SEDIMENTOLOGY OF THE CUTOFF FORMATION (PERMIAN), WESTERN GUADALUPE MOUNTAINS, WEST TEXAS AND NEW MEXICO

by

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Sedimentology of the Cutoff Formation (Permian) Western Guadalupe Mountains, West Texas and New Mexico

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The Cutoff Formation records a complex history of basin facies deposition and erosion in latest Leonardian and earliest Guadalupian time. It is commonly 60 to 80 meters thick, and predominantly a fine-grained, dark, slightly argillaceous limestone, locally silty. The Cutoff strata exposed along the north-south trending western escarpment of the Guadalupe Mountains overlie a 3 kilometer wide shelf margin that had a depositional relief from shelf to basin of about 300 meters. This shelf margin faces the Delaware Basin to the south-southwest and was the site of erosion and deposition during Cutoff time.

Due to post-Cutoff, early Guadalupian erosion, the Cutoff strata occur in three discontinuous areas: shelf, shelf margin, and basin. Correlation from one area to another has long been problematical. In this study more certain correlation from shelf to basin was established by the recognition of five correlative units which occur within the Cutoff in an upward vertical succession: 1) black, medium bedded, laminated to non-laminated, cherty lime mudstone (generally absent along the shelf margin due to intraformational erosion); 2) dark gray to brown, very thinly

bedded, finely laminated, interbedded lime mudstone and shale; 3) dark gray, laminated to non-laminated, medium bedded lime mudstone in laterally continuous beds; 4) interbedded lime mudstone-shale; 5) dark gray, medium bedded, laminated to non-laminated lime mudstone, beds are laterally discontinuous. Northward across the shelf 10 kilometers at the type section (Cutoff Mountain), the middle three units lose their distinctiveness, and the upper limestone (Unit 5) grades into medium gray lime mudstone with a few thin wackestone layers.

Modern anoxic models (Byers, 1977) have not been previously applied to the Cutoff strata. The distribution pattern of rock types, laminations, and fauna (primarily brachiopods) indicate the Delaware Basin was an anoxic basin with a deep sill (about 400 meters depth) during deposition of the Cutoff strata. The basin environment was anaerobic (oxygen absent), and the shelf margin was dysaerobic (low oxygen) throughout Cutoff deposition. The shelf environment was initially dysaerobic but later aerobic (abundant oxygen), possibly by sediment accumulation raising the depositional surface. Based on the interpretations of the anoxic models, I infer an initial shelf depth of 65-85 meters for Cutoff deposition.

The lower and upper contacts of the Cutoff Formation are interpreted as submarine unconformities (Pray, 1971) which extend from shelf to basin. The surface between lower and upper Cutoff strata is another, possibly widespread submarine unconformity. The truncation along the upper unconformity causes the discontinuous distribution of the Cutoff strata along the shelf margin. The maximum truncation of underlying strata (300 meters) occurs along the shelf margin at the lower unconformity. This removal occurred by submarine erosion, apparently at a time of shelf subsidence. Steep, spoon-shaped "half-channels" (Pray, Crawford, Harris, and Kirkby, 1980) are enigmatic features along the unconformities which truncate at least 100 meters of strata at the shelf margin. These surfaces are generally oriented nearly parallel to the shelf edge.

Within the Cutoff are numerous, less persistent erosion surfaces. These are smaller, basinward-oriented channels ranging from broad (200-meter wide), flat-sided surfaces to narrow (10-meter wide), steep-sided features. Channel fills are generally intraclastic rudstone, megabreccias, and lutites, but skeletal rudstone and sandstone also occur. The clast lithologies suggest as their source both underlying units (Victorio Peak Formation and Bone Spring Limestone), and lithified Cutoff strata. The upper part of the shelf margin is believed to have been an area of episodic erosion throughout Cutoff time and may have been the source area.

The relationships of channel fillings and erosion surfaces indicate that Harms' (1974) model of basin sedimentation by density-driven interflows can be applied to deposition of the Cutoff strata.

The age of the upper Cutoff Formation is Guadalupian, based on fusulinids. I suggest that the lower Cutoff Formation may be Leonardian, based on the lack of Guadalupian fusulinids and the unconformity separating it from the upper Cutoff strata.

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INTRODUCTION

"Nature loves to hide."
Heraclitus

Purpose and Scope of the Project

This study is an investigation of the sedimentology of the Cutoff Formation of middle Permian age of the western Guadalupe Mountains of West Texas and New Mexico. Work concentrated in a 16 kilometer-long area which extends from shelf to basin. The transition from shelf to basin is abrupt and has a relief of 300 meters over a distance of about 3 kilometers. It occurs in the southern third of the study area. The Cutoff strata, consisting mostly of dark gray limestones and shales, has been the subject of much controversy. Wilde and Todd (1968) summarize the situation: "Perhaps no other rock unit in the Trans-Pecos region of Texas has attracted so much attention and controversy as the Cutoff Formation, yet it is one of the least imposing rock bodies in the region." The formation is well defined in the shelf area but basinward correlations have long been disputed. Generally fine-grained, the Cutoff was once termed the "Cutoff Shale" (King, 1965) but it is largely limestone, and also contains spectacular carbonate megabreccias. It also has abundant erosional features. Little was known about the distribution, abundance, and details of these sedimentologic and erosional features because of the lack of detailed study. Further, the precise age of the Cutoff was uncertain due to problems in understanding the Cutoff rather than lack of faunal evidence.

The most detailed observations prior to this study were those of the Marathon Oil Company Research Group (McDaniel, Pray, Harms and others) in the early and middle 1960's. They concentrated on the underlying strata but made major advances in understanding the Cutoff. Unfortunately this work was only published in incomplete form. This and further work by Pray has highlighted the need for further study.

The major research questions addressed here are:

1) What basin rocks correlate to the shelf Cutoff? How can this be proven?
2) Do the fine-grained rock types change from shelf to basin? If so, how, and why?
3) What is the distribution and origin of channel and scour phenomena?
4) What is the age of the Cutoff?

For this investigation a series of 14 stratigraphic sections of the Cutoff Formation was measured and described along the west escarpment of the Guadalupe Mountains along a trend nearly perpendicular to the strike of the shelf margin. The lithologic pattern established allows evaluations of previous correlations, environmental suggestions, and models of depositional processes.

Contributions of this Study

This study is a major contribution to the understanding of the depositional and erosional events in Cutoff time. It is to my knowledge, the first detailed study of the Cutoff Formation from shelf to basin. The major findings are outlined below and will be fully discussed in this report.

1) Recognition of a vertical succession of five lithologic units within the Cutoff Formation. These form a drape over the shelf, shelf margin, and basin. The fine-grained rock types are suspension deposits, probably in part from density interflows. The distribution and sequence of rock types are best explained with an anoxic basin model.
2) Confirmation of the previous correlation of Cutoff strata from the shelf to the basin, correlations which were first suggested by the Marathon group, and partially recognized by earlier workers.
3) A detailed analysis of channel fillings and distribution of scour features within the Cutoff Formation.
4) Confirmation of upper and lower contacts as submarine unconformities (Pray, 1971) which slope basinwards 5-10° at the shelf margin.
5) Clarification of the stratigraphy, indicating that most

of the Cutoff is of Guadalupian age, as previously suggested by Wilde (Wilde and Todd, 1968) based upon his study of the sparse fusulinids. The lower Cutoff Formation is considered to be of Late Leonardian age.

Field Area

Location

The Guadalupe Mountains are carved from an uplifted block of Permian rock located at the northwest end of the Delaware Basin, and the adjacent Northwestern Shelf (Fig. 1). They form a broad V-shaped range opening to the north. The west escarpment exposures studied extend for 16 kilometers southward from the New Mexico-Texas line. These exposures trend at an oblique angle across the basin edge (Fig. 2).

Accessibility

The west escarpment study area is located within the Guadalupe Mountains National Park. Most of the area can be reached on game trails from the Williams Ranch site (Fig. 3). High clearance vehicles are required to reach this site. The nearest city, Carlsbad, New Mexico, is 112 kilometers away by paved and dirt roads. The Cutoff Mountain section can best be reached by private ranch roads (permission required) from Dell City, Texas, followed by 3.2 kilometers of cross-country hiking (see appendix 1 for road log to Cutoff Mountain.

