmetric reversals not shown), NA sills (intruded during deposition of dum), and upper member (du); c—Cardenas Basalt, flows and sandstone interbeds
N-N'—Nankoweap Formation: Nl—lower (ferruginous) member, Nu—upper member;
Cg-C'k—Chuar Group: g—Galeros Formation, k—Kwagunt Formation
S—Sixtymile Formation
CA sills—central Arizona sills, in part from Helsley and Spall (1972);
ma—argillite member of Mescal Limestone, Apache Group, central Arizona.
Js—Jacobsville Sandstone of Keweenaw Peninsula, northern Michigan (Roy Robertson, 1978) (overlaps polar path for Nonesuch and Freda Formations)
Cs—Chequamegon Sandstone of northern Michigan (McCabe and Van der Voo, 1983)
UM-UM'—poles 1-6, Uinta Mountain Group, Utah and Colorado (Bressler, 1981)
LDb—Little Dal Group, Mackenzie Mountains, northwest Canada (Park, 1980, 1981)
Ts—~770-Ma sills in Tsezotene Formation beneath Little Dal Group (Park, 1981; Armstrong and others, 1982).

Figure 3. Magnetostratigraphically controlled apparent polar wandering path from Middle and Late Proterozoic successions of western and central North America (generalized from Elston and Bressler, 1980 and in review; Elston and Grommé, 1974, 1979, 1984, and in review; and Elston, 1984). Solid symbols—normal polarity; open symbols—reversed polarity; half-solid—half-open symbols—mixed polarity. Ages along apparent polar wandering path are from U-Pb and nonconflicting Rb-Sr isochron ages determined from igneous rocks of Lake Superior, central and northern Arizona, Montana, and northwest Canada.

the overlying Dripping Spring Quartzite of the Apache Group. The Dripping Spring and overlying Mescal Limestone appear to correlate with strata of early and middle Keweenawan age of the Lake Superior region and the Grand Canyon of northern Arizona. A pole from the argillite member of the Mescal Limestone (Apache Group of central Arizona) correlates with poles from the lower middle and upper middle members of the Dox Sandstone (Grand Canyon), which plot near and at the apex of the Unkar loop. Paleomagnetic poles from thick sills in the Unkar Group correlate with poles from intrusions of middle Keweenawan age of the Lake Superior region and with poles from sills that intrude the Apache Group and Troy Quartzite of central Arizona. These poles, all approximately 1120 Ma old from the U-Pb analysis of zircon, plot near the apex of the Unkar and Keweenawan loops. The diabase sills of Arizona and the Lake Superior region thus appear to have been emplaced contemporaneously.

The dashed line on figure 3, which extends to the south beyond poles for the Cardenas Basalt and the ferruginous member of the Nankoweap, marks the trace of late Keweenawan poles from the Jacobsville Sandstone of northern Michigan. The Jacobsville-Freda path is not represented in strata from northern Arizona, nor elsewhere in the western United States. The dashed line that connects the uppermost Jacobsville pole to the pole for the upper member of the Nankoweap Formation of the Grand Canyon passes through a pole for the Chequamegon Sandstone, which appears to be the youngest Keweenawan unit in the Lake Superior region. The upper member of the Nankoweap Formation thus appears to be slightly younger than the Chequamegon Sandstone and to record accumulation of the youngest red beds generally correlative with Keweenawan rocks of the Lake Superior region. About 100 Ma (from about 1050 Ma to 950 Ma) has been estimated to allow time for generation of each of these two legs of the composite polar path defined from upper Keweenawan rocks of the Lake Superior region, which are not represented in the Grand Canyon Supergroup.

