Late Precambrian Sixtymile Formation and Orogeny at Top of the Grand Canyon Supergroup, Northern Arizona

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LATE PRECAMBRIAN SIXTYMILE FORMATION AND OROGENY AT TOP OF THE GRAND CANYON SUPERGROUP, NORTHERN ARIZONA

By Donald P. Elston

ABSTRACT

The Sixtymile Formation, a 60-m-thick red-bed unit at the top of the late Precambrian Chuar Group, crops out at three places in the Chuar syncline in the eastern Grand Canyon. Its base is marked by a transition from gray marine shale to red sandstone. The Sixtymile was deposited in the deepening trough of the north-trending Chuar syncline during and as a consequence of regional uplift, tilting, and large-scale block faulting. Folding to form the Chuar syncline occurred in response to faulting on the parallel-trending Butte fault, about 1 km to the east. About 3.2 km of structural relief was developed across the Butte fault, principally during deposition of the lower member of the Sixtymile Formation. Landslide debris shed from the upthrown block on the east constitutes a major part of the material in the lower member. Conglomeratic strata of the upper member of the Sixtymile were deposited after the last increment of subsidence on the Chuar syncline, indicating that deposition of the Sixtymile Formation spanned the time of the structural disturbance. The folding and faulting are part of a regional structural episode that here is called the Grand Canyon orogeny, an event that signaled the end of deposition of strata of the Grand Canyon Supergroup and the beginning of a long interval of erosion.

The age of the Grand Canyon orogeny is estimated at about 830 m.y., inferred from an evaluation of maximum and minimum reset K-Ar ages reported for the 1,100-m.y.-old Cardenas Lavas of the Unkar Group. In age and structural style, the Grand Canyon orogeny appears generally correlative with the East Kootenay orogeny of British Columbia, which separates the Purcell (Belt) and Windermere Supergroups. By analogy, strata of the Chuar Group below the Sixtymile Formation are correlated with strata of the upper part of the Belt Supergroup, and conglomeratic strata of the Sixtymile deposited after the structural episode are correlated with conglomeratic strata of the Windermere that unconformably overlie the Belt.

INTRODUCTION

The upper two formations of the Chuar Group of the Grand Canyon Supergroup contain evidence of structural events that resulted in the end of deposition of the late Precambrian strata of the Grand Canyon. Details of folding, faulting, and landsliding reported here are part of a regional episode of block faulting and tilting of strata, an episode called the Grand Canyon revolution by Maxson (1961) and here called the Grand Canyon orogeny. The faulting gave rise to fault-block mountains with relief measured in kilometers. This report is concerned with the geologic history deduced from exposures preserved in Sixtymile Canyon near the Colorado River (fig. 1).

Fieldwork leading to this report was carried out October 14–17, 1973. The north fork of Sixtymile Canyon was reached by helicopter; a suitable landing site was found on the west side of the Chuar syncline, on a point and small flat that is developed on the upper bed of a pair of ledge-forming carbonate beds in the Walcott Member of the Kwagunt Formation. This site allows ready access to the type section of the Sixtymile Formation exposed in the trough of the syncline. Reference hand samples and drill-core samples collected on close stratigraphic spacings are available for inspection. They currently are stored in the U.S. Geological Survey's Paleomagnetics Laboratory in Flagstaff, Ariz.

GEOLOGIC SETTING

The Chuar Group (Chuar Group of Walcott, 1883; Ford and Breed, 1972a, 1973) is the upper of three divisions of the Grand Canyon Supergroup (Elston and Scott, 1976; table 1). The Chuar Group is subdivided by Ford and Breed (1972a, 1973) into three formations, the Galeros and Kwagunt Formations, which total 1.9 km in thickness, and the overlying Sixty Mile Formation,[1] which is 60 m thick. The Galeros and Kwagunt Formations are dark-gray marine shale with subordinate locally stromatolite-bearing carbonate rocks and a few red beds. This study is concerned with gray shale and dolomite in the Walcott Member of the Kwagunt Formation and with overlying red sandstone and landslide breccia of the Sixtymile For-

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[1] Ford and Breed's (1972a, p. 5, 8) name Sixty Mile Formation is here revised to Sixtymile Formation to agree with the spelling of the canyon as it appears on the topographic map of the Vishnu Temple quadrangle.
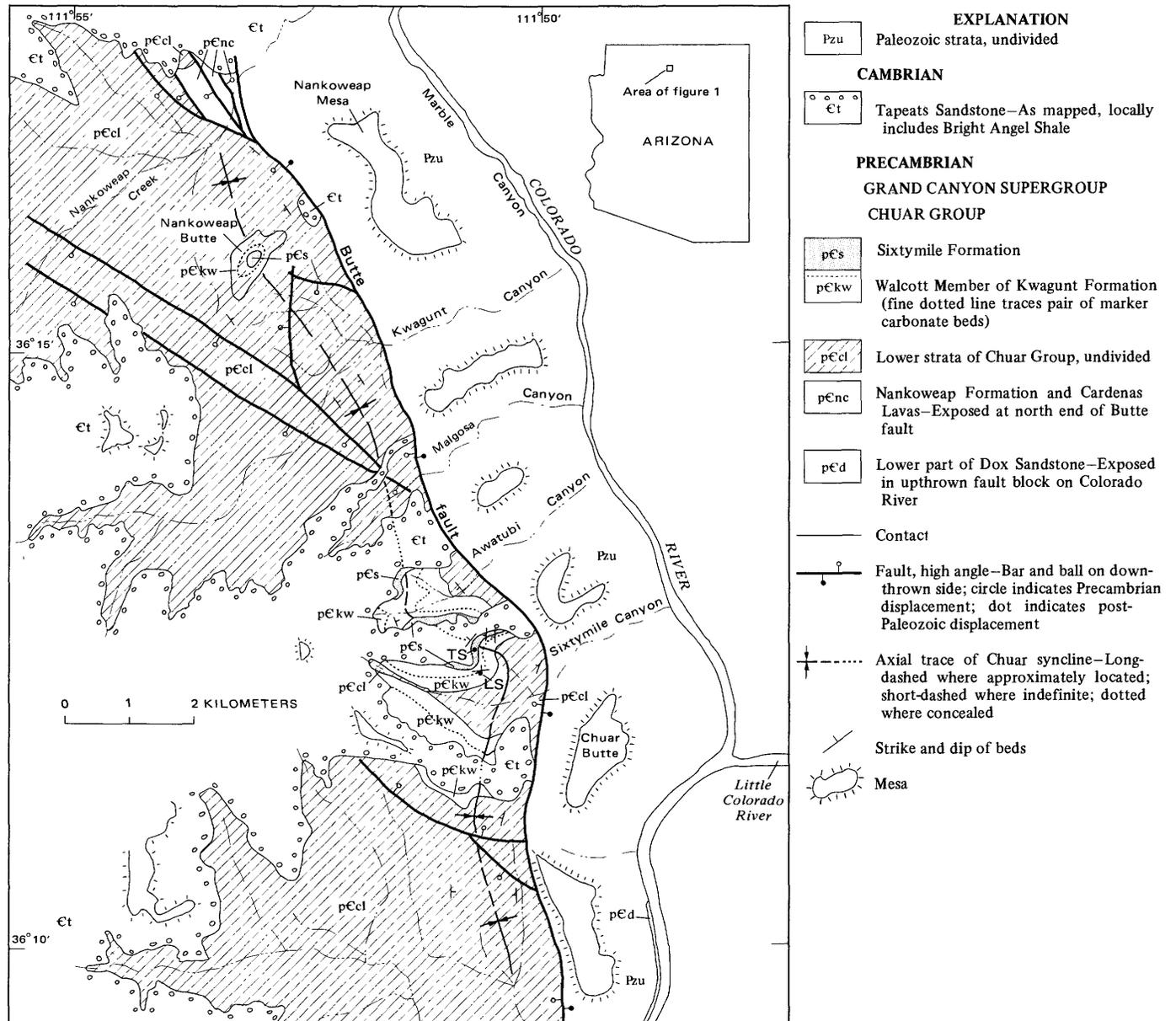
FIGURE 1.—Geologic map of Precambrian Sixtymile Formation in Chuar syncline, eastern Grand Canyon, Ariz. Modified from Ford and Breed (1973, fig. 1). LS, landing site; TS, type section.

mation (table 1). The Sixtymile was examined at its type locality at the head of the north fork of Sixtymile Canyon (fig. 1), where the most complete section exists and where evidence is preserved of its history of deposition and origin.

PREVIOUS WORK

Materials of the Sixtymile Formation were first recognized and described by Walcott (1894, p. 508, unit 1; table 2) from exposures at the top of Nankoweap Butte (fig. 1). He assigned the reddish-brown sandstone, which he noted passes into sandy and argillaceous shale at the base, to the upper part of the upper

division of his Chuar terrane, which he had earlier called the Chuar Group, attributing the name to J. W. Powell (Walcott, 1883, p. 440). The thickness Walcott reported is 61 m, almost identical to the thickness reported here for its type section in Sixtymile Canyon. Walcott indicated that reddish-brown sandstone containing fragments (breccias and conglomerates of the Sixtymile Canyon section) is 38 m thick and that this unit overlies 23 m of reddish sandy shale. Walcott's twofold subdivision parallels relations described for the lower part of the Sixtymile Formation at Sixtymile Canyon.

The Sixtymile Formation was named and described

TABLE 1.—*Late Precambrian and Cambrian strata exposed in eastern and central Grand Canyon, Arizona*[1]

	Thickness (meters)	
	Units	Cumulative
Cambrian:		
Tonto Group	180–395	
Muav Limestone	180	395
Bright Angel Shale	0–105	215
Tapeats Sandstone	0–110	110
Unconformity		
Precambrian:		
Grand Canyon Supergroup	3,689–4,503	
Chuar Group	1,956	
Sixtymile Formation	60(+)	60
Kwagunt Formation	594	
Walcott Member	[2]174	234
Awatubi Member	344	578
Carbon Butte Member	76	654
Galeros Formation	1,302	
Duppa Member	174	828
Carbon Canyon Member	471	1,299
Jupiter Member	462	1,761
Tanner Member	195	1,956
Unconformity		
Nankoweap Formation	113–150(?)	
Upper member	100(+)	2,056
Unconformity		
Ferruginous member	13(+)	2,069
Unconformity		
Unkar Group	1,620–2,197	
Cardenas Lavas	[3]244–450 (300)	2,369
Dox Sandstone	884–915 (900)	3,269
Shinumo Quartzite	324–475 (400)	3,669
Unconformity		
Hakatai Shale	131–253 (200)	3,869
Bass Limestone	37–104 (75)	3,944

[1]Tonto Group from McKee and Resser (1945); Chuar Group from Ford and Breed (1972a, 1973); Nankoweap Formation and Unkar Group from Elston and Scott (1976); with modifications from unpublished data.
[2]Thickness reported by Walcott (1894, p. 508, units 2–9) from south side of Nankoweap Butte.
[3]Nominal thicknesses for strata of the Unkar Group are shown in parentheses and are used in the listing of cumulative thickness.

by Ford and Breed (1972a, p. 8; 1973, p. 1252–1255) and Breed and Ford (1973, p. 12–18). They reported a thickness of 36 m for the Sixtymile, which they measured on Nankoweap Butte. Because Ford and Breed reported breccia at the base of the Sixtymile and because the thickness they reported is close to the thickness of the upper fragmental unit of Walcott, it appears that more than 20 m of red sandy shale underlying the breccia has been excluded from the redbed unit in Ford and Breed's study. Although Ford and Breed (1973) designated exposures in the north fork of Sixtymile Canyon as the type locality, most of their description of the Sixtymile Formation has come from the sections at Nankoweap Butte and Awatubi Canyon (fig. 1).