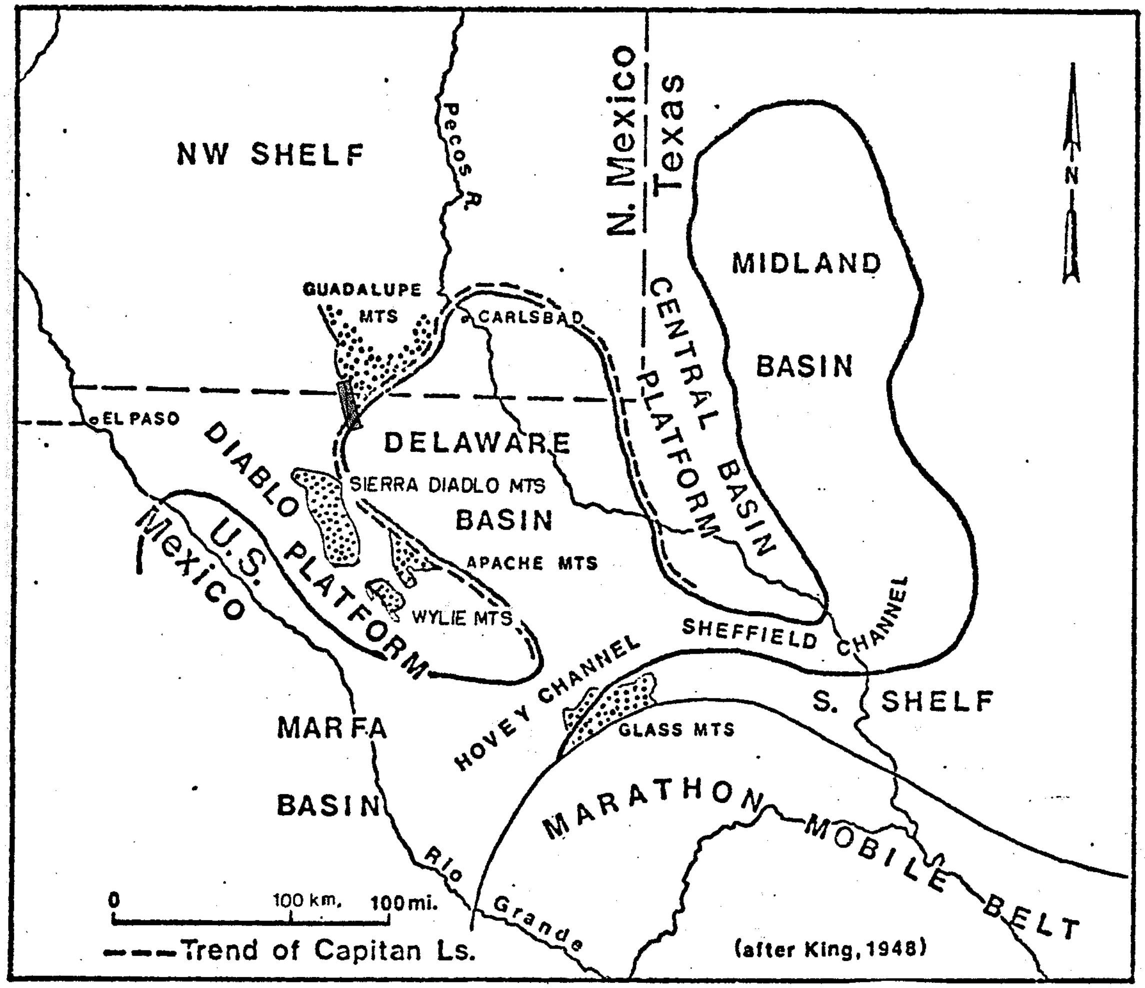


Figure 1: Permian Basin complex, West Texas & New Mexico. Mountain ranges mentioned in the text are shaded. Study area is shown in red.

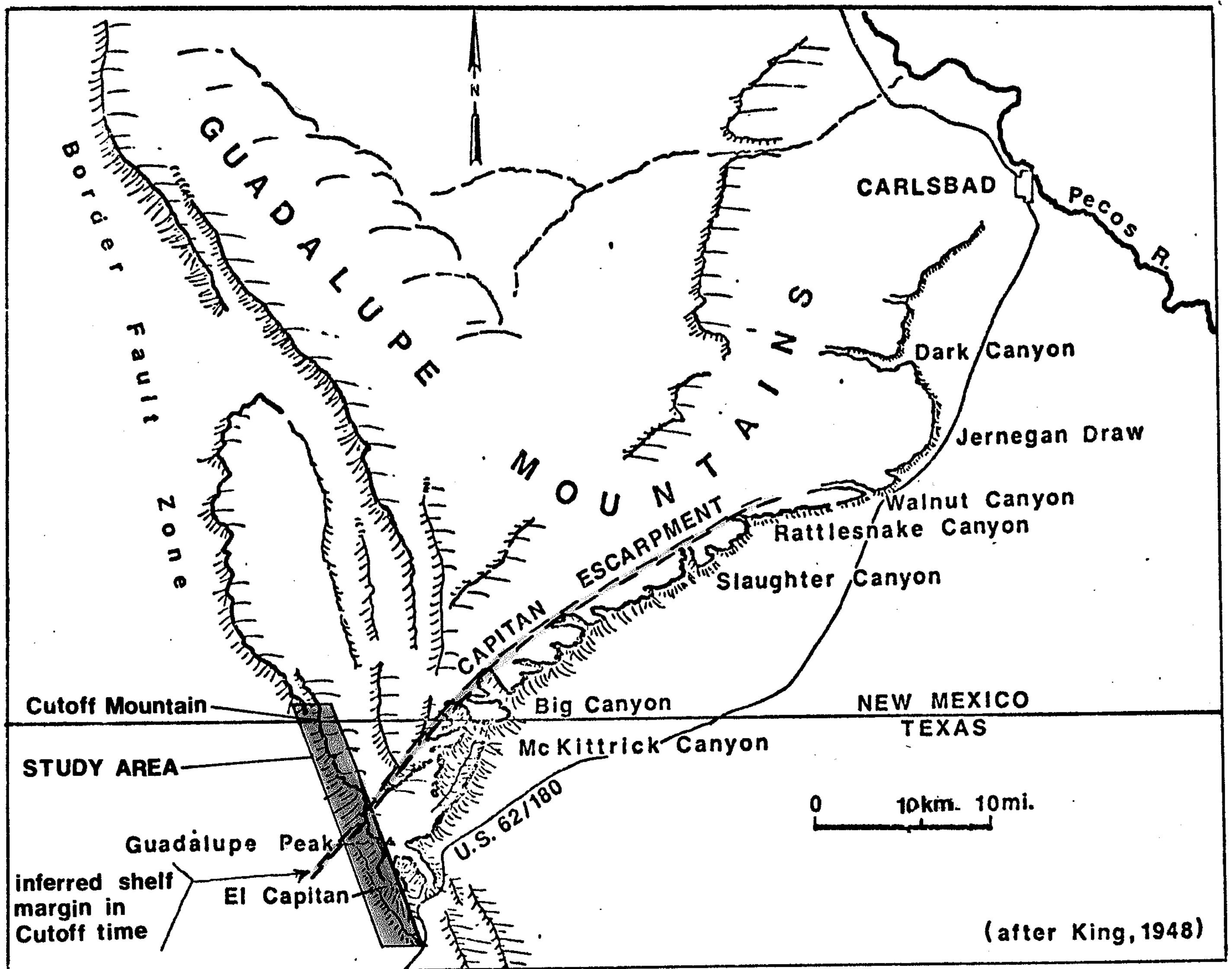


Figure 2: Location of the study area, Guadalupe Mountains

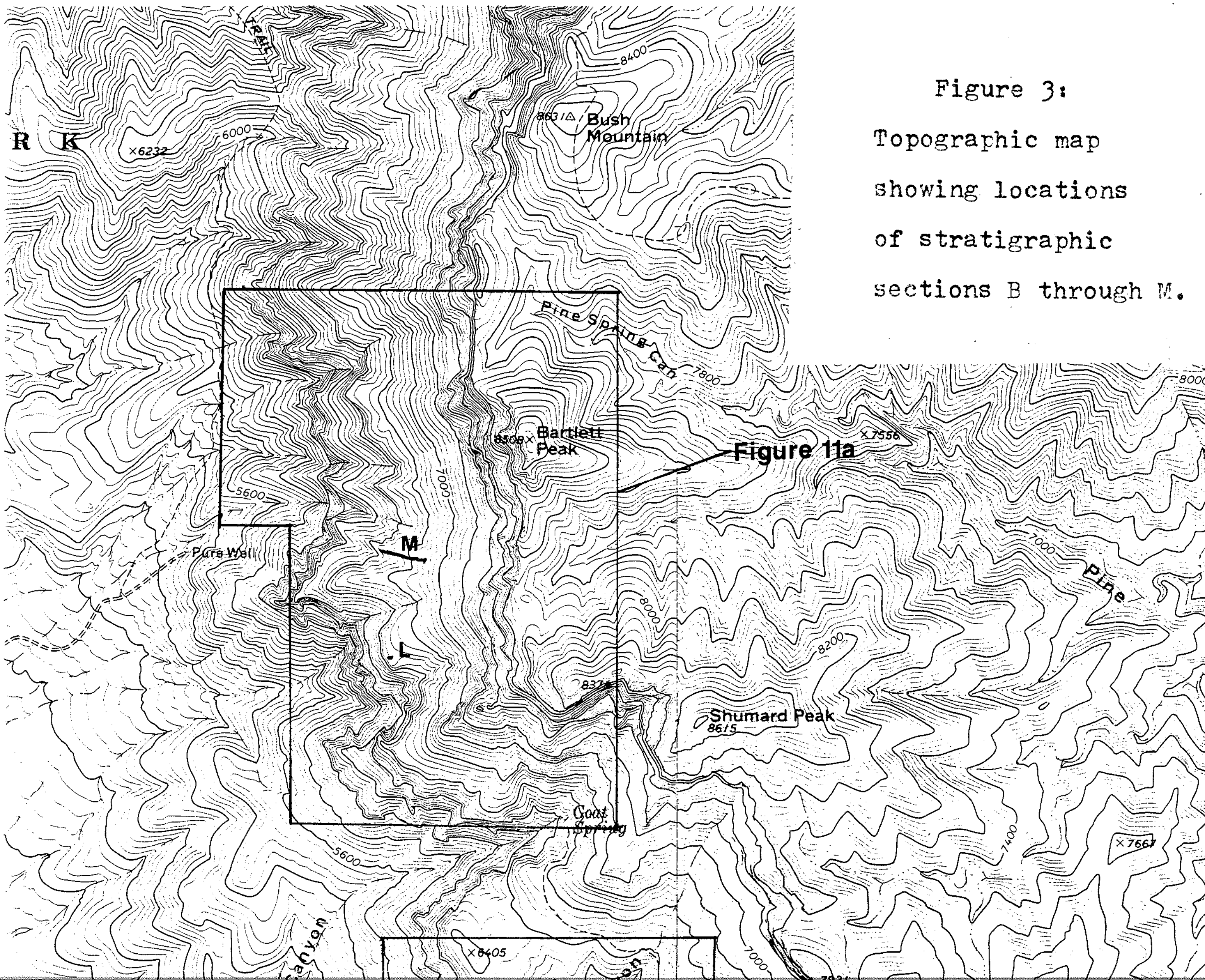


Figure 3:
Topographic map
showing locations
of stratigraphic
sections B through M.