Little in the way of apparent polar motion occurred during accumulation of the upper member of the Nankoweap Formation and much of the Chuar Group, but a strong westerly shift occurred sometime before deposition of the Sixtymile Formation. The westerly position of the Sixtymile pole indicates a correlation of the uppermost part of the Chuar (Kwagunt) with strata of the *Chuaria*-bearing Little Dal Group of the Mackenzie Mountains Supergroup (Northwest Territories, Canada). A sill in the Tsezotene Formation of the Mackenzie Mountains, dated at 770 Ma, has a pole that is identical with the Sixtymile pole. Intrusion of this sill is considered, on geologic grounds, to have taken place either shortly before or else very early during accumulation of the glacigenic Rapitan Formation, Windermere Supergroup, Canada. Increments of faulting followed deposition of the Little Dal Group, recorded by the accumulation of "copper cycle" strata that separate the Little Dal from the Rapitan (Eisbacher, 1981). Thus, the "copper cycle" strata of the Mackenzie Mountains Supergroup appear to correlate with the Sixtymile Formation of the Grand Canyon, and the interval 770 to 825 Ma is interpreted to embrace the time of the Grand Canyon-Mackenzie Mountains disturbance in the western Cordillera (Elston and McKee, 1982).

A general correlation between the Chuar Group and the Uinta Mountain Group of Utah and Colorado is seen from a comparison of their paleomagnetic poles (fig. 3). The correlation between the Uinta Mountain and Chuar Groups includes a westward shift in pole position near the top of both sections. This accords with a correlation from microbiotas of the Red Pine Shale of the Uinta Mountain Group and the Kwagunt Formation of the Chuar Group, both of which are near the top of their respective successions.

BOUNDARY BETWEEN MIDDLE AND LATE PROTEROZOIC ERAS

The boundary between strata of Middle and Late Proterozoic age in the Grand Canyon Supergroup is here drawn at the unconformity that separates the upper member of the Nankoweap Formation from the Chuar Group. This boundary serves to separate red-bed strata from strata that record a time of flourishing of plankters and suppression of red beds. No structural disturbance is recognized at this horizon. Previously, the boundary was drawn to correspond with a structural disturbance (the Grand Canyon-Mackenzie Mountains disturbance) at the top of the Chuar Group, to which a nominal 800-Ma age was assigned (Elston, 1979). The structural disturbance preceded onset of glacial conditions recorded in the Late Proterozoic Windermere Supergroup of Canada. The boundary between the Middle and Late Proterozoic Eras has recently been assigned a general age of 900 Ma. (Harrison and Peterman, 1982). It is a geochronometric boundary drawn at a place in the time scale so as to escape the effects of orogenic activity. The boundary between the Nankoweap Formation and Chuar Group meets this general requirement and also seems to reasonably correspond with the nominal 900-Ma age of the geochronometric boundary. The assignment of the Chuar Group to the Late Proterozoic also accords with paleobiologic correlations of the microbiota, in which the Chuar biota are considered to be Late Proterozoic and "late Riphean" in age (Vidal and Ford, 1985; Vidal, 1986).

SUMMARY

Deposition of the Unkar Group of the Grand Canyon Supergroup began about 1250 Ma, near the end of deposition of the highest formation of the Belt Supergroup

of western Montana. Beginning at the level of the base of the Shinumo Quartzite, deposition of the Unkar Group appears to correlate paleomagnetically with the beginning of deposition of the Keweenawan Supergroup, occurring about 1200 Ma. Onset of Keweenawan deposition and volcanism was a time marked by recurrent faulting in northern Arizona. The Dripping Spring Quartzite of the Apache Group in central Arizona, inferred to correlate with the Shinumo Quartzite of the Grand Canyon, presumably also began accumulating at this time. Early and middle Keweenawan time, a time of development and then abrupt deepening of the Lake Superior basin, and the first third of late Keweenawan time (to about 1070 Ma) are recorded in strata of the Unkar Group. In central Arizona the Middle Proterozoic record ends with intrusion of mafic sills of middle Keweenawan age at about 1120 Ma. In northern Arizona a 100-Ma span of time (~1050—~950 Ma) that encompassed terminal events of the Grenville orogeny is represented by an unconformity separating the lower and upper members of the Nankoweap Formation. The depositional record in northern Arizona resumed at ~950 Ma with accumulation of the upper member of the Nankoweap. Deposition of strata of the Chuar Group is inferred to have begun at ~900 Ma and to have ended at ~825 Ma (or later) with uplift and block faulting associated with the Grand Canyon-Mackenzie Mountains disturbance of the western Cordillera. This also appears to have been a time of disturbance and cooling in eastern North America.

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