Ford and Breed (1973) reported an unconformity at the base of the Sixtymile Formation marked by breccia and by deep bleaching and silicification of the underlying Kwagunt Formation. They also recognized that beds of the Sixtymile are slumped toward the axis of the Chuar syncline and that angular breccia fragments were derived from the Kwagunt Formation. Breed (1975) since proposed that the Sixtymile Formation is a slide breccia. Breed and Ford (1973, p. 14)

reported three units in the Sixtymile, which in ascending stratigraphic order are "(a) massive yellow to purple breccia with clasts of silicified shale. 15–30 ft. (4.5–9 m); (b) massive red-brown sandstone with frequent slump structures and irregular masses of breccia. 100–130 ft. (30–33 m [sic]); (c) massive unbedded breccia with clasts of silicified shale up to 2 ft. [0.6 m] diameter. 21 ft. (6 m)." The total thickness of these units is appreciably greater than the nominal 36-m thickness they reported for the Sixtymile and approaches the 60-m thickness given in this report. There are, moreover, differences between the stratigraphy reported by Breed and Ford (1973) and the stratigraphy that can be seen in Sixtymile Canyon.

Because Ford and Breed considered the contact between the Kwagunt and Sixtymile Formations to be an unconformity, they assumed that an unknown thickness of beds of the Kwagunt has been eroded (Ford and Breed, 1973, fig. 2) and that warping of the Chuar syncline and deposition of the Sixtymile occurred in some undefined interval of late Precambrian time between deposition of the Kwagunt Formation and the Cambrian Tapeats Sandstone. This concept

TABLE 2.—*Walcott's (1894, p. 508) stratigraphic section of upper division of his Chuar terrane measured on Nunkoweap butte (= Nankoweap Butte) with stratigraphic nomenclature of Ford and Breed (1973) shown on right*

	Thickness		
	Meters	(feet)	Unit
Chuar terrane			Chuar Group.
Upper division			
1. a. Massive reddish-brown sandstone, with irregular layers of similar color and containing numerous fragments of sandstone-shale of lighter color	38	(125)	Sixtymile Formation.
b. The sandstones of 1 become shaly near their base and pass into a reddish, sandy, and then argillaceous shale, with a few thin compact layers of sandstone in the shale	23	(75)	Not reported.
2. Black fissile argillaceous shale that crumbles on exposure to the weather	69	(225)	Kwagunt Formation. Walcott Member.
3. Compact gray limestone in massive layers; buff on weathered surface	16	(50)	(Doublet carbonate marker beds of this report.)
4. Shale similar to 2	19	(60)	
5. Gray limestone similar to 3	16	(50)	
6. Black argillaceous shale similar to 2 and 4	43	(140)	
7. Hard buff limestone with irregular oolitic, cherty bands that at times constitute most of the stratum	1	(4)	Pisolitic chert.
8. a. Black argillaceous shale with compact layers two or three inches thick	9.1 (30)		
b. Dark earthy limestone	.3 (1)	10	(33)
c. Black shale	.6 (2)		
9. Gray Stromatopora[1](?) limestone	2	(8)	Flaky dolomite. Awatubi Member.
10. Black argillaceous shale with variegated shales below, containing more or less arenaceous matter in the form of arenaceo-argillaceous shale and thin layers of sandstone. On the slopes light-drab, pea-green, vermilion, chocolate, maroon, and buff-colored shales of various shades alternate	245	(740)	
11. Massive stratum of concretionary limestone	3–8	(10–25)	

[1]Probably a species of Cryptozoon. (Walcott's note.)

has affected the timing of geologic events they have deduced from the stratigraphy (Breed and Ford, 1973, p. 17).

The following sections document that the Sixtymile is the uppermost formation of the Chuar Group and that no significant hiatus occurred between deposition of the Kwagunt and Sixtymile Formations. The Sixtymile thus should be considered as the uppermost "few pages of Chapter two" (late Precambrian) in the history of the Grand Canyon, and not as a separate "Chapter two-and-a-half" (Breed and Ford, 1973).

STRUCTURE

Walcott (1890) recognized that the Chuar strata are preserved in a syncline bounded on the east by the north-trending Butte fault and truncated beneath Paleozoic strata on the west. The Chuar syncline has been described by Ford and Breed (1973, p. 1255). Its axial trace north of Sixtymile Canyon (fig. 1) has been drawn from Ford and Breed's description and from the distribution of outcrops shown on their map. The axis of the Chuar syncline closely parallels the trace of the Butte fault. Strata in the comparatively narrow east limb tend to have steeper dips than strata in the west limb and locally near the Butte fault dip very steeply. At the head of the north fork of Sixtymile Canyon, the strike of the axis of the Chuar syncline shifts abruptly to the northwest, paralleling a shift in the trace of the Butte fault.

West of the axis of the syncline, strata of the Chuar Group dip rather uniformly to the east. Southwest of the area of figure 1, underlying strata of the Grand Canyon Supergroup also dip about 10° eastward (see Maxson, 1967; Huntoon and others, 1976). These relations reflect a regional eastward tilting of the Precambrian strata during an episode of block faulting, the youngest decipherable Precambrian structural event in the Grand Canyon (see Maxson, 1961; Huntoon and Sears, 1975). The regional and local settings thus indicate that the Chuar syncline is a local feature related to high-angle faulting on the Butte fault.

The Butte fault was named by Walcott (1890, p. 50) for the line of six spectacular buttes that lie east of the fault and that in part owe their origin to the fault (fig. 1). The Butte fault is exposed where Paleozoic strata have been eroded from the East Kaibab monocline, an east-facing structure of post-Paleozoic age. The East Kaibab monocline extends northward about 200 km, well into Utah. Exposures in the Grand Canyon indicate that this very long Phanerozoic structure is underlain by a Precambrian fault.

As is the case with a number of other faults in the Grand Canyon, the Butte fault has undergone re-

peated movements. In general, the northwest- and north-trending faults in the Grand Canyon show down-on-the-west senses of displacements in Precambrian rocks and down-on-the-east displacements in overlying Paleozoic rocks. The decipherable record of faulting begins during deposition of the Shinumo Quartzite of the Unkar Group (table 1), with high-angle reverse faulting, east side up, on the northeast-trending Bright Angel fault (Sears, 1973; Huntoon and Sears, 1975). The Bright Angel fault is about 20 km southwest of Sixtymile Canyon. Because strata as old as the Shinumo Quartzite and Hakatai Shale are not exposed along the Butte fault, evidence for such early movement is concealed. However, 10–13 km south of Sixtymile Canyon, complex relations exist that reveal faulting on the Butte fault and on associated faults after deposition of the Cardenas Lavas and before and during deposition of the Nankoweap Formation (Elston and Scott, 1976). Thus, the Butte fault was in existence before deposition of sediments of the Chuar Group.

Two episodes of movement are recognized on the Butte fault since deposition of the Nankoweap Formation. The older is a Precambrian episode that marked the end of deposition of Precambrian strata, and which this report describes. The younger is a post-Paleozoic episode that was assigned to the Tertiary by Walcott (1890, p. 57) from studies of C. E. Dutton (1882) and that probably is of "Laramide" (Late Cretaceous or early Tertiary) age (Huntoon, 1971, 1974). The post-Paleozoic displacement is about 810 m, down on the east, measured on the base of the Cambrian Tapeats Sandstone (Ford and Breed, 1973, p. 1255). The pre-Paleozoic displacement was about 3.2 km, down on the west. This estimate is derived from the thickness of Precambrian strata removed from the eastern, upthrown side of the Butte fault before deposition of the Tapeats. The Tapeats rests on the Sixtymile Formation west of the Butte fault but east of the fault directly overlies beds in the lower part of the Dox Sandstone (fig. 1; table 1; Elston and Scott, 1976, p. 1768), at least 3,200 m stratigraphically beneath the Sixtymile Formation. Strata of the entire Chuar Group, Nankoweap Formation, Cardenas Lavas, and most of the Dox Sandstone were eroded from the upthrown block before deposition of the Tapeats.

STRATIGRAPHY

Ford and Breed (1973, p. 1244, 1252–1253) designated the type section of the Sixtymile Formation as outcrops of breccia and sandstone on cliffs on the north side of the upper part of Sixtymile Canyon and indicated its location by the letter H on their figure 2.

AGE	UNIT		LITHOLOGY	THICK-NESS IN METERS	EXPLANATION

Figure content with columns:

AGE: CAMBRIAN — Tapeats Sandstone

Unit 3
Unit 2

17.9+m

PRECAMBRIAN — Sixtymile Formation

Upper member — Sandstone facies
Unit 4
Unit 3
Unit 2
Unit 1

Unit 1
Conglomerate facies

12+m

Middle member

25m

Lower member
Unit 6
Unit 5
Unit 1
Unit 4
Unit 2
Unit 3

Landslide block derived from unit 1 of Walcott Member and detached from scarp of Butte fault