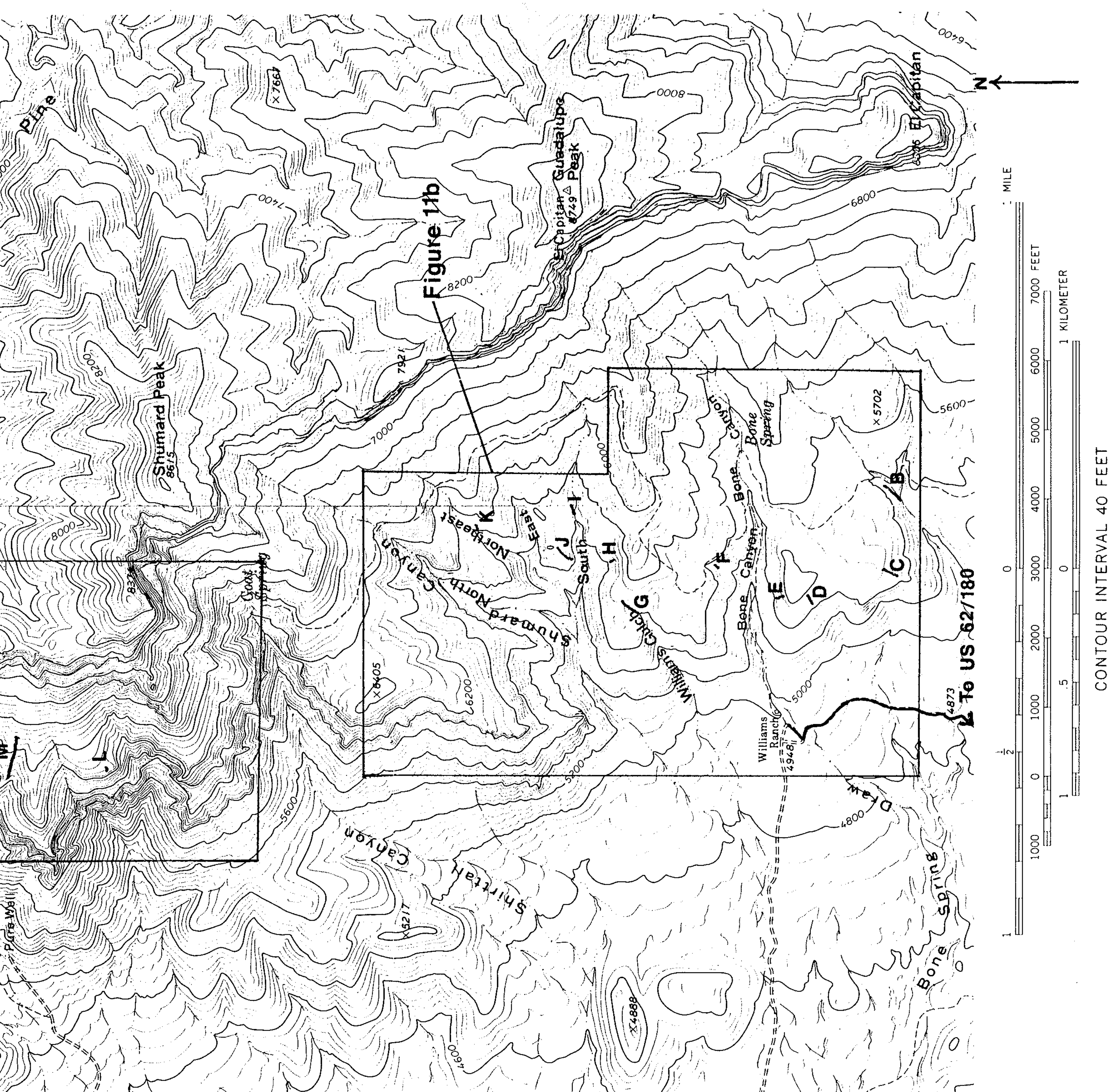


Figure 11b
Shumard Peak
8615
El Capitan
Guadalupe Peak
8749
El Capitan
Pine
Goat Spring
Shumard North Canyon
Northeast
East
South
Williams Gulch
Bone Canyon
Bone Spring
Williams Ranch
4948
To US 62/180
Shirttail Canyon
Bone Spring
Draw
N
MILE
FEET
1 KILOMETER
CONTOUR INTERVAL 40 FEET

Geography

The west escarpment is the surface expression of the Border Fault Zone (King, 1948). The escarpment rises from about 1400 meters to a maximum elevation of 2667 meters at Guadalupe Peak. The Salt Flats, a playa, are to the west about 10 kilometers at an elevation of 1100 meters. The study area is characterized by steep to vertical slopes between the elevations of 1525 and 2135 meters. The major peaks and canyons mentioned in this report are indicated in figure 3. The Cutoff Formation outcrops are in the lower 500 meters of the escarpment.

The climate is semi-arid. No running water is available in the study area. Vegetation is that of the Chiluahuan Desert. Prior to the 1940's the area was used for livestock grazing but overgrazing resulted in the present greasewood-lecheguilla flora. Areas within the National Park are slowly beginning to return to their original condition.

Structural Setting

The Guadalupe Mountains are a gently tilted, east-northeasterly dipping fault block bounded on the west by a zone of Cenozoic age high-angle normal faults. This zone is the Border Fault Zone, named by King (1948). It has an offset of approximately 1200-1500 meters, downthrown to the west. This fault zone trends north-northwest to south-southeast, slicing across the shelf margin at an oblique high-angle. Leonardian and Guadalupian rocks are well exposed along the scarp east of the fault zone. The strata have been but little deformed by faulting making them well suited to this study.

Field work and laboratory methods

The author was first introduced to the Guadalupe Mountains during a field trip in early November, 1978 with a group from the University of Wisconsin-Madison led by Dr. Lloyd Pray. The summer of 1979 and three weeks of January, 1980 were spent along the west escarpment doing field work. During this time 14 stratigraphic sections (plates 1-14) totalling 481 meters were described and plotted with accessory curves using Brunton compass, tape, and eye-leveling techniques. (Symbols and accesory curves are explained in appendix 2.) Generally stratigraphic sections were located along gullies and steep canyon walls for maximum exposure. Lateral correlations were walked out where feasible and photo mosaics of canyon walls were made to portray lithologic relationships. A geologic map (Fig. 4) along the trend of the Cutoff outcrop was constructed on a 1:12,000 scale topographic base map.

Representative samples of the rock types in the Cutoff were examined in Madison to check field descriptions. Polished slabs (100), thin sections (100) and insouble

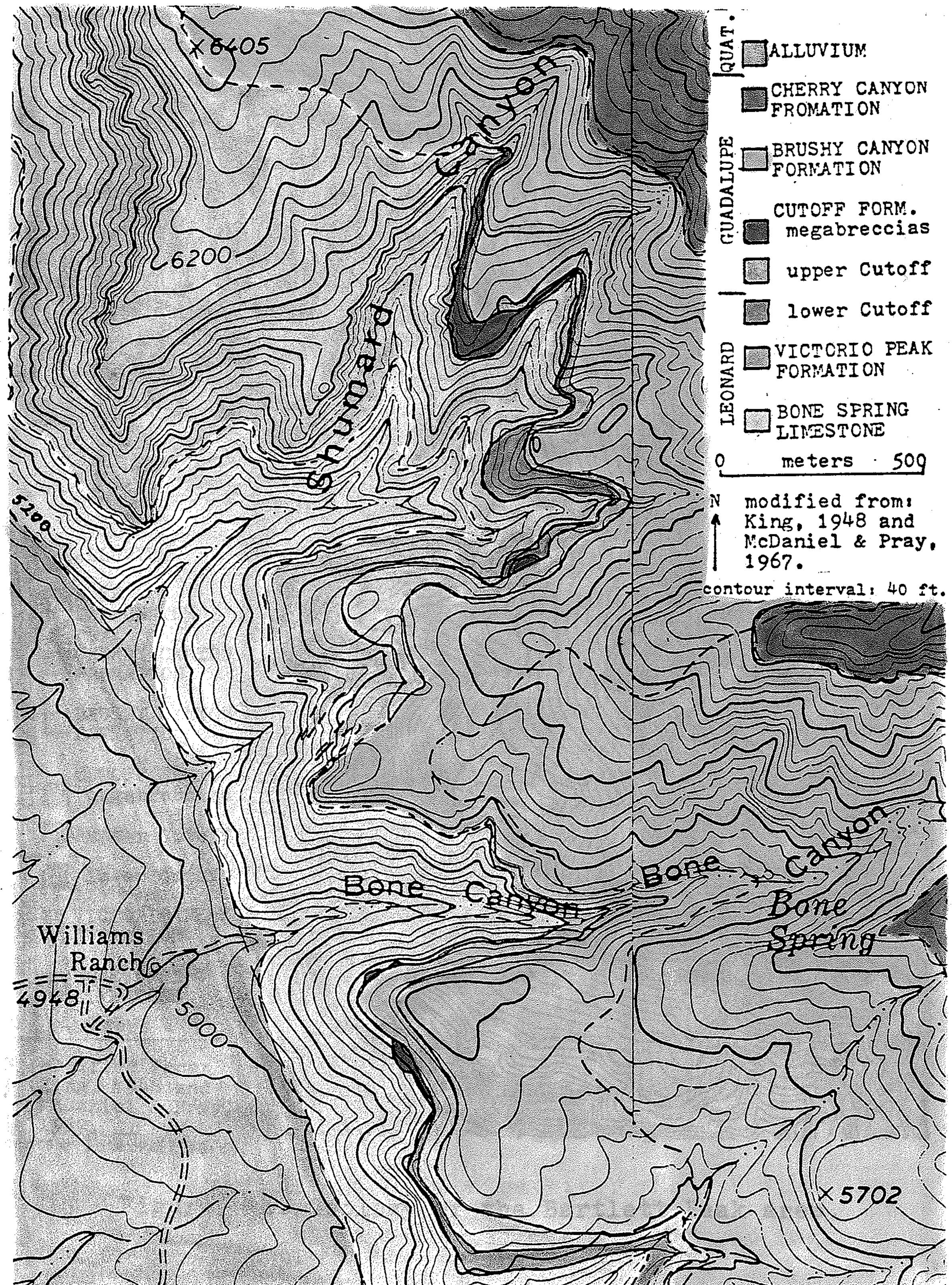


Figure 4a: Geology of the Bone Canyon-Shumard Canyon area.

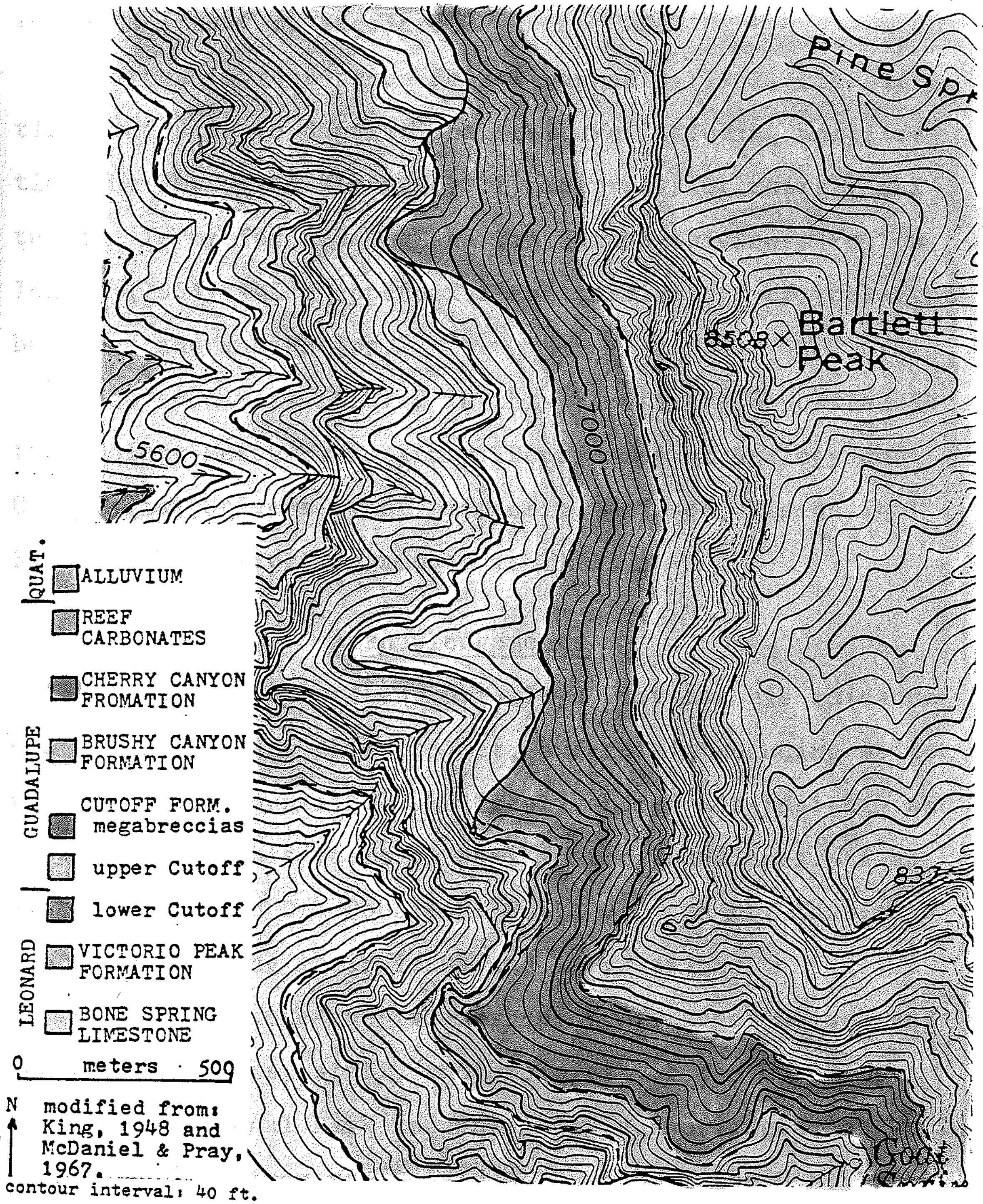


Figure 4b: Geology of the Bartlett Peak area.

residues (25) were examined.

Carbonate rock names follow Dunham's (1962) classification according to depositional texture including modifications by Embry and Klovan (1971) for rocks of coarser textures. Terms for bedding and lamination thickness follow Ingram (1954). See appendix 3 for terminology of rock types, bedding, and lamination.

The specimens figured in this report are deposited in the Geology Museum repository, Department of Geology and Geophysics, University of Wisconsin, Madison, Wisconsin 53706. The collection number is UW 1719.

Acknowledgements

I would like to thank Dr. Lloyd Pray for his guidance and support during this project, and for introducing me to the Guadalupe Mountains. He freely shared his insights and knowledge from his years of work in the Guadalupes. I am also grateful to Dr. Robert H. Dott, Jr. and Dr. Charles W. Byers for sharing their ideas and speculations.

The assistance and friendship of Mr. Roger Reisch and the other rangers, staff, and employees of the Guadalupe Mountains National Park is gratefully acknowledged, as well as cooperation from Mr. Donald A. Dayton of the U.S. Park Service who provided collection permits. Mrs. Bertha Glover is to be thanked for providing a friendly ear and refuge during storms. Mr. Ed Hammond and Mr. Windy Lewis kindly granted permission to cross their ranches for access to northern portions of the study area.

Financial support of the fieldwork by the New Mexico Bureau of Mines and Mineral Resources, Dr. Frank E. Kottlowski, Director, is acknowledged with gratitude.

University of Wisconsin graduate students who especially helped this project through lively discussions and different perspectives are: G. Allen Crawford, Marie Frank Smith, and Robert Goldstein.

Finally, I must thank my wife Nancy for her patience and encouragement.

STRATIGRAPHY

'The world is the geologist's great puzzle box.'
Agassiz

At the surface in the Guadalupe Mountains (Fig. 5) the Cutoff Formation unconformably overlies the Leonardian-age Bone Spring Limestone and Victorio Peak Formation, and is in turn overlain by the sandstones of the Brushy and Cherry Canyon Formations of the Delaware Mountain Group (King, 1948). Laterally the Cutoff grades shelfward into the lower San Andres Formation (Boyd, 1958), and basinward the Cutoff disappears from view into the subsurface of the Delaware Basin. In the subsurface the Cutoff strata can be tentatively traced throughout the Delaware Basin but may be confused with a basal shale in the Brushy Canyon Formation (Wilde and Todd, 1968). Other regional surface correlations will be discussed below.

The Cutoff strata of the shelf area are consistently 60 to 80 meters thick and composed of lime mudstone and siliceous shales. Shelfward these grade into the lower San Andres Formation through a transition zone 19 to 23 kilometers north of the shelf break (Boyd, 1958). Field relations north of Bone Canyon indicate the Cutoff was deposited across 300 meters of depositional relief at the 3.2 kilometer wide shelf margin (McDaniel and Pray, 1967). At this shelf margin post-Cutoff erosion has thinned the Cutoff

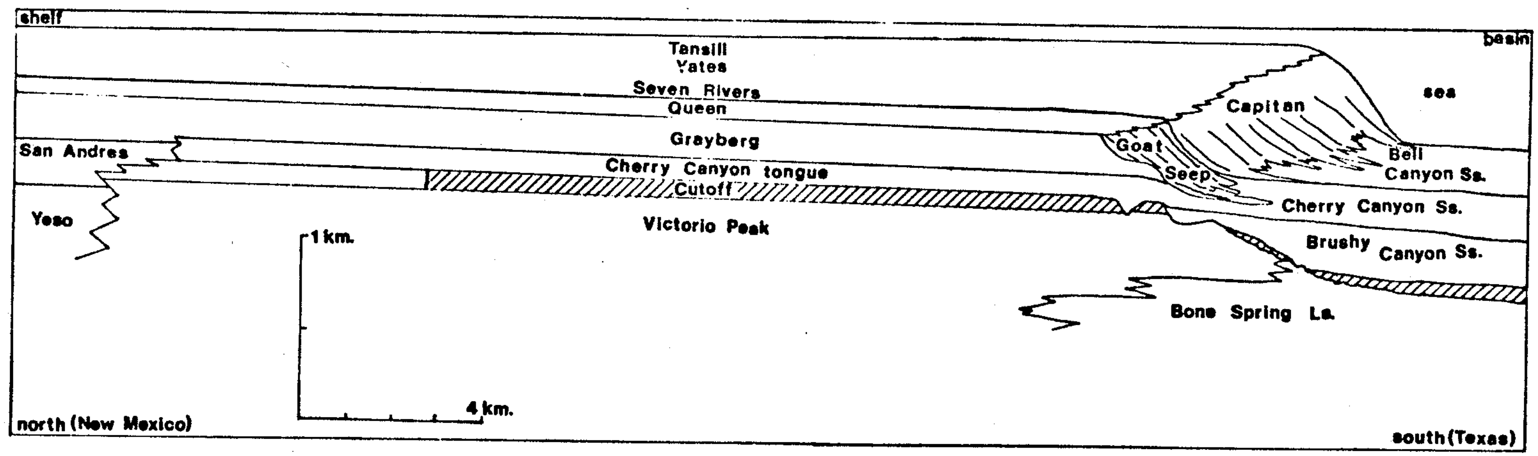


Figure 5: Cross section through the Guadalupe Mountains at the end of Guadalupian time. Strata studied in this report are shaded. Modified from Boyd, 1958.

strata to a maximum preserved thickness of 46 meters and locally removed all of it. The formation is here composed of lime mudstone, siliceous shale, and minor breccia lenses. The Cutoff strata of the basin are of the same lithologies as at the shelf margin, but thicken to an estimated 110 meters at a distance of 2 kilometers south of the toe of the slope.

Lower and upper Cutoff Formation

This study divides the Cutoff Formation into lower and upper Cutoff. This terminology is derived from King's (1948) recognition of a "lower unit of the Cutoff" in the shelf margin area (Shumard Canyon). This study laterally extends the lower Cutoff to include strata of the shelf and basin. This correlation is based on lithologic similarity to the distinctive lithology of the lower Cutoff (black, cherty lime mudstone) and on the occurrence of a pre-Cutoff unconformity which cuts into the Bone Spring Limestone and Victorio Peak Formation. The lower Cutoff's upper surface is a major intraformational unconformity. The upper Cutoff forms 80-90% of the Cutoff Formation, and overlies the lower Cutoff and Victorio Peak Formation.