22—27m

Kwagunt Formation — Walcott Member
~70m
Unit 2
Unit 4
Unit 3
Unit 1

EXPLANATION

Dolomitic limestone

Black shale

Laminated or thin-bedded sandstone

Sandstone, conglomeratic Breccia- and chert-bearing

Quartzite Chert-bearing

Landslide Monomict (□) and polymict (○)
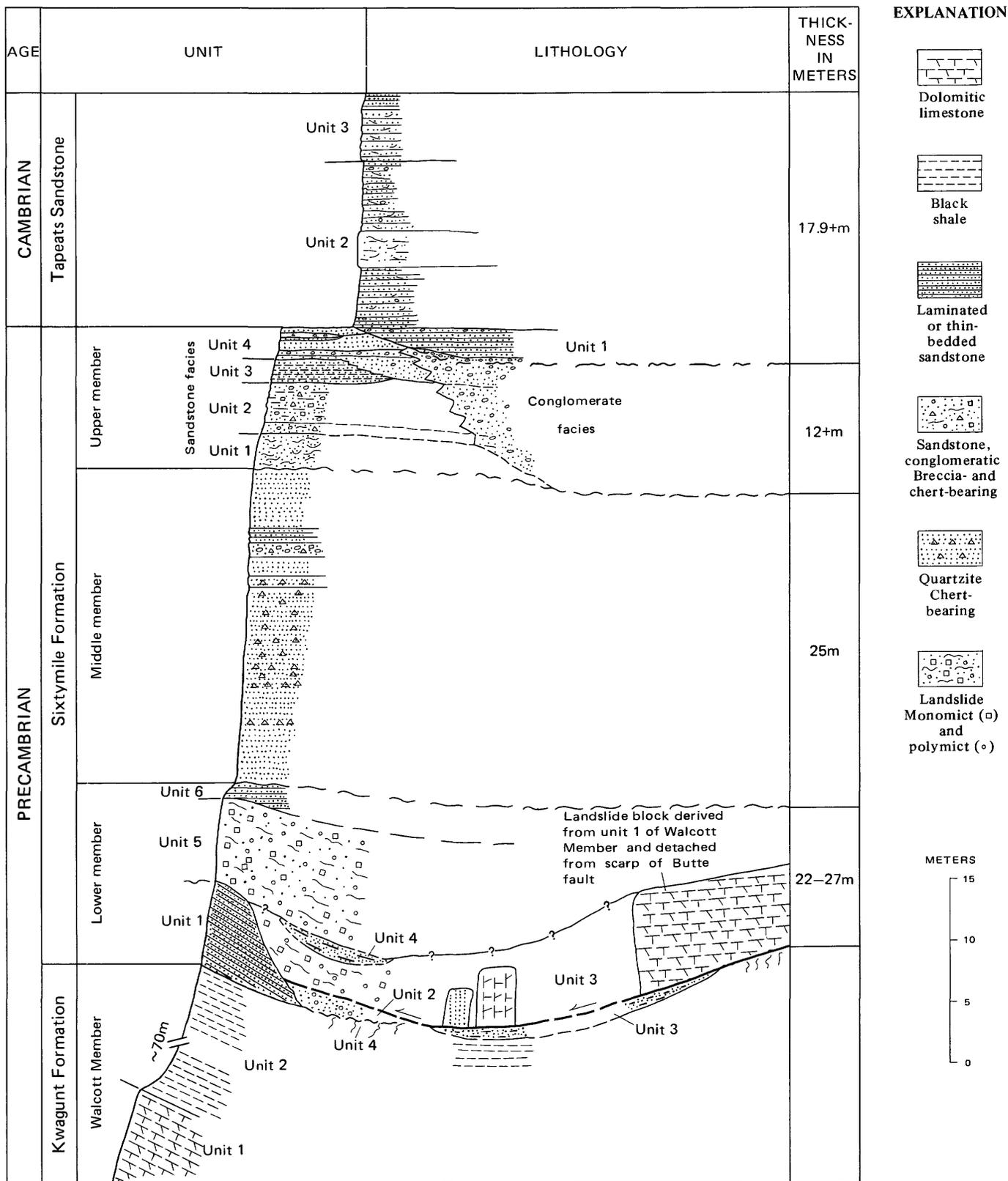
METERS
15
10
5
0

FIGURE 2.—Type section of Sixtymile Formation and units described at end of report. Wavy lines indicate an erosion surface.

A description of the type section, including immediately underlying and overlying strata, is given at the end of this text (table 4) and is shown diagrammatically on figure 2. These excellent exposures have enabled the stratigraphy and facies relations of the Sixtymile to be understood, in turn providing new insight on the formation of the Chuar syncline and faulting on the Butte fault.

PRE-SIXTYMILE STRATA

Strata of the Chuar Group beneath the Sixtymile Formation are mainly drab, monotonous sequences of gray to blue-black shale and subordinate interbedded limestone and dolomite. Three horizons of algal stromatolitic limestone, in part biohermal, and the primitive organism *Chuaria* are found within sequences of shale of the Chuar Group (Ford and Breed, 1972b, 1973). Additionally, microflora consisting of spheroids and filaments have been discovered by Schopf, Ford, and Breed (1973) in a thin cherty pisolite bed 20 m above the basal dolomite bed of the Walcott Member of the Kwagunt Formation (tables 1 and 2). On morphologic and geologic grounds, Schopf, Ford, and Breed believe that the siliceous pisoliths are of biologic origin, formed in a shallow, gently agitated marine setting. The gray shale and carbonate beds are very similar in aspect to gray marine shale and limestone of Paleozoic and Mesozoic age. The lithologic similarity and the presence of probable marine plant fossils suggest that much of the Chuar was deposited in a marine to possible intertidal environment. Sandy, silty, and shaly red beds occur at two horizons within the dominantly gray shale section of the Chuar Group and presumably reflect fairly brief intervals of emergence from beneath sea level and deposition near sea level.

KWAGUNT FORMATION

The Kwagunt Formation, nearly 600 m thick, was named by Ford and Breed (1972a, p. 7–8; 1973, p. 1242–1255), who subdivided it into three members (table 1). This report is concerned only with the upper or Walcott Member, which is about 175 m thick. The Walcott is dominantly gray to black shale. The strata at the type section of the Walcott Member on the south side of Nankoweap Butte (Ford and Breed, 1973, fig. 1) were measured and described by Walcott (1894, p. 508, units 2–9; table 2). It seems appropriate, in the absence of a detailed stratigraphic description, to designate Walcott's description as the description of the type section for the Walcott Member.

Three buff- or brown-weathering dolomitic limestone beds serve as marker beds in the Walcott. One is at the base of the member (unit 9 of Walcott), and a pair (or "doublet") occurs in the interval 90–105 m above the base (unit 3 of Walcott). The pisolitic chert bed that contains the microflora is unit 7 of Walcott's section. Except for one other interval of limestone (unit 5 of Walcott), the intervening materials are dark shale.

The basal bed, 2.5 m thick, is informally called the Flaky Dolomite by Ford and Breed (1973, p. 1252), who noted that it contains "wildly oriented" silicified flakes of what probably are relict algal laminations, which Walcott called "Stromatopora(?)." Ford and Breed suggested that the source rock was a disrupted stromatolitic limestone and that the cause of the disruption may have been contemporary seafloor slumping.

Two layers of buff-weathering dolomitic limestone form a distinctive ledge-forming doublet in the Walcott (figs. 3 and 4). In Nankoweap Butte, the interval is reported by Walcott (1894, p. 508, unit 3) to be 15 m thick and its top to lie 68.6 m below red strata of unit 1 (Sixtymile Formation). Characteristic thicknesses for the carbonate layers reported by Ford and Breed (1973, p. 1252) are about 7.5 m for the lower bed and about 12 m for the upper bed, separated by about 12 m of shale. Time was not available for the measurement and description of these beds in the trough of the Chuar syncline in Sixtymile Canyon during this study. However, the pair of beds are persistent in the trough and west limb of the syncline (fig. 1), and they thin and in part pinch out toward the Butte fault in the east limb of the syncline (figs. 3 and 4). The stratigraphic interval between the top of the doublet beds and the Sixtymile Formation on the axis of the syncline is estimated to be about 70 m. The upper bed of the doublet, observed at the helicopter landing site on the west limb of the syncline, is a limestone, in part fragmented, in which the fragments have been dolomitized and silicified. In this respect, it is similar to the flaky dolomite at the base of the Walcott.

DEVELOPMENT OF CONTACT RELATIONS

The contact of the Walcott Member with the overlying Sixtymile Formation has been described as an unconformity, beneath which shale of the uppermost 15 m of the Walcott is silicified (Ford and Breed, 1973, p. 1253). This observation applies to the east limb of the Chuar syncline in the Sixtymile Canyon area, where landslide material of the Sixtymile Formation rests on altered shale of the Walcott. However, landslide is not the stratigraphically lowest material of the Sixtymile; it overlies basal red laminated sandstone (unit 1) and siltstone of the Sixtymile that is preserved locally on the west limb and in the trough of the syncline (figs. 3, 4, and 5). In the trough of the syncline the uppermost Walcott is unaltered, and it contains beds in a 1.5-m interval that are transitional between underlying black shale typical of the Walcott and overlying

0   100   200   300 METERS
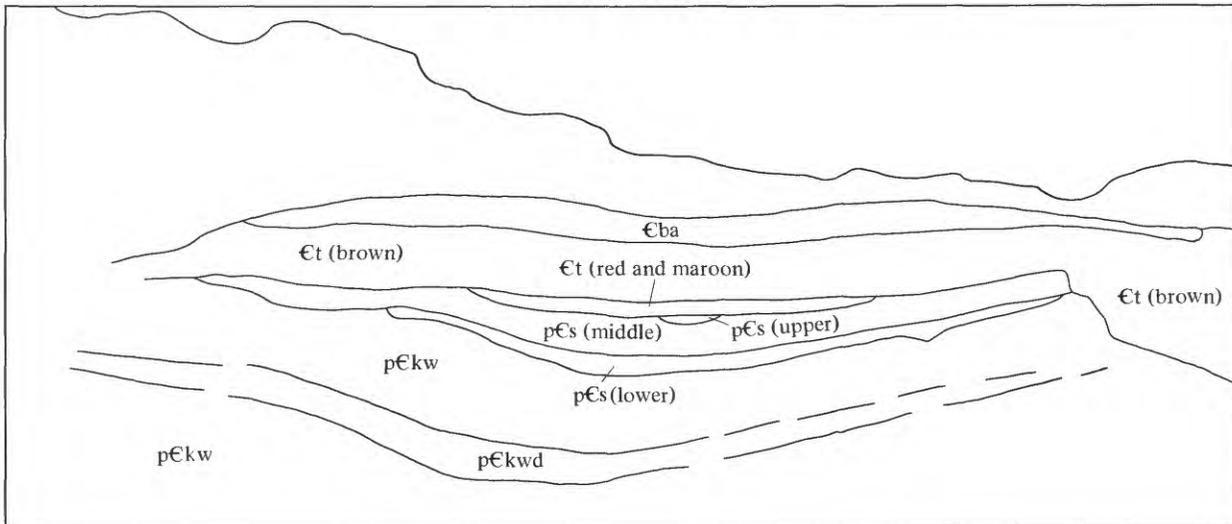APPROXIMATE SCALE

FIGURE 3.—Sixtymile Formation and Chuar syncline in north fork of Sixtymile Canyon. View is to north-northwest. p-Ckw, Walcott Member of Kwagunt Formation; pCs (lower), pCs (middle), and pCs (upper), respectively, of Sixtymile Formation; Ct (red) and Ct (brown), red beds and brown beds, respectively, of Tapeats Sandstone; Cba, Bright Angel Shale.

red sandstone of the basal unit of the Sixtymile Formation. Although the contact of unit 1 of the Sixtymile with the Walcott is concealed by colluvium on the west limb of the syncline for an interval of one to a few meters, no alteration of underlying beds of the Walcott was observed, and the character of the contact is presumed to be transitional, as it is in the exposure in the trough of the syncline. The transition beds and the basal laminated red sandstone of the Sixtymile do not contain fragmental or exotic materials, unlike succeeding strata. Field relations thus indicate that deposition was continuous across the Kwagunt-Sixtymile boundary.

The thin interval of red siltstone preserved in the syncline normally would be included with the Six-tymile. However, for convenience of portrayal of stratigraphic relations in the figures of this report, the transition beds in the syncline are considered to be at the very top of the Walcott Member, and the boundary between the formations is arbitrarily drawn between laminated red sandy siltstone below (in the trough of the syncline) and laminated very fine grained red sandstone above (on the west limb of the syncline).