Lower Cutoff Formation

The lower Cutoff Formation is composed of black, cherty lime mudstone with minor (<5%) amounts of other lithologies restricted to channel fillings. Within the Cutoff

Formation the black, cherty mudstone is restricted to the lower Cutoff strata. The rock types are described in the sections on rock types. Because the extent of the lower Cutoff strata has not been previously recognized, it is discussed below.

On the shelf the lower Cutoff thins from 3 meters at Cutoff Mountain (section N) to a pinchout 8-8½ kilometers to the south between Bush Mountain and Bartlett Peak. Where well exposed at Cutoff Mountain, the upper surface of the cherty mudstone is undulatory due to a low-angle truncation surface. In sporadic exposures the thickness of the mudstone varies between 1 to 3 meters, because of the differential erosion along the undulatory surface. The disappearance of the cherty mudstone southwards on the shelf may also be related to this erosion surface.

In the shelf margin area the cherty mudstone is only recognized in Shumard Canyon (section J) where it occupies a 30 meter deep channel cut into the underlying Victorio Peak Formation. This channel fill was first recognized by King (1948) who separated this lens from the rest of the Cutoff, terming it the "lower unit of the Cutoff". The cherty mudstone which fills this channel has been sharply truncated by a smooth erosion surface, probably correlative with the undulatory surface on the shelf.

In the basin the cherty mudstone reappears south of

Bone Canyon (sections A, B, and C) as a basinward thickening wedge with a smoothly truncated upper contact. This equivalent of King's lower unit of the shelf margin has not been previously recognized, probably because it is lithologically very similar to the underlying Bone Spring Limestone. However, Lloyd Pray and I were able to unambiguously follow the Bone Spring-Lower Cutoff contact for 0.4 to 0.8 kilometers south of Bone Canyon (and I traced it with less certainty another 0.8 to 1.5 kilometers farther south) where at the base of the escarpment, it disappears from view into the subsurface.

The contact between the Bone Spring Limestone and lower Cutoff is placed at the unconformity at the base of the Cutoff. Similarly the upper surface of the cherty mudstone is an unconformity. This intraformational unconformity is sharp. It truncates bedding (Fig. 13) and has reduced the distribution of the black, cherty mudstone to its present abbreviated extent. The cherty mudstone is inferred to have originally covered the entire shelf, shelf margin, and basin area studied prior to this erosional episode. These unconformity surfaces serve to bound the lower Cutoff (which includes the cherty mudstone and minor associated rock types).

<u>Upper Cutoff Formation</u>

The upper Cutoff strata of the shelf area are consistently 60 to 80 meters thick and composed of lime mudstone and siliceous shale. At the shelf edge these strata are abruptly truncated by a post-Cutoff erosional surface. In the shelf margin area the upper Cutoff consists of lime mudstone, siliceous shale, and minor (<5%) breccia lenses, and has a maximum thickness of about 50 meters. These strata are also truncated by a post-Cutoff erosion surface. The upper Cutoff strata of the basin are of the same lithologies as at the shelf margin but thicken to an estimated thickness of 110 meters at a distance of 2 kilometers south of the toe of slope in Bone Canyon. The upper surface of the Cutoff strata in the basin is truncated by a very low angle (1-5°) undulatory surface. This post-Cutoff erosional surface is probably correlative to the surface which truncates the upper Cutoff strata of the shelf margin. The strata generally thickens basinward (to the south) below the surface as it disappears into the subsurface. The distribution of the Upper Cutoff Formation is more fully discussed below after discussion of its lithologies.

Previous Work

Evolution of a stratigraphic framework (1904-1948)

The term "Cutoff" was first used by King (1942) for rock bodies in the Guadalupe and Sierra Diablo Mountains. This recognition was the final step of 40 years of finer and finer subdivisions of the Permian rocks of the Delaware

Basin region (Fig. 6). The process began with Richardson's (1904) simple column and culminated in King's masterful synthesis (1948) which firmly established a detailed stratigraphy.

King's original description (1942) of the Cutoff is as follows:

> "At the north end of the Sierra Diablo, east of Sierra Prieta, the Victorio Peak gray member is separated from the overlying sandstone tongue of the Cherry Canyon formation (Delaware Mountain group) by several hundred feet of buff, dove-gray, to black, thin-bedded limestones and siliceous shales. The limestone weathers characteristicly into angular, hackly fragments. The beds are termed the Cutoff shaley member of the Bone Spring Limestone... A characteristic exposure is found near the Texas-New Mexico line on the west face of Cutoff Mountain, from which it is named."

A generalized type section and its precise location were included in King (1948).

King noted many features central to this author's interpretations. He recognized the unconformable nature of the upper contact: "The Cutoff member is assigned to the Bone Spring limestone because 2 miles north of Bone Spring, the beds are truncated and overlain unconformably by the Delaware Mountain Group" (King, 1942). The unconformable, channeled nature of the lower contact (including a deep channel cut into the underlying Victorio Peak) was also recognized (King, 1948). The erosional events and stratigraphic relationships at the shelf margin, combined with

Figure 6: Evolution of stratigraphic terminology

Richardson, 1904		Blanchard & Davis, 1929		King, 1934		King, 1942; 1948		
DELAWARE MOUNTAIN FORMATION	dark ls. member	DELAWARE MOUNTAIN FORMATION (part)	Delaware Mountain Sands	DELAWARE MOUNTAIN GROUP (part)	dark ls. member	DELAWARE MOUNTAIN GROUP (part)	Cherry Canyon Fm.	Goat Seep Ls.
	sandstone member				sandstone member			Cherry Canyon Ss. tongue
							Brushy Canyon Fm.	hiatus
	black ls. member	BONE SPRING LIMESTONE		BONE SPRING LIMESTONE	gray member	BONE SPRING LIMESTONE	Cutoff shaley member	
							Victorio Peak gray member	
					black ls. member		black ls. member	
HUECO LIMESTONE		HUECO LIMESTONE		HUECO LIMESTONE		HUECO LIMESTONE		

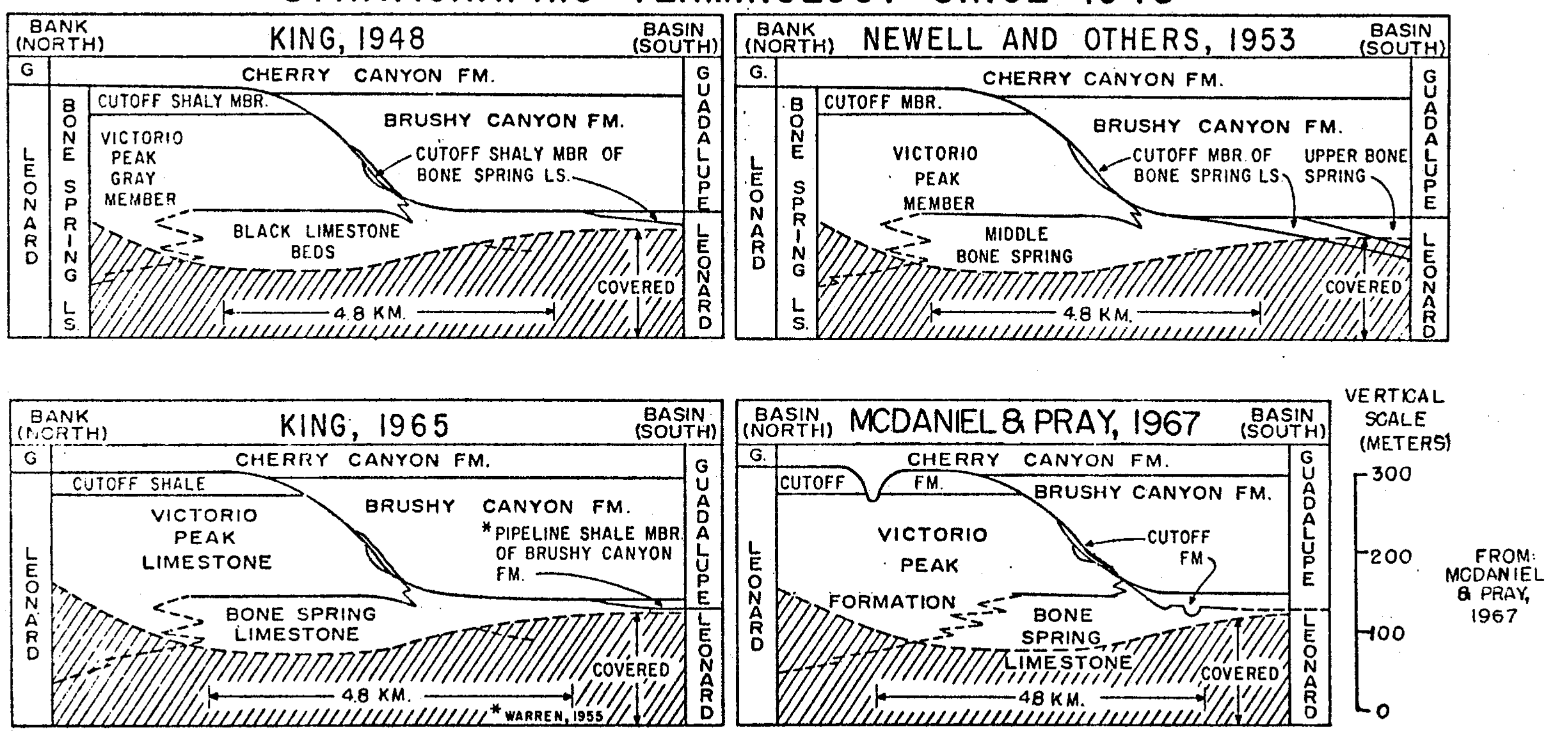
some disruption of the bedding by the Cenozoic faulting, led King (1948) to postulate the existence of a "Bone Spring flexure". This flexure was believed to be parallel to the basin edge (southwest-northeast), cross-cutting the escarpment north of Bone Canyon. South of this flexure, King's correlations of the Cutoff into the basin were tentative due to removal of the Cutoff strata along the flexure by post-Cutoff erosion. An upper member of the Bone Spring Limestone composed of shale, sandstone, and thin limestones (with conglomerate blocks in the lower 8 meters) was tentatively correlated to the shelf Cutoff. The shale at the top of this sequence as exposed 5 kilometers to the south, was termed the "Pipeline Shale" by Warren (1955).