Red laminated sandstone of the lowermost Six-tymile (unit 1) is preserved only locally on the west limb of the syncline. Equivalent beds almost certainly once rested on red laminated siltstone in the trough of the syncline but were removed by landsliding. Contorted, sheared green and red siltstone, 3–5 cm thick, presently separates unaltered and undisturbed red
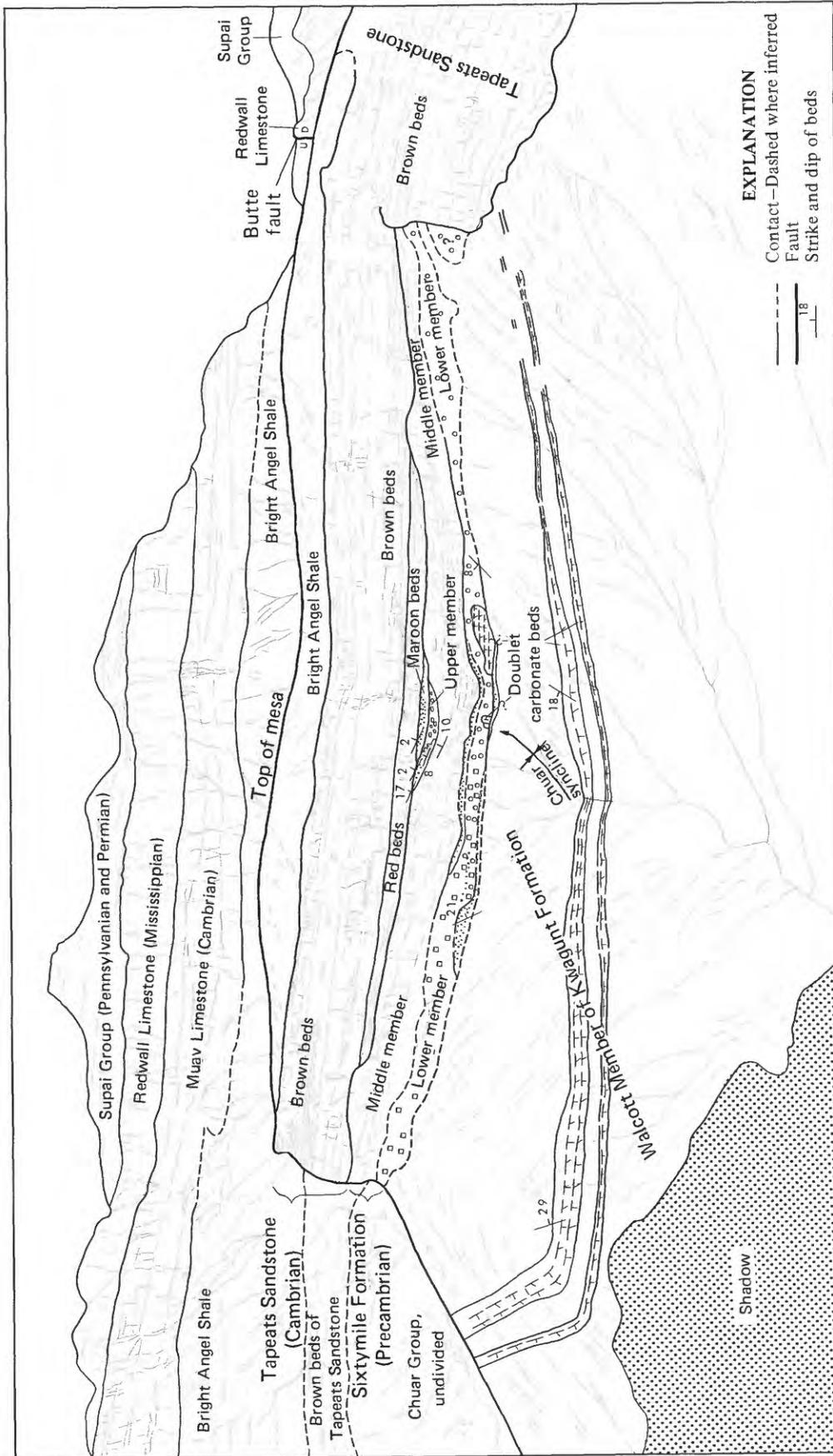
FIGURE 4.—Stratigraphic relations in Chuar syncline, north fork of Sixtymile Canyon. View is to northwest. In Walcott Member, note section containing pair of ledge-forming carbonate beds thins eastward toward Butte fault and upper carbonate bed pinches out.

Muav Limestone

Bright Angel Shale

Brown beds

Sandstone

Red beds

Middle member

Brown beds

3
2
1

Formation

Tapeats

Red beds

Maroon beds

Upper member

Middle member

Lower member

6

5
4
3
2
1

Sixtymile

member

8

Transition beds

Doublet carbonate beds?

Chuar syncline

Walcott Member of Kwagunt Formation

18

EXPLANATION

———— Contact–Dashed where inferred
———— Line of measured section
21
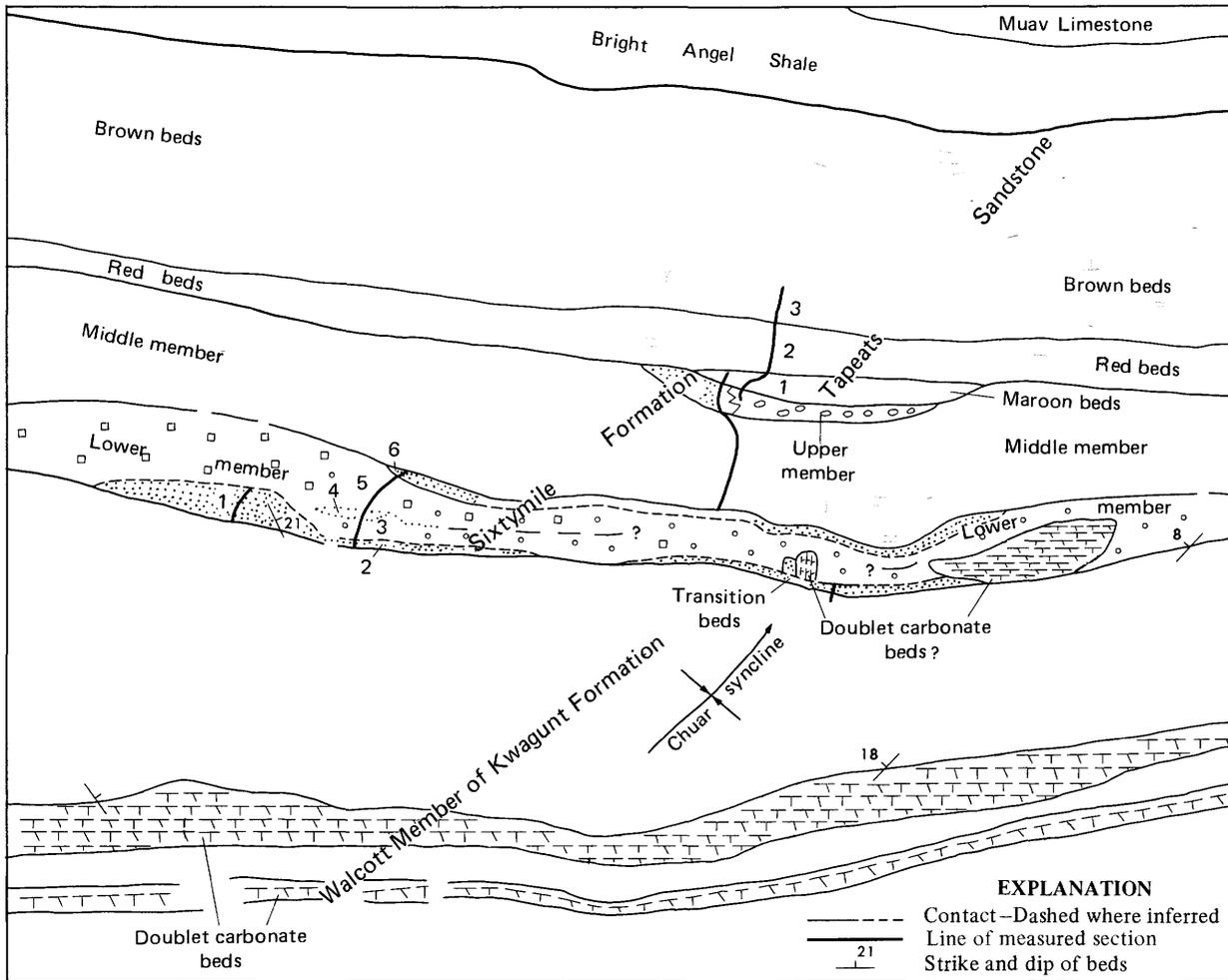Strike and dip of beds

Doublet carbonate beds

FIGURE 5.—Details of stratigraphic relations in central part of Chuar syncline showing lines of section used for measurement of type section of Sixtymile Formation. Numbers refer to table 3.

siltstone below from overlying landslide material of unit 3 of the lower member of the Sixtymile (figs. 2, 4, and 5; see table 4). The contact on and east of the axis of the syncline is an unconformity separating landslide material from unaltered and altered beds of the Walcott Member. The landslide material of units 3 and 5 contains an increasing proportion of clasts of red sandstone of the Sixtymile as it is traced westward from the axis of the syncline. Near slumped beds of red, laminated Sixtymile sandstone in the west limb of the syncline, the landslide becomes a monomict breccia consisting entirely of angular fragments of Sixtymile sandstone. Thus laminated sandstone once present in the trough of the syncline was disrupted and incorporated in the landslide. Evidence for an east-to-west movement of polymict landslide materials is summarized in the description of the Sixtymile Formation. The monomict and polymict landslide materials overlie and clearly are younger than the laminated red sandstone at the base of the Sixtymile Formation.

To summarize the above: beds of the uppermost Walcott are preserved in the trough of the syncline. They are transitional in color and lithology between lower Walcott rocks and laminated red sandstone of the Sixtymile Formation that is preserved locally on the southwest flank of the syncline. The transition beds are unaltered in the axis of the syncline, and no evidence for alteration was found beneath the laminated red sandstone of the Sixtymile on the west limb of the syncline. These facts indicate that a transition in depositional conditions occurred between deposition of the Walcott and Sixtymile and that deposition was continuous across the formational boundary.

The stratigraphic relations are interpreted to record the following events in the development of the contact relations between the Walcott Member and the Sixtymile Formation: (1) emergence from euxinic marine conditions to an aerated tidal-flat or littoral marine environment, which resulted in deposition of laminated red sandstone at the base of the Sixtymile (unit 1); (2) subsidence on the Chuar syncline, presumably

reflecting an increment of movement on the Butte fault, caused slumping of the basal (unit 1) sandstone toward the axis of the syncline; (3) erosion removed some of the sandstone of unit 1, locally exposing shale of the Walcott west of the axis of the syncline and widely exposing shale of the Walcott on the eastern limb of the syncline; (4) after moderate weathering of the Walcott shale, sandstone containing small rock fragments (unit 2) was deposited west of the axis of the syncline, and on the eastern limb of the syncline weathering of the Walcott continued, resulting in deep alteration; and (5) landsliding from the east disrupted sandstone strata of the Sixtymile in and west of the trough of the syncline. The last event recorded the first of two or more major structural pulses, reflecting large displacements on the Butte fault that presumably occurred during the course of strong regional uplift.

SIXTYMILE FORMATION

The Sixtymile Formation is subdivided into three informal members (fig. 2): (1) a lower sandstone and landslide breccia member; (2) a middle cherty quartzite member; and (3) an upper breccia-bearing sandstone and conglomerate member that exhibits an abrupt change in facies. The lower member, in and east of the trough of the Chuar syncline, is made up of landslide debris derived from the area and former scarp of the Butte fault. The polymict breccia passes into monomict breccia in the west limb of the syncline, where the materials consist of angular fragments of red sandstone derived from the subjacent basal unit of the Sixtymile. The landslide overlies red sandstone of the basal Sixtymile that is slumped toward the axis of the syncline and underlies red sandy siltstone at the top of the lower member of the Sixtymile. The stratigraphic and structural relations indicate that a progressive deepening of the Chuar syncline accompanied movement on the Butte fault and deposition of landslide material of the lower member.

The middle member is a laminated and thin-bedded very fine grained cherty quartzite. It probably was deposited in standing water, presumably a lake that occupied a topographic low in the syncline. The upper member, west of the axis of the syncline, consists of fine-grained fluviatile and fanglomeratic sandstone that grades abruptly into sandy conglomerate toward the axis of the syncline. In the lower member, the coarse materials were derived by landsliding from the east and northeast, from the area of the Butte fault. In the upper member, the coarse materials show the effects of stream transport and deposition along the axis of the syncline, and except for the basal bed of the upper member their deposition postdated folding on the syncline.

The Sixtymile Formation in the area of its type section is shown in a photograph of the north fork of Sixtymile Canyon (fig. 3). Most of the stratigraphic units shown in figures 2, 4, and 5 may be identified in the photograph. Figures 4 and 5 were drawn from a photograph that looks more directly down the axis of the Chuar syncline. The locations of the lines of section measured for the composite stratigraphic section (fig. 3 and table 4) are shown in figure 5.

Thicknesses reported for the Sixtymile Formation show some variability because several of the units were deposited in an actively deepening trough. The stratigraphic interval along the lines of section on the west limb near the axis of the syncline (fig. 5) totals 51 m. A composite stratigraphic section that includes the basal sandstone (unit 1; 6.4 m thick) preserved updip from the main line of section (fig. 5) and an estimated 1.5 m of strata stratigraphically above the highest accessible beds of the upper member results in a reconstructed thickness of 59 m for the Sixtymile at the type section. Siltstone of unit 6 of the lower member may be about 5 m thicker at the axis of the syncline than where measured on the west limb. If so, the maximum reconstructed thickness of beds preserved in the syncline is about 64 m. The nominal thickness reported here for the Sixtymile is 60 m.

LOWER MEMBER

Six purplish-red units are recognized in the lower member (fig. 2). In ascending order they are unit 1, laminated hematitic sandstone; unit 2, thin-bedded micaceous sandstone containing rock fragments, which overlies weathered Walcott shale; unit 3, monomict and polymict breccia; unit 4, crudely bedded sandstone; unit 5, monomict and polymict breccia; and unit 6, thin-bedded soft sandy siltstone. These units record four intervals of sandstone deposition and two or more episodes of landsliding.

The contact relations of units 1, 2, and 3 with the Walcott Member have been summarized in the section "Development of Contact Relations." On the west, unit 3 breccia is monomict and crudely stratified and consists of disrupted angular fragments of well-lithified sandstone derived mainly from unit 1. The breccia becomes polymict toward the axis of the syncline where it consists mainly of altered and silicified fragments derived from the Kwagunt Formation. A few fragments of sandstone made up of rounded grains of quartz are exotic to both the Kwagunt and Sixtymile Formations. Their source is not known. The polymict breccia in the trough of the syncline is not apparently stratified, and the various materials are chaotically distributed. Landslide material of unit 3 is 8 m or more thick in the trough of the syncline, and two large exotic blocks, vertically oriented with respect to their bedding, rest side by side in the axis

(figs. 2 and 5). Proceeding eastward, up the east limb of the syncline, a large buff-weathering carbonate body about 8 m thick and 40 m long crops out at the base of the unit 3 landslide. Judging from its lithology and thickness, this mass was derived from the upper of the doublet carbonate beds of the Walcott Member or else from another stratigraphically much lower carbonate bed. In the Walcott Member in the trough of the syncline, the upper of the marker beds lies about 70 m stratigraphically beneath the Sixtymile Formation. The landslide block has not been tumbled but rather arrived at its position by sliding on its basal surface down the east limb of the Chuar syncline. Presumably the bed was once exposed in the scarp on the upthrown side of the Butte fault. The upslope part of the landslide block rests on altered, weathered Walcott shale. Its downslope end overrides and rests on unaltered red transition beds of the Walcott.

The foregoing relations indicate that significant displacement occurred on the Butte fault early during the deposition of the Sixtymile. Just how much displacement had taken place by the time of deposition of landslide of unit 3 is not known. Displacement was at least 100 m and may have been much greater. A block of tan-weathering white quartzite at the base of the landslide mass in the axis of the syncline (figs. 2, 4, and 5) is foreign to the Chuar Group. The stratigraphically closest possible source is quartzite at the top of the Nankoweap Formation, some 2 km below the top of the Kwagunt Formation. Displacement on the Butte fault at the time of emplacement of the polymict landslide of unit 3 thus was at least 100 m and possibly was 2 km or more.

On the west side of the syncline (figs. 2 and 4), a poorly stratified and sorted sandstone (unit 4) overlies breccia (unit 3) and in turn is overlain by a dominantly monolithologic breccia (unit 5). The monolithologic breccia is made up of angular clasts of sandstone derived principally from unit 1. As is the case for unit 3, breccia of unit 5 becomes polymict toward the axis of the syncline, where no plane of separation between units 3 and 5 is apparent. Deposition of sandstone of unit 4 thus records a brief(?) interval between two large landslide events early in the deposition of the Sixtymile.

The record preserved in the lower member ends with deposition of soft thin-bedded sandy red siltstone (unit 6) that is exposed locally on the west side of the syncline. This unit is sharply and unconformably(?) truncated by the middle member, wedging out at the base up the limb of the syncline. Toward the axis of the syncline unit 6 is concealed by talus. A hiatus of unknown extent exists between deposition of unit 6 and beds of the middle member of the Sixtymile. The hiatus may have been geologically short, reflecting a change from mudflat to lacustrine deposition.

MIDDLE MEMBER

The middle member is a cherty quartzite, 25 m thick, which resists erosion and characteristically forms cliffs. It can be traced across the area of exposure of the Sixtymile Formation and is responsible for the preservation of the Sixtymile in the Chuar syncline. Its resistance to erosion led to the formation of small hills on either side of the syncline in late Precambrian time before deposition of the Tapeats Sandstone. The hills appear to have protected the lowest beds of the less resistant upper member from complete removal from the axis of the syncline before deposition of the Tapeats Sandstone. The middle member may be crossed, without resorting to technical climbing techniques, at one place in the trough of the syncline (fig. 5).

The quartzite of the middle member is thin bedded and finely laminated, and the grains are very fine sand to silt size. The lower part is purplish red, grading upward to a creamy mottled and streaked red. Chert is common to abundant, and the middle part contains numerous thin discontinuous beds of chalky-white chert. Breccia is sparse, one lens possibly of landslide origin occurring near the top. The very fine grain size, the thin regular bedding, and the bedded chert are evidence for deposition in quiet standing water, perhaps a lake along the axis of the Chuar syncline.

The middle member is folded on a moderately large scale, and the thin beds and laminations are crinkled in a manner that reflects slumping of the member toward the axis of the Chuar syncline. Slumping occurred after deposition of the member, because no internal folds independent of other folds were observed across the member. Folding probably occurred after deposition of the overlying basal sandstone bed of the upper member, which displays contorted bedding that may reflect the same slumping event. Slumping probably was in response to minor(?) renewed subsidence in the Chuar syncline, which in turn presumably reflected renewed displacement on the Butte fault. The slumping and subsidence produced a narrow trough in which strata of the upper member were deposited, and subsequently preserved.

The contact of the middle and upper members is sharp and unconformable. The basal sandstone of the sandstone facies of the upper member at one place truncates 1.5 m of beds of the middle member. Toward the axis of the syncline, in inaccessible exposures, conglomerate overlies the middle member with apparent unconformity. The length of the hiatus in deposition is not known, but possibly was not long geologically.

UPPER MEMBER

The upper member, about 12 m thick, is preserved in a narrow trough-shaped area in the axis of the Chuar syncline. Two facies, a sandstone facies and a conglomerate facies, are recognized. The sandstone is present southwest of the axis of the syncline (fig. 5), is pale red to brown, and contains scattered rock fragments that include chalky-white chert derived from the middle member. Some of the strata are fluvially crossbedded, and some of the sandstone is fanglomeratic. A siltstone bed 2 m thick is present in the lower part of the section. Parts of the sandstone facies grade laterally northeastward toward the axis of the syncline, over a distance of 3–4 m, into massive-weathering maroon conglomerate. Stratification in the conglomerate is obscure but where seen in a few lenses of contained sandstone is horizontal. Much of the coarsest detritus in the conglomerate is subangular and has undergone only comparatively short transport. However, some of the detritus in the conglomerate is subrounded, suggestive of moderate transport. The conglomerate and laterally equivalent beds of sandstone were deposited by a stream that once flowed along the trough of the syncline.

Sandstone and conglomerate beds at the top of the upper member, unlike beds near the base, are essentially flat lying. These uppermost beds of the Sixtymile dip 2° NW., identical to the dip of parallel laminated beds of the directly overlying Cambrian Tapeats Sandstone. This indicates that strata of the upper member record a simple filling of the synclinal trough and that folding on the Chuar syncline ceased before the end of deposition of the Sixtymile. The final increment of subsidence on the syncline, from the presence of a contorted breccia-bearing sandstone, occurred very early during deposition of the upper member (table 4). Strata above the basal breccia-bearing sandstone of the upper member thus appear younger than disturbances related to the Grand Canyon orogeny, and these beds presumably record the deposition of an apron of detrital material shed from high-standing terrain onto and across downfaulted terrain. Judging from the 3 km of structural relief across the Butte fault, it is conceivable that the apron of material once was many hundreds of meters thick, following which it was nearly entirely removed by pre-Tapeats erosion.

TAPEATS SANDSTONE

The Tapeats Sandstone, of Early and Middle Cambrian age (McKee and Resser, 1945), was deposited across the region of the Grand Canyon about 570 m.y. ago as a consequence of west-to-east marine transgression. An irregular hilly terrain existed, and some hills had a topographic relief of more than 200 m. The highest hills were not buried until after the end of deposition of the Middle Cambrian Bright Angel Shale (table 1). During deposition of the Tapeats, a small amount of relief in the Sixtymile Canyon area was present as a consequence of the resistance to erosion of the middle member of the Sixtymile Formation (fig. 4). Erosion and removal of the upper member of the Sixtymile from all but the central part of the syncline produced a swale or channellike depression, with 20–30 m of erosional relief, between hills on both sides of the Chuar syncline. Red beds of the Tapeats were deposited across the area, and the original red coloration is preserved in the swale between the hills (fig. 4). These beds are nearly flat lying and dip 2° NW., indicating that the syncline is entirely of Precambrian age.