Disputes, debates, and reinterpretations (1953-1970's)

The Newell group (1953) worked on the stratigraphic details and the paleoecology of the entire Permian Reef Complex. Newell studied the Bone Spring, Victorio Peak, and the Cutoff Formation in the west escarpment area. He correlated the shelf Cutoff strata with the lower part of King's suggested basin correlatives plus some of the underlying beds (Fig. 7). The bulk of the Cutoff equivalent was considered to be a shale below the Pipeline Shale, while the Pipeline Shale was placed in the Brushy Canyon Formation. Newell interpreted lenses of light colored limestone within the Cutoff strata along the lower contact at the Bone Spring

Figure 7:

STRATIGRAPHIC TERMINOLOGY SINCE 1948



flexure to be patch reefs.

The Marathon group added significant observations and interpretations. Pray and Stehli (1963) re-interpreted the "patch reefs" to be channel lenses of megabreccia, allochthonous carbonate blocks redeposited from their original site of deposition. This is now generally accepted. McDaniel and Pray (1967) did a detailed study of the Bone Spring-Victorio Peak strata underlying the Cutoff, as discussed below. In the Cutoff they recognized channel forms, erosional surfaces, and suggested basin equivalents. Pray (1971) and Harms and Pray (1972) interpreted the upper and lower Cutoff contacts along the shelf margin as submarine basin-dipping unconformities. They inferred these were due to bank margin retreat by erosional processes. This interpretation removed the need for King's Bone Spring flexure to explain the stratigraphic relationships in the area of the bank edge.

The dark color, fine grain size, and depositional relief of the Cutoff Formation have led workers (King, 1948; Newell et al., 1953; Warren, 1955; Boyd, 1958) to conclude it was deposited in deep, anoxic waters that transgressed northward onto the Northwestern shelf over the Victorio Peak shallow water deposits. Two questions repeatedly discussed (cf. Wilde and Todd, 1968) are the shelf to basin correlation and the age of the Cutoff. There are problems correlating the Cutoff over the entire area from the northern Guadalupe Mountains southward to the Apache Mountains (Fig. 1). Correlative units to the southern Guadalupe Mountain section have been reported in the northern Guadalupe Mountains (Hayes, 1959; 1964), Apache Mountains (Wood, 1968), Sierra Diablo Mountains (King, 1965), and Wylie Mountains (Hay-Roe, 1957). The age of the Cutoff has been in dispute because it is at or near the boundary of the Leonardian and Guadalupian stages. The Cutoff strata has been reported to contain both Leonardian ammonites and Guadalupian fusulininds (Wilde and Todd, 1968). The unrecognized allochthonous nature of many early fossil collections has created confusion in the past (Wilde and Todd, 1968).

The Cutoff was raised from member to formational status by King (1965), who used the term "Cutoff Shale". This term was used because fissile limestone and shale make up about one-half to two-thirds of the Cutoff strata. Wilde (Wilde and Todd, 1968) recognized the predominance of limestone in the Apache Mountains and informally used the term "Cutoff Formation". Because of this, and in view of the lithologic variation, I am using the term "Cutoff Formation" as the formal name for the unit in this report.

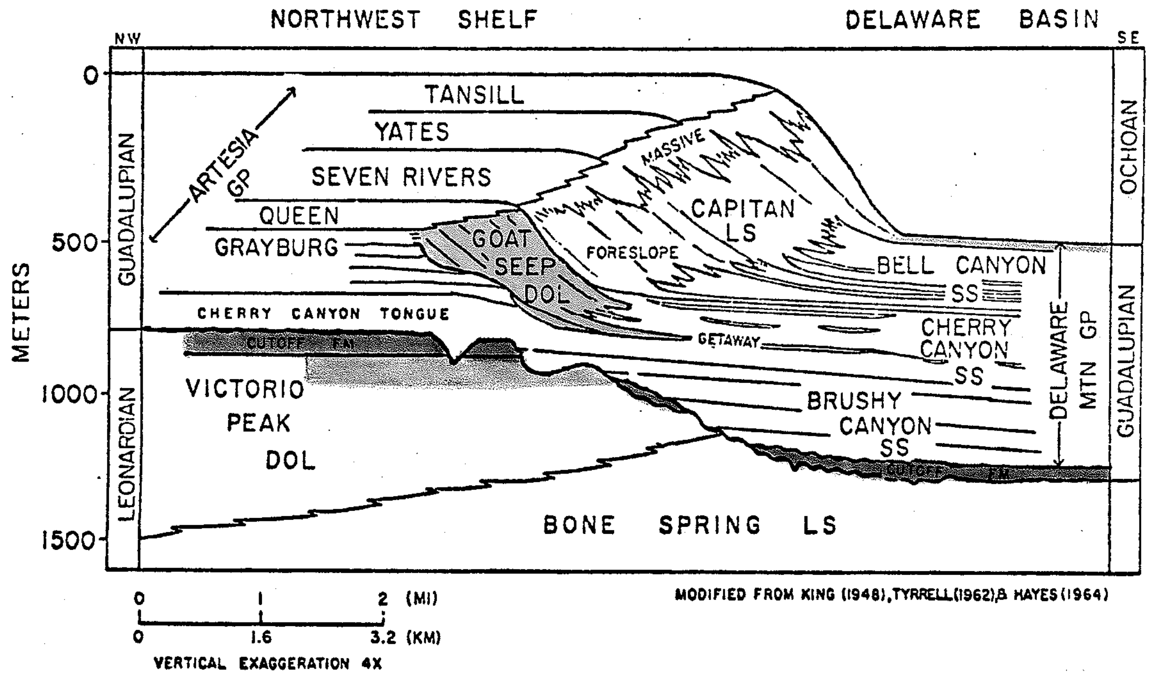
This thesis is one part of an overall research program on the Permian Reef Complex by the University of Wisconsin-

Madison under the direction of Dr. Pray. Works relavent to this study are shown in figure 8: Crawford (in progress), Kirkby (in progress), and L. Babcock (1974). Additional thesis work on the Guadalupian strata was published in Hileman and Mazzulo (1977) and Pray and Esteban (1977).

Kent Kirkby's current master's work is very relevent to this report. He is studying the lithologies, diagenesis, and erosion surfaces of the upper Victorio Peak Formation of the Guadalupe Mountains in the same area as this report. The geologic events during and following deposition of the Victorio Peak Formation may be useful in understanding the Cutoff Formation. The rock types may reflect a transition into the Cutoff depositional environment. The diagenesis study may provide an independent determination of the environment of the Cutoff-Victorio Peak unconformity.

Leonardian bank-basin sequence

The units beneath the Cutoff Formation, the Bone Spring Limestone and the Victorio Peak Formation, occur throughout the West Texas-Southeast New Mexico region. They comprise a Leonardian carbonate bank and basin sequence (McDaniel and Pray, 1967). Typically the Bone Spring Limestone is a finely laminated, medium bedded, black, cherty mudstone. It has been interpreted as an anoxic (or euxinic) basin deposit (Lloyd, 1929; Newell *et al*., 1953; McDaniel and Pray, 1967). The Victorio Peak Formation is an unlaminated, thickly



STRATIGRAPHIC DIAGRAM GUADALUPE MOUNTAINS

UNIVERSITY OF WISCONSIN
CARBONATE RESEARCH GROUP

Figure 8: Stratigraphic Diagram of the Guadalupe Mountains by the University of Wisconsin Carbonate Research Group. Recent thesis work of particular pertinence to this study are highlighted: blue= L. Babcock (1974), yellow= Crawford (in progress), green= Kirkby (in progress), red= this study.

bedded, gray dolomite and limestone with a texture ranging from wackestone to grainstone. It has been interpreted as a normal marine bank and bank margin deposit (Newell *et al.*, 1953; McDaniel and Pray, 1967). The depositional slope is inferred to have been low. McDaniel and Pray (1967) suggested an angle of 1-5°. The sharp transition from bank to basin occurs over a distance of 0.8 to 1.6 kilometers just north of Bone Canyon, as first noted by King (1948) and detailed by McDaniel and Pray (1967). Both these Leonardian units contain scour phenomena, channel lenses, and erosional surfaces (King, 1942; 1948; McDaniel and Pray, 1967; Pray, 1971; Harms and Pray, 1974) similar to those to be described in the Cutoff.

Cutoff shelf profile

Following deposition of the Leonardian bank-basin sequence (Victorio Peak-Bone Spring) an erosional episode steepened the slope along the bank edge in the Guadalupe Mountains region (Pray, 1971). The erosional surface is a sharp, basin-sloping unconformity above the Leonardian bank margin. The resulting surface had three topographic areas (Fig. 9): a flat to very slightly sloping shelf (0^o - 1^o), a more steeply dipping shelf margin (5^o - 15^o), and a low relief basin surface which flattens out to a low angle (5^o to $<1^o$). This profile persisted throughout Cutoff deposition. The relief at the shelf margin was 300 meters