In the axis of the syncline, the contact of the Tapeats with the conglomerate and locally with sandstone of the upper member of the Sixtymile is a disconformity. A few meters to the south of the axial part of the syncline, an angular discordance between the formations of 6° to 10° can be seen. Within the Chuar syncline, about 20 m of the red beds and an estimated 5–10 m of overlying brown (bleached) beds of the Tapeats wedge out against beds of the middle member of the Sixtymile (fig. 4).

The basal unit of the Tapeats in the Chuar syncline is a parallel-bedded maroon sandstone, 2.5 m thick, that is not known elsewhere in the eastern Grand Canyon. It is similar to and presumably correlates with parallel-bedded maroon sandstone in the lower part of the Tapeats in the central Grand Canyon, seen opposite and slightly downstream from Deer Creek (river mile 136.5). If the parallel-bedded sandstone is correlative, the swale in the trough of the syncline was topographically low at the onset of deposition of the Tapeats.

Beds of unit 2 of the Tapeats are pale red to reddish brown and are typical of the color and stratification of unbleached sections of the Tapeats seen at places in the central Grand Canyon. The color of the red beds of units 1 and 2 in the topographic swale above the Chuar syncline probably was preserved because ground water did not percolate through these beds in Cenozoic time. Red sandstone is known to occur very locally at the base of the Tapeats at a few other places in the eastern Grand Canyon. In each case the lack of bleaching is seemingly related to a physical configuration that would have impeded Cenozoic ground water flow.

TABLE 3.—*Outline of depositional and structural events of Grand Canyon orogeny, Sixtymile Canyon, eastern Grand Canyon, Ariz.*

Stratigraphy	History
Tonto Group:	
Tapeats Sandstone	Regional west-to-east Cambrian transgression. Chuar syncline was topographically as well as structurally low and received initial deposits characteristic of older strata of the Tapeats to the west.
Great unconformity	Planation of the upthrown fault blocks; removal of nearly all of the late Precambrian detrital deposits on the downthrown fault blocks as erosion cut deeply across the region. Preservation of Sixtymile Formation in a structural low.
Chuar Group:	
Sixtymile Formation:	
Upper member:	Deposition of an apron of detrital deposits across downthrown fault block during subaerial erosion of high-standing fault block.
Unit 4 3 } Fluviatile sandstone and con- 2 glomerate.	Filling of Chuar syncline with stream deposits.
1 .... Fluviatile sandstone and breccia with contorted bedding.	Final orogenic pulse: Increment of subsidence in Chuar syncline resulted in slumping of the middle member toward axis of Chuar syncline and disruption of basal bed of upper member; subsidence accompanied by minor(?) faulting on Butte fault.
Unconformity Middle member ___ Thin-bedded and laminated cherty quartzite.	Interval of quiet deposition: Deposition of middle member in a lake localized along axis of Chuar syncline; small landslide breccia near top.
Unconformity Lower member: Unit 6 ...... Sandy red siltstone	Mudflat deposition. Main orogenic pulses accompanied by strong regional uplift:
5 ...... Landslide .... 4 ...... Red sandstone .... 3 ...... Landslide .... 2 ...... Red sandstone with rock fragments resting on weathered Walcott shale.	d. Large displacement on Butte fault (1 km?). c. Brief(?) interval of deposition of sandstone. b. Major displacement on Butte fault (2 km?). a. Folding on Chuar syncline; slumping of unit 1 sandstone accompanied by partial removal; exposure and weathering of shale of Walcott Member; deposition of unit 2 sandstone.
Unconformity 1 ...... Thin-bedded laminated red sandstone.	Subaerial deposition at or near sea level.
Kwagunt Formation:	
Walcott Transition beds	Emergence accompanying regional uplift.
Member Black shale.	
Pair of carbonate marker beds and intervening shale.	Uplift of the east limb of the Chuar syncline in response to faulting on the Butte fault. Structural relief was 20 m or more.
Thinning of lower marker bed and overlying shale, and pinchout of upper marker bed toward Butte fault to east. Disruption of upper marker bed on west side of Chuar syncline. Black shale. Flaky dolomite bed	Possible initial faulting of Grand Canyon orogeny on preexisting Butte fault and initiation(?) of Chuar syncline.
Disruption by contemporary seafloor slumping. Awatubi Member ...... Black shale.	

Left margin labels (top to bottom):
- Marine deposition — ~570 m.y.
- Continental deposition
- Grand Canyon Supergroup — ~830 m.y.
- Grand Canyon orogeny (845–810 m.y.)
- Marine deposition

HISTORY AND AGE

The Grand Canyon orogeny began during deposition of black shale and carbonate beds of the Walcott Member of the Kwagunt Formation (table 3). The first movements in the north-trending Chuar syncline and nearby Butte fault may have taken place as early as deposition of the flaky dolomite at the base of the Walcott Member. Contemporary slumping of the seafloor that has been suggested by Ford and Breed for the disruption of materials in this bed could have been triggered by displacement on the already existing Butte fault. However, the first direct evidence for deepening of the Chuar syncline is seen in an interval of strata that lies about 70–85 m below the top of the Walcott Member. The strata consist of two buff-weathering dolomitic limestone beds separated by shale. In the Sixtymile Canyon area, the lower bed and the overlying shale thin eastward toward the Butte fault, and the upper bed pinches out. The thinning and pinchout record 20 m or more of relative structural uplift of beds near the Butte fault during deposition of the Walcott. The upper dolomite bed in the syncline locally appears disrupted and fragmented. Disruption and fragmentation of the possible algal laminations may have been due to some combination of desiccation and wave action or perhaps by an earthquake associated with movement on the Butte fault.

Regional uplift terminated deposition of the Walcott Member. This uplift is marked by the deposition of shale and siltstone that is transitional in color and lithology between black shale of the Walcott Member below and very fine grained red sandstone of the Sixtymile Formation above.

After emergence from the sea, at least 6 m of very fine grained thin-bedded and laminated red sandstone (unit 1 of lower member of Sixtymile) was deposited in the area of the Chuar syncline. Deposition was in quiet, standing water, presumably at or very near sea level. Aeration presumably caused the formation of a pervasive red hematite pigment.

The laminated basal sandstone strata of the Sixtymile then underwent slumping toward the axis of the Chuar syncline, presumably in response to a deepening of the syncline and the beginning of large displacements on the Butte fault. With uplift of the east limb of the syncline toward the Butte fault, erosion removed material of the Sixtymile, exposing the Walcott, and weathering and alteration of the black shales began. In the trough of the syncline, erosion removed much of the red sandstone of the Sixtymile and locally exposed Walcott shale low in the west limb, where minor weathering also took place. The transition beds of the Walcott in the trough of the

syncline escaped alteration. After exposure and minor alteration of Walcott shale on the west limb of the syncline, a local(?) red sandstone, 1.5 m thick, that contains sparse rock fragments and fresh white mica (unit 2 of lower member) was deposited downslope from slumped beds of unit 1. The contact of unit 2 with the Walcott is a disconformity, and the sandstone wedges out with probable unconformity against unit 1.

After deposition of the two lower sandstone units of the Sixtymile, two strong episodes of faulting occurred on the Butte fault, accompanied by a deepening of the Chuar syncline and steepening of its limbs. Landslides cascaded westward down the east limb of the syncline. The first landslide contained a large stratigraphically coherent block derived from one of the resistant carbonate beds of the Chuar Group that was exposed in the upthrown block and detached from the fault scarp. Displacement on the Butte fault was at least 100 m and probably was much more. A quartzite block at the base of the landslide in the trough of the syncline is foreign to the Chuar Group and may have been derived from quartzite at the top of the Nankoweap Formation. If this is the case, displacement on the Butte fault at the time of the first landslide was at least 2 km. This is about two-thirds of the maximum stratigraphic displacement that can be deduced from the erosion of strata from the eastern upthrown block. Landslide material west of the axis of the syncline contains an increasing proportion of red sandstone fragments derived from the Sixtymile, and the landslide becomes monomict high on the west limb of the syncline. A poorly stratified red sandstone (unit 4) separates two episodes of landsliding and brecciation in the west limb (units 3 and 5). The two landslide units, however, could not be distinguished in the axis of the syncline, because the intervening sandstone is not present. If the first landslide reflects a large increment of displacement on the Butte fault, then the second landslide also presumably represents a major pulse of faulting. Soft sandy red siltstone (unit 6) was then deposited on the landslide, the last depositional event that is recorded for the lower member of the Sixtymile. From the relative paucity of breccia in overlying strata, most of the regional uplift, folding, and faulting of the Grand Canyon orogeny occurred during deposition of the lower member.

The middle member of the Sixtymile Formation, 25 m thick, is a thin-bedded and laminated cherty quartzite that was deposited in standing water, probably a lake in the trough of the Chuar syncline. The middle member unconformably overlies the lower member and in turn is truncated with at least local angular unconformity by the basal unit of the upper member. The lengths of the hiatuses are not known, but

they probably were short. The middle member displays folding that reflects slumping toward the axis of the Chuar syncline after deposition. Bedding of the overlying basal sandstone bed of the upper member also is contorted, and it reflects the last increment of slumping in the syncline, and by inference the last increment of Precambrian displacement on the Butte fault.

Strata of the upper member consist of fluviatile sandstone and conglomerate, 12+ m thick. Dips decrease upward and at the top are nearly horizontal. A dip of 2° NW. at the top is identical to the dip of directly overlying parallel-bedded sandstone of the Cambrian Tapeats Sandstone. The horizontal attitude and the lack of folding in these uppermost beds of the Sixtymile indicate that folding on the Chuar syncline and faulting on the Butte fault had ended. The fluviatile deposits simply aggraded in the synclinal trough produced at the time of slumping of the middle member and the basal sandstone of the upper member.

The record for the Grand Canyon orogeny thus is contained principally in the lower and middle members of the Sixtymile Formation and only to a minor extent in the underlying Walcott Member of the Kwagunt Formation. Two major increments of folding and faulting occurred during deposition of the lower member of the Sixtymile, and a third final increment of folding, and probably faulting, occurred shortly after the beginning of deposition of the upper member.

An age for the Sixtymile Formation, and the Grand Canyon orogeny, is estimated from reset K-Ar ages obtained from the Cardenas Lavas of the Unkar Group (table 1) and is believed to lie in the interval 845–810 m.y. The age estimate is valid if argon loss accompanied deep burial and heating of the lavas and if argon retention began with a reduced geothermal regime after regional uplift, faulting, and the erosion of overlying strata. Geologic evidence for regional uplift and faulting, followed by erosion of a high-standing fault block, is developed in this study. Isotopic ages can be examined to see if they are compatible with the geologic history and with a reasonable model for argon loss and retention.

Flows of the Cardenas Lavas, the uppermost formation of the Unkar Group, lie about 2 km stratigraphically below the top of the Chuar Group (table 1). Samples from six different lava flows collected in Basalt Canyon, 11 km south-southwest of the Sixtymile Canyon area, have yielded a whole rock Rb-Sr isochron of 1,090± m.y. (McKee and Noble, 1976). This age of about 1.1 b.y. is probably the extrusion age of the lavas. Much younger K-Ar ages for samples from three different flows of the Cardenas were obtained by McKee and Noble (1976), who suggest the young ages may reflect an episode of heating about 800 m.y. ago.

McKee, when first reporting the results of the young K-Ar ages (McKee and Noble, 1974), proposed that they might represent the time of the Grand Canyon disturbance. The K-Ar ages, in descending stratigraphic order and starting with the topmost flow of the Cardenas, are 810±20, 790±20, and 781±20 m.y. The second and third ages are from flows in the upper- and lower-middle parts of the 300-m-thick section of flows. The progression in ages suggests that argon retention began at the top of the Cardenas earlier than in the lower-middle part of the section. Such a progression is consistent with the idea of a progressive removal of overlying strata following uplift and a progressive downward cooling of the section. Such would imply that the minimum age for the Grand Canyon orogeny is about 810 m.y.

Another K-Ar age of 832±30 m.y. was determined by M. L. Silberman (written commun., 1976) from a sample high in the Cardenas flow sequence in a structurally high block east of the Butte fault and south of the Palisades fault and Cedar Mesa monocline (Elston and Scott, 1976, fig. 1). This age also is in agreement with the argon retention model outlined before.

A K-Ar age of 845±15 m.y. is reported by Ford and others (1972) for a sample of basalt collected randomly in Basalt Canyon. This age, somewhat older than the two youngest K-Ar ages reported by McKee and Noble (1976), serves to place a maximum limit on the time of beginning of argon retention and would thus appear to represent a maximum age of the Grand Canyon orogeny. The spread in reset K-Ar ages allows a nominal age of about 830 m.y. to be provisionally assigned for the time of regional uplift and principal displacements on the Butte fault.

During the interval about 830–570 m.y., the beginning of Cambrian time (Geol. Soc. London, 1964), the region remained above sea level. After the accumulation of an unknown but perhaps substantial thickness of fanglomeratic deposits derived from high-standing blocks and deposited on downthrown fault blocks, erosion removed nearly all these deposits and then reduced the surface to an irregular rolling plain marked by scattered hills of the Shinumo Quartzite (Unkar Group) that stood as much as 200 m above the plain. In the area of Sixtymile Canyon, about 20–30 m of relief was developed on the resistant middle member of the Sixtymile Formation. A channellike swale was eroded in the Chuar syncline, principally by the removal of less resistant beds of the upper member of the Sixtymile Formation. Marine transgression from the west occurred in Early Cambrian time, marked by the deposition of parallel-bedded sandstone at the base of the Tapeats Sandstone in the central Grand Canyon, and similar beds were deposited in the channellike swale in the Chuar syncline. These beds are

not found at the base of the Tapeats elsewhere in the eastern Grand Canyon, which suggests that the swale was topographically low at the time of transgression.

CORRELATION

Stewart (1976, p. 14) has proposed that a marked change in the tectonic setting of North America occurred about 850 m.y. ago. The change was from deposition in scattered locally deep epicratonic troughs to deposition in miogeoclines that were marginal to and that extended almost continuously around North America. Stewart considered the Windermere Group, which occupies the stratigraphic position between the Precambrian Belt Supergroup and the earliest Cambrian rocks, to be the basal unit of the Cordilleran geosyncline. K-Ar ages from a small comparatively unmetamorphosed and unaltered area of greenstone (basalt) of the Windermere in northeastern Washington have been determined by Miller and others (1973), who reported that extrusion probably occurred between 827 and 918 m.y. ago. There is considerable scatter in the calculated ages, and several of the ages are less than 800 m.y. (Miller and others, 1973, table 1). This very approximate age for the Windermere is fully compatible with the provisional 830-m.y. age for the Sixtymile Formation and the Grand Canyon orogeny estimated from reset K-Ar ages from the Cardenas Lavas.

Structural and stratigraphic relations described for strata of the Purcell (Belt) and Windermere Supergroups in the southern Cordillera of Canada, particularly in southeastern British Columbia, are similar to the relations seen at the top of the Grand Canyon Supergroup. Gabrielse (1972, p. 528) regarded the east Kootenay orogeny of British Columbia as an episode of regional uplift accompanied by regional metamorphism and perhaps minor folding that terminated the long period of Purcell sedimentation in the southern Cordillera about 800 m.y. ago. Lis and Price (1976) reported that about 9 km of conglomeratic strata of the Windermere Supergroup (Young and others, 1973) was deposited on the northwest, downthrown side of a fault system that bounds the Purcell anticlinorium and that the maximum stratigraphic separation on Purcell strata was 13 km or more. Lis and Price (1976) proposed that the conglomeratic units represent fanglomerates that accumulated adjacent to a fault scarp separating the uplifted source area on the southeast and the deep structural basins on the northwest. They concluded that the magnitude of the stratigraphic separation associated with this late Precambrian faulting indicates that it represents a structure of crustal dimensions. As pointed out by Harrison and Reynolds (1976, p. 905),

the tectonics of the Western United States during the late Precambrian seem to have been characterized by vertical tectonics without the occurrence of either plate tectonics or collision.

The magnitude of faulting on the Butte fault in the eastern Grand Canyon is considerably less than that reported at the Purcell-Windermere boundary of southeastern British Columbia, but the structural senses of displacement, the changes in depositional conditions, and the timing appear similar. In both areas regional uplift was accompanied by high-angle block faulting, south and east sides up, about 800 m.y. ago, which resulted locally in the end of marine deposition and in the deposition of conglomeratic materials derived from fault-block mountains. The foregoing leads to the suggestion that pre-Sixtymile strata of the Chuar Group are correlative with strata of the upper part of the Belt (Purcell) Supergroup and that conglomeratic strata of the upper member of the Sixtymile Formation, deposited after Precambrian faulting had ended on the Butte fault, are correlative with conglomeratic strata of the basal parts of the Windermere Group (Supergroup in Canada). These correlations suggest that the Grand Canyon and East Kootenay orogenies are cogenetic.

On the east coast of North America, Rankin (1976) reported that Appalachian salients and recesses are inherited from the initial breakup of a continental mass beginning about 820 m.y. ago. The Grand Canyon and East Kootenay orogenies thus may be part of a major structural episode in the history of North America.

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TABLE 4.—*Description of strata at type section of Sixtymile Formation, north fork of Sixtymile Canyon, (36°12'42"N., 111°50'45"W.), eastern Grand Canyon, Arizona*

Thickness
(meters)

Cambrian:
  Tapeats Sandstone:
    3. Sandstone, coarse- to medium-grained; pale red (10R 6/2) to very pale orange (10YR 8/2) at top; quartzose; rounded coarse- to granule-size grains of pale-yellowish-orange (10YR 8/6) quartz are common; moderately well sorted; medium and thick bedded, parallel bedded, and cross laminated; forms cliff. Contains three 2.5-cm-thick beds of laminated red very fine grained silty sandstone enclosed by yellowish sandstone in upper 0.75 m; these are the highest red beds in the Tapeats of the Sixtymile Canyon area _____   4.75
    2. Sandstone; medium grained with subordinate beds ranging from fine to coarse grained and granule and pebble bearing; pale red (10R 6/2-5R 6/2) and moderate red (5R 5/4) subordinately streaked pale yellowish orange (10YR 8/6) to very pale orange (10YR 8/2); quartzose; grains subrounded to subangular; well cemented; subordinate interstitial silt; well to poorly sorted; scattered pebbles and granules of rock fragments are probably from Sixtymile Formation; dominantly thin and parallel bedded and subordinately cross laminated. Conspicuous ledge-forming yellow-brown fine-grained sandstone bed, 2.9 m thick, is 5.06 m above base of unit; overlying 2.5 m consists of red and yellowish, soft and resistant, locally pebble-bearing sandstone; first appearance of yellow quartz that characterizes much of Tapeats occurs 0.5 m below top, in 5-cm-thick coarse-grained red-brown and yellow sandstone that contains angular pebble-size fragments _____   10.45
    1. Sandstone; very fine grained and fine to medium grained with scattered coarse quartz grains and granules of rock fragments; locally pebble bearing in top 0.1 m; dominantly grayish red (5R 4/2), in part streaked pale red (5R 6/2); thin and parallel bedded, in part finely laminated; basal 0.3 to 0.4 m is conglomeratic sandstone reworked from directly underlying material of Sixtymile and distinguished from it only by character of stratification; hematite-rich very fine grained sandstone, 0.4 m thick, directly overlies reworked sandstone; hematite is somewhat less abundant in overlying 1.45–1.85 m of coarser grained beds; unit pinches out 10–15 m to south against resistant beds of upper member of Sixtymile Formation that formed a ledge or step in the erosion surface _____   2.3–2.7
        Thickness of Tapeats Sandstone _____   17.9+
Unconformity
    Disconformable, becoming unconformable to south away from axis of syncline.
Precambrian:
  Chuar Group:
    Sixtymile Formation:
      Upper member—fluviatile sandstone and conglomerate:
        Conglomerate facies; occupies axial part of syncline; grades abruptly southward into parts of sandstone facies; inaccessible sharp lower contact on middle member to north marks probable unconformity:
        Silty conglomeratic sandstone and conglomerate; fine to coarse grained with angular to subangular granule-, pebble-, and scattered small boulder-size rock fragments; grayish red (5R 4/2) to light blackish red (5R 3/2), in part weathering pale red (5R 6/2); weathered or altered rock fragments impart a pale-yellowish-orange (10YR 8/6) and very pale orange (10YR 8/2) mottling and streaking; a few thin sandstone lenses are free of conglomeratic material; sandstone is quartzose; where medium grained and locally uncoated by silt, grains display pyramidal crystal faces; intergranular silt abundant. Crude subparallel stratification on centimeter and decimeter intervals with beds increasing in thickness toward axis of syncline; in places; abundant angular rock fragments are suspended in a fine-grained matrix with no hint of internal stratification, suggesting mudflow deposition. Fragments consist of fine-grained and aphanitic yellowish (weathered) quartzite, in part possibly exotic to the Sixtymile Formation, and reddish sandstone fragments apparently derived from the Sixtymile. Thickness approximately same as sandstone facies _____   11(+)
      Sandstone facies:
        4. Sandstone and sandy siltstone, in part breccia-bearing, irregularly bedded, thin- to medium-bedded, lenticular.
          d. Siliceous, very fine grained silty sandstone, grayish-orange-pink (10R 8/2), faintly laminated, containing a few lenses of fine sand; resistant; forms ledge; slightly bleached and silicified beneath the Tapeats; 0.3 m thick.
          c. Siliceous siltstone and very fine grained sandstone; pale red (10R 6/2); thin bedded to laminated, containing very fine to medium grains and 1–10-mm-thick discontinuous depositional layers of white very fine grained to aphanatic quartzite that impart the general aspect of a breccia; 0.24 m thick; units 4c and 4b occupy a swale in unit 4a and pinch out 2 m south where unit 4d rests on unit 4a.
          b. Sandy siltstone, moderate-orange-pink (10R 7/4), thin-bedded and laminated; poorly sorted, containing fine- to coarse- and granule-size grains of white to grayish-orange-pink (10R 8/2) rock fragments probably derived from middle member; 0.33 m thick.
          a. Sandstone, quartzose, fine- to medium-grained; pale red (10R 6/2) weathering moderate red (5R 5/4); grains subangular to subrounded; moderately well to poorly sorted; well cemented; moderate intergranular silt. Resistant; forms ledge. Locally contains coarse to very coarse, rounded to angular grains and fragments of rock; angular white chert fragments probably are from middle member; rounded to subrounded grains of very fine grained gray quartzite may be exotic to Sixtymile Formation, as are sparse fresh to moderately altered mafic grains whose source may have been a crystalline terrane. 0.67 m thick at section measured, becoming 2 m thick 6 m to north where bed grades into conglomerate of conglomerate facies.
            (Thickness of unit 4 at measured section _____   1.5)
          About 5 m south of measured section, in an inaccessible face, 1.5 m of resistant irregularly bedded sandstone overlies unit 4d. The resistant sandstone was once exposed as a ledge against which beds of the Tapeats (unit 1 and lower part of unit 2) pinch out by onlap.
            Maximum thickness of unit 4 _____   3.0
        3. Siltstone and very fine grained silty sandstone, pale-reddish-brown (10R 5/4); very finely and irregularly laminated; massive weathering; in 2–3 m to the north and to the south grades abruptly into purplish sandstone similar to overlying sandstone of unit 4a; pinches out 7 m to north _____   2.0