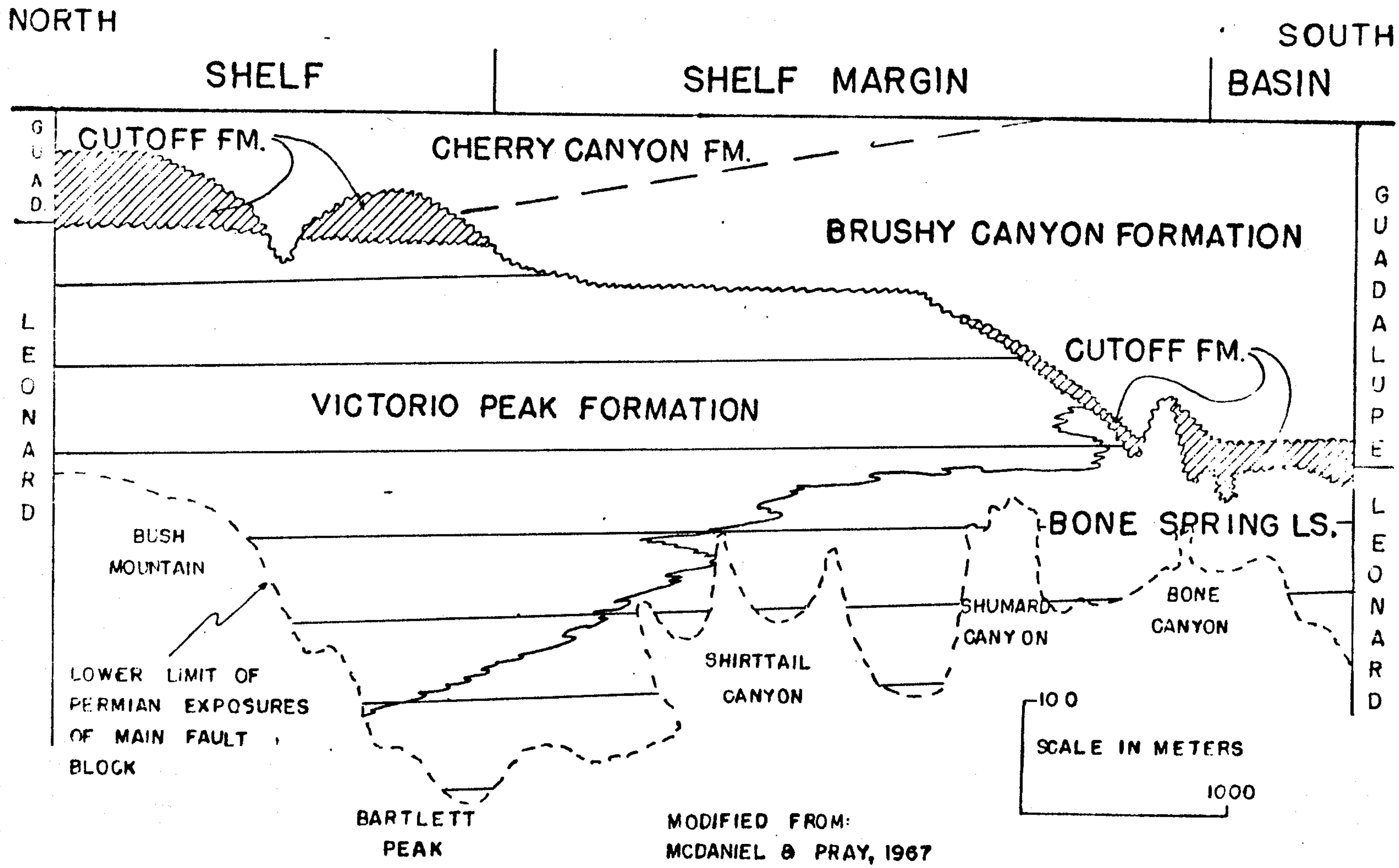


Figure 9: Cross section of the bank to basin transition area.

over a distance of 3.2 kilometers in the area of the present Shumard and Bone Canyons. This relief was established by field tracing of the Bone Spring - Victorio Peak strata by McDaniel and Pray (1967).

Projections of the Leonardian bank profile from the highest (youngest) preserved strata indicate truncation of 250 meters of strata along the basin-sloping unconformity, whose cutting involved shelfward retreat of the bank edge (Pray, 1971; Harms and Pray, 1974). The unconformity extends both shelfward and basinward at a very low angle, as indicated by the minor truncation of the underlying strata in both the shelf and basin areas.

Regional correlations and implications

The shelf Cutoff or its equivalent is preserved above the Victorio Peak in four ranges of West Texas (Wilde and Todd, 1968), namely the Guadalupe, Sierra Diablo, Apache, and Wylie Mountains (Fig. 10). Correlations of these shelf sections are shown in figure 11. In contrast, the Cutoff of the shelf margin and basin areas only is exposed at the surface in the Guadalupe Mountains due to the ravages of tectonics and erosion.

The Cutoff shelf strata in both the Guadalupa and Sierra Diablo Mountains all have a distinct basinal aspect and are similar lithologically (King, 1948; 1965; this study). Dark, fine-grained limestone and siliceous shales

Figure 10:

Distribution of surface exposures of the Cutoff Formation.

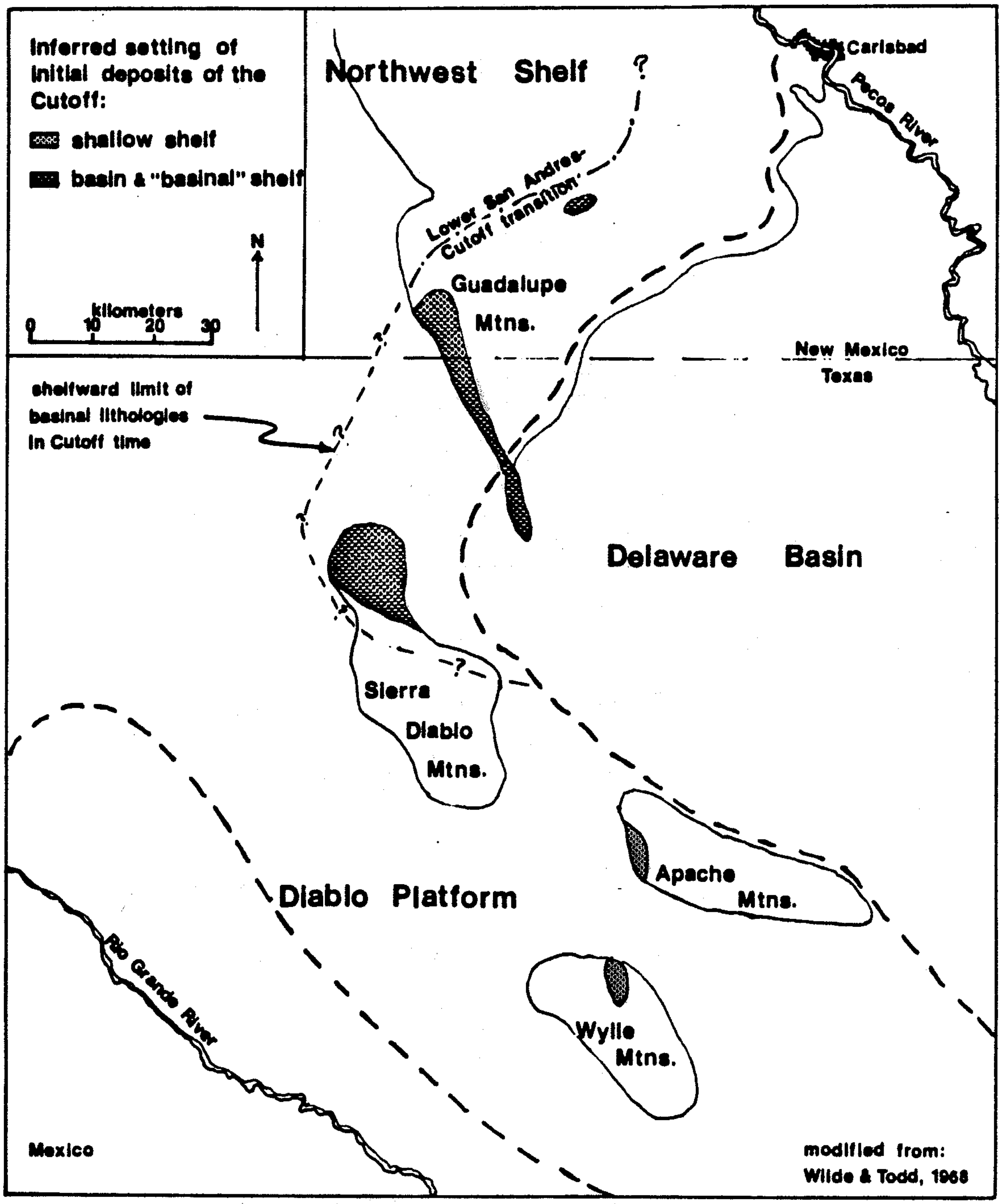
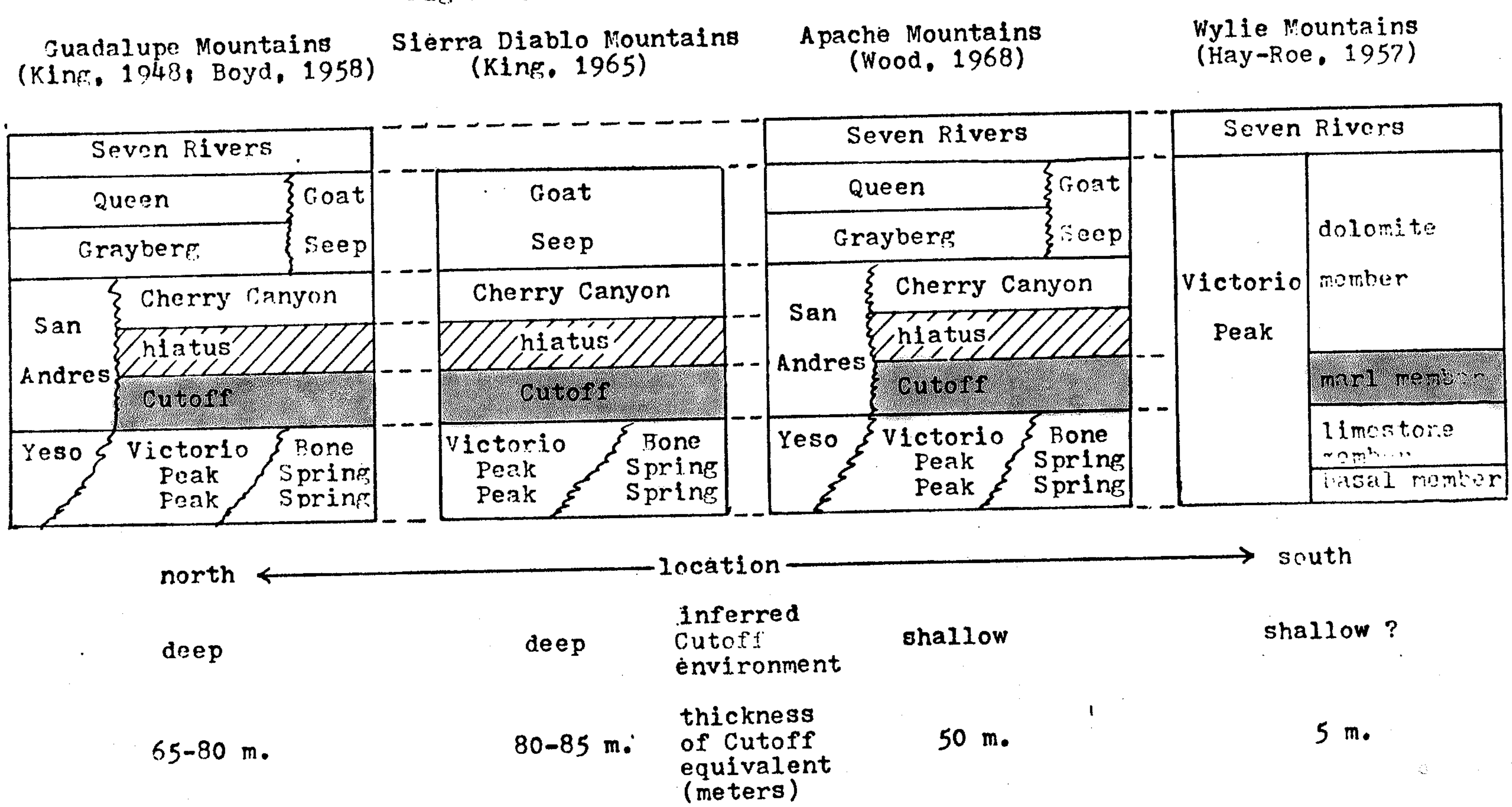