TABLE 4   19

TABLE 4.—*Description of strata at type section of Sixtymile Formation, north fork of Sixtymile Canyon, (36°12'42"N., 111°50'45"W.), eastern Grand Canyon, Arizona—Continued*

Precambrian—Continued
    Chuar Group—Continued
        Sixtymile Formation—Continued
            Upper member—fluviatile sardstone and conglomerate—Continued
                Sandstone facies—Continued

2. Sandstone, very fine to fine-grained, quartzose; silty to locally clean with scattered angular to subrounded rock fragments ranging from very coarse grained to small boulder size; grayish red (10R 4/2-5R 4/2), locally pale reddish brown (10R 4/2), pale red (10R 6/2), and moderate orange pink (10R 7/4); subordinate lenses and flakes of very pale orange (10YR 8/2) siltstone; poorly sorted and crudely stratified with some lenses of well-sorted sandstone. Angular fragments of chalky white chert and silicified sandstone from middle member are conspicuous __   4.6

1. Sandstone, medium- to fine-grained, pale-red (10R 6/2) to grayish-red (5R 4/2), mottled and swirled moderate-orange-pink (10R 7/4), quartzose; grains subangular to subrounded; well sorted with subordinate intergranular silt; laminae and flakes of moderate-orange-pink (10R 7/4) siltstone common. Basal 0.5 m very fine grained siliceous fragmental sandstone, variably moderate red (5R 5/4) and grayish orange pink (10R 8/2), containing seams and fragments of whitish siliceous siltstone. Massive weathering; forms ledge. Bedding disrupted as a consequence of slumping toward axis of Chuar syncline where unit transects uppermost 1.5 m of beds of middle member. Disrupted stratification reflects youngest recognized increment of subsidence in syncline _____   2.8

        Thickness of upper member _____ 10.9–12.4(+)

Unconformity
Middle member—cherty quartzite:

1. Quartzite, very fine grained to silt-sized and aphanatic; pale red (10R 6/2) in lower 5–6 m and grayish orange pink (10R 8/2) mottled with pale red above; irregularly finely laminated and thin bedded with some medium-bedded layers. Abundant bedded chalky white chert begins about 5 m above base; hematite-rich beds about 15.5 and 20 m above base; breccia layer about 1 m thick 18.5 m above base contains angular clasts of sandstone of lower member and altered Kwagunt siltstone in disrupted matrix material of middle member. Resistant. Forms cliffs and ledges. Slumped on large and small scale toward axis of syncline, probably at time of disruption of overlying basal bed of upper member.

        Thickness of middle member _____   25

Unconformity
Lower member—sandstone and landslide breccia:

6. Siltstone, finely laminated to very thin bedded; pale red (5R 6/2); hematite-rich; comparatively soft, weathering to a slope where not protected by resistant middle member of Sixtymile Formation. About 1.2 m exposed on updip end, where it can be seen to overlie unit 5 and wedge out beneath middle member; concealed by talus toward axis of syncline; may be present in unvisited exposure in axis where unit could be 6 m or more thick _____   1.2–6(?)

5. Landslide breccia. Similar to unit 3; well cemented where dominantly monolithologic on south limb of syncline, containing angular fragments and matrix derived from unit 1; exotic detritus derived from Kwagunt Formation increases toward axis of syncline _____   9.1

4. Sandstone, fine- to coarse-grained with abundant hematitic intergranular silt; pale red (5R 4/2); poorly sorted and mostly crudely stratified; quartz grains angular to subrounded and dominantly amber; dark minerals sparse to locally abundant; upper ⅓ m in part thin bedded _____   1.5

3. Landslide breccia:
    Matrix: Sandstone, very fine to very coarse grained, pale-red to grayish-red (5R 6/2-5R 4/2), finely irregularly bedded to crudely stratified, contorted and slumped, moderately well cemented; material principally derived from units 1 and 2, but also contains grains derived from Kwagunt Formation _____   1.8–2.4

    Fragments; at line of section, west limb of syncline:
      a. Siltstone, very pale orange (10R 8/2); weathering grayish-orange (10YR 7/4); compact; laminated to thin bedded. Similar to altered siltstone described in unit 4 of Kwagunt Formation.
      b. Sandstone, quartzose, fine- to coarse-grained and silty; in part contains altered Kwagunt rock fragments and red sandstone of Sixtymile Formation; grayish orange pink (10R 7/4) and mottled grayish red (5R 4/2); mostly poorly sorted; in part displays irregular disrupted stratification; medium to coarse quartz grains are well rounded and frosted, not characteristic of underlying sandstone of the Sixtymile, and perhaps derived from the disintegration of sandstone exposed in an upraised fault block.
    Fragments; in axis of syncline at base of breccia, a and b are from large vertical blocks, and c is a breccia fragment:
      a. Dolomite and dolomitic limestone, very fine grained, yellowish-gray (5Y 8/1) to light-olive-gray (5Y 6/1); weathering pale yellowish brown (10YR 6/2) to pale brown (5YR 5/2); locally contains light-olive-gray chert; bed, 3-4 m thick and about 6 m high, possibly derived from one of brown-weathering carbonate beds of Walcott Member.
      b. Quartzite, very fine sand- to silt-size, white (N 9) to very pale orange (10YR 8/2); weathering light brown (5YR 6/4); well sorted and clean; finely porous; thin to medium-bedded; about 2 m thick and 3 m high. Exotic to Chuar Group. Source may have been Nankoweap Formation.
      c. Quartzite, cryptocrystalline to very fine grained, very pale orange (10YR 8/2); weathering grayish orange (10YR 7/4) to light brown (5YR 6/4); thin bedded and finely laminated. Silicified and altered shale or siltstone from Chuar Group.

2. Sandstone; directly underlies breccia and overlies altered shale of Walcott Member, west of axis of syncline:
    Sandstone, quartzose, silty and micaceous; fine to very fine grained with very sparse coarse-grained rock fragments; pale red (5R 6/2); white mica flakes are fresh and may have been derived from a newly exposed crystalline terrane; common to abundant opaque minerals; thin bedded; moderately

TABLE 4.—*Description of strata at type section of Sixtymile Formation, north fork of Sixtymile Canyon, (36°12'42"N., 111°50'45"W.), eastern Grand Canyon, Arizona*—Continued

Precambrian—Continued
    Chuar Group—Continued
        Sixtymile Formation—Continued
            Lower member—sandstone and landslide breccia—Continued
                Sandstone, quartzose, etc.—Continued

                    well sorted. Overlies altered or weathered material described under unit 4 of Walcott Member; alteration of underlying shale and presence of rock fragments and exotic minerals in the sandstone indicate an unconformity and deposition after unit 1 of lower member _____   1.5

Unconformity

1. Basal sandstone; preserved on west limb of syncline:

    Sandstone, quartzose, very fine grained; pale and moderate red (5R 6/2-5R 5/4), and moderate pink (5R 7/4) near top; weathers grayish red to dusty red (5R 4/2-5R 3/4); laminated to very thin bedded; well sorted, compact, and firmly cemented, with laminae displaying various amounts of intergranular hematite and subordinate clay; no exotic materials observed. Contact with Walcott Member is concealed over interval of 2 m or more but probably grades into transition beds equivalent to those described in unit 3 of Walcott Member. Unconformably overlain by breccia of unit 5 _____   6.4(+)

                Thickness of lower member _____   21.5–26.9(+)

                    Thickness of Sixtymile Formation _____   57–64(+)

Kwagunt Formation:
    Walcott Member:

    4. Altered (weathered?) shale. Underlies sandstone of unit 2 of lower member of Sixtymile Formation, west of axis of syncline.

        Siltstone and claystone, well-indurated; pale greenish yellow (10Y 8/2) with white flecks and seams and dusky-red (5R 3/4) very fine to coarse hematite grains; weathers grayish orange pink (5YR 7/2) to yellowish gray (5Y 8/1). Thin bedded, in part very finely laminated and in part appears fragmental. Forms slightly resistant ledges _____   ~1.5

    3. Unaltered transitional beds in axis of syncline.

        At base, shaly siltstone, light-olive-gray (5Y 6/1) to greenish-gray (5GY 6/1); gradational over about 10 cm with silty gray shale below; about 0.75 m above base grades upward into pale-red (5R 6/2) and grayish-red (5R 4/2) laminated and very thin bedded sandy siltstone that contains moderate intergranular clay and opaque minerals; red beds are similar to but slightly finer grained than basal sandstone (unit 1) of Sixtymile Formation. Forms slope. Separated from landslide (unit 3) of Sixtymile by slightly more resistant, 2–4-cm-thick interval of contorted compact siltstone that is mottled pale red (5R 6/2), grayish red (5R 4/2), grayish orange pink (10R 8/2), and dark yellowish orange (10YR 6/6). Contorted siltstone marks plane of landsliding _____   1.5

    2. Shale, medium- to dark-gray (N 3/5) and bluish-gray (5B 5/1); chippy weathering; forms slope ____   ~70

    1. Upper bed of pair of brown-weathering carbonate beds near small flat, southwest side of Chuar syncline. Limestone, dolomitic, fine-grained; light olive gray (5Y 6/1); weathering pale yellowish brown (10YR 6/2); locally fragmental ranging from coarse-grained rounded oolitelike grains to subangular fragments of gray dolomite and very sparse angular pebbles of tan siltstone; fragmental material in part silica cemented. Forms ledge _____   ~8