Figure 11 : Correlation of regional shelf sections



are the dominant rock types.

The shelf Cutoff in the Apache Mountains is a group of lithologies about 45 meters thick which appears conformable on the Victorio Peak (Wood, 1968). The strata is composed of thinly bedded, yellowish-brown claystone and siltstone with few thin beds of dark gray micrite which grades upward into a sequence of very thinly bedded limestones, micrites to sparites with intraclasts and fossils. Wood interpreted this sequence as a shallow water deposit representing an environment similar to the upper Victorio Peak. Detectable basinal sedimentation did not take place in this area.

In the Wylie Mountains, the Victorio Peak Formation includes the stratigraphic equivalents to the Victorio Peak, Cutoff, Cherry Canyon, and Goat Seep Formations of the Guadalupe Mountains shelf area. A 4.6 meter thick marl member is considered equivalent to the Cutoff due to stratigraphic position (Wilde and Todd, 1968). It "contains harder layers of finely silty, clayey micro-grained dolomite" and is unfossiliferous (Hay-Roe, 1957). The depositional environment and depth are not discussed by Hay-Roe. I suggest that this marl member is a shallow water shelf deposit of Cutoff age. The thinness of the marl member suggests that a major shift to a basin style of sedimentation did not occur. However, there was the increase in fine siliciclastic sediment which is characteristic of Cutoff time. The inclusion of the marl member within the Victorio Peak Formation reflects a consistency of rock type and probably depositional setting as well.

The Cutoff equivalents in both the Apache and Wylie Mountains appear to be shallow shelf sections, not the deep "basinal-style" deposits of the shelf in the Southern Guadalupe and Sierra Diablo Mountains. The variety of lithology and inferred environment of deposition can be explained by shelf subsidence in the northwest portion of the Delaware Basin and neighboring shelf. Boyd (1958) demonstrated that basinal sediments of the Cutoff transgressed 19 to 23 kilometers onto the older shelf deposits of the Victorio Peak Formation (Fig. 10). The transition to shallow water shelf deposits is marked by small, discontinuous reefs which may mark a slope break as suggested by Boyd (1958). This postulated subsidence can explain how basinal deposits could transgress over the Victorio Peak bank in the area of the Guadalupe and Sierra Diablo Mountains, while uninterrupted shallow water sediments accumulated on the more stable shelf in the area of the Apache and Wylie Mountains.

The depth of the subsidence cannot be directly estimated. Water depths for lithologies similar to the Cutoff have been estimated by Newell _et al_. (1953). Their maximum is 520 meters for the Lamar limestone (Guadalupian), based on the height of the reef foreslope. Their minimum estimate is 150 meters for the Bone Spring Limestone, based upon the incorrect interpretation of channel megabreccias as patch reefs. Another approach, independent of the reef interpretations, is to consider the entire shelf sequence of Cutoff-Cherry Canyon-Grayberg-Queen. This is a progradational, shallowing upwards sequence 300 meters thick. This is a maximum figure for the water depth of the basal Cutoff on the shelf because later post-Cutoff subsidence probably increased the thickness of this sequence. This author's estimate of the initial depths of the basal Cutoff is 65-85 meters for the shelf at the type section and 400 meters for the basin equivalents. The basis of this estimate will be developed in the final sections of this report.

More important than the exact water depth for the understanding of events in Cutoff time is the implication of the regional pattern of Cutoff-age shelf sediments, basinal versus normal shelf. The pattern implies that the unconformity surface cut into the top of the Leonardian bank formed at a time of shelf subsidence, as suggested by Pray (1971) and supported by Kirkby's study (in progress) of the uppermost Victorio Peak. This contrasts with the suggestion of King (1948) and Newell _et al_. (1953) who believed that this unconformity was formed as an emergent surface during a time of subaerial exposure.

ROCK TYPES & DEPOSITIONAL PROCESSES

"The history of any one part of the earth, like the life of a soldier, consists of long periods of boredom and short periods of terror."
Ager

General association

The Cutoff strata can be divided into two major rock groupings, both clastic. These are: 1) a succession of predominantly lutites (table 1) which form persistent layers over the shelf, shelf margin, and basin. 2) a variety of rock types (mostly coarse) which form channel fills (lenses and sheets) along the shelf margin and basin.

The lutites are rock types with a predominant grain size smaller than sand (1/16 millimeter). So defined, lutites include siltstone. The lower Cutoff almost entirely consists of medium bedded, cherty lime mudstone. Other lower Cutoff rock types are limited to channel fillings. The upper Cutoff strata consists of about 1/2-2/3 interbedded lime mudstone and shale, and 1/2-1/3 medium bedded, dark gray, lime mudstone. Most of the lower half of the upper Cutoff is made up of interbedded lime mudstone-shale which is composed of about equal amounts of fissile lime mudstone and siliceous shale, with a minor amount of siltstone present as well. The upper half of the upper Cutoff is medium bedded lime mudstone. The thickness of this limestone is reduced along the shelf margin by

Table 1:

Lithology	Composition	Color[1]
black, cherty lime mudstone	$CaCO_3$	black (N1) to dark gray (N3)
thinly laminated fissile lime mudstone	$CaCO_3$	dark gray (N3) to black (N1) with minor dark brown (10YR 4/3)
siliceous shale	terrigenous silicates	dark gray (N3) to black (N1) with minor dark brown (10YR 4/3)
siltstone	terrigenous silicates	dark brown (10YR 4/2) to tan (10YR 7/2)
thinly laminated, medium bedded, lime mudstone	$CaCO_3$	dark gray (N2-4)
faintly laminated to non-laminated, medium bedded, lime mudstone	$CaCO_3$	dark gray (N2-4)
medium gray, lime mudstone	$CaCO_3$	medium gray (N5-6)
medium gray, lime wackestone	$CaCO_3$	medium gray (N5-6)

Notes:

1. Numerical values from GSA Rock Color Chart.
2. See appendix for definition of bedding and lamination terms.
3. Range of 2 to 4 samples. Residues contain clay with lesser am

Table 1: Lutites

	Bedding[2]	Laminations[2]	Insoluble Residues[3]	Correlation Unit
) to (N3)	medium	thin to none	20.4-56.9%	1
(N3) to) with k brown)	(fissile)	thin	33.6-92.8%	2 & 4
(N3) to) with k brown)	(fissile)	thin	94.3-99.3%	2 & 4
n) to tan)	thin	thin	(not determ.)	2 & 4
(N2-4)	medium	thin	6.9-34.3%	3 & 5
(N2-4)	medium	thin and faint to none	10.4-37.1%	3 & 5
ay (N5-6)	medium	none	2.8-13.8%	5
ay (N5-6)	layers within medium gray mudstone	none	3.9-4%	5

nation terms.

with lesser amounts of quartz silt and chert.

post-Cutoff erosion.

The channel-lens rock types are: carbonate megabreccias, carbonate rudstones, quartz sandstone, and lutites. Sheet-shaped bodies are comprised of carbonate megabreccias and rudstones. These channel fills and sheets occur along the shelf margin and basin throughout the Cutoff strata, but are volumetrically very minor (less than 1%).

Recognizeable skeletal grains are marine invertebrates composed of calcium carbonate, and siliceous sponges.

Lutites

ROCK TYPES

Black, cherty lime mudstone

This rock type is black, medium bedded, lime mudstone (Fig. 12). It typically has thin laminations except on the shelf where laminations are faint or not present. Black chert is abundant (5-15%) occurring as thin seams (2 centimeters) and nodules in nearly every bed. This lithology is a distinctive rock type found only in the lower Cutoff Formation. It is not present in all sections, but where found it is the basal lithology.

The black cherty mudstone is best exposed in the basin (section B). Here it is laterally continuous and thick (24 meters). Locally the cherty mudstone contains thick chert seams (up to 10 centimeters) (Fig. 13). Small folds locally

Figure 12: Black, cherty lime mudstone.

A. Laminated texture from basin area. Polished slab, section B, 22' level, specimen U.W. 1719/1.

B. Same as A. Thin section, specimen U.W. 1719/2.

C. Bedded chert in basin area. Bed below pack is solid chert. Field photograph, section B, 78' level.

D. Non-laminated texture from shelf area. Thin section, section N, 2' level, specimen U.W. 1719/3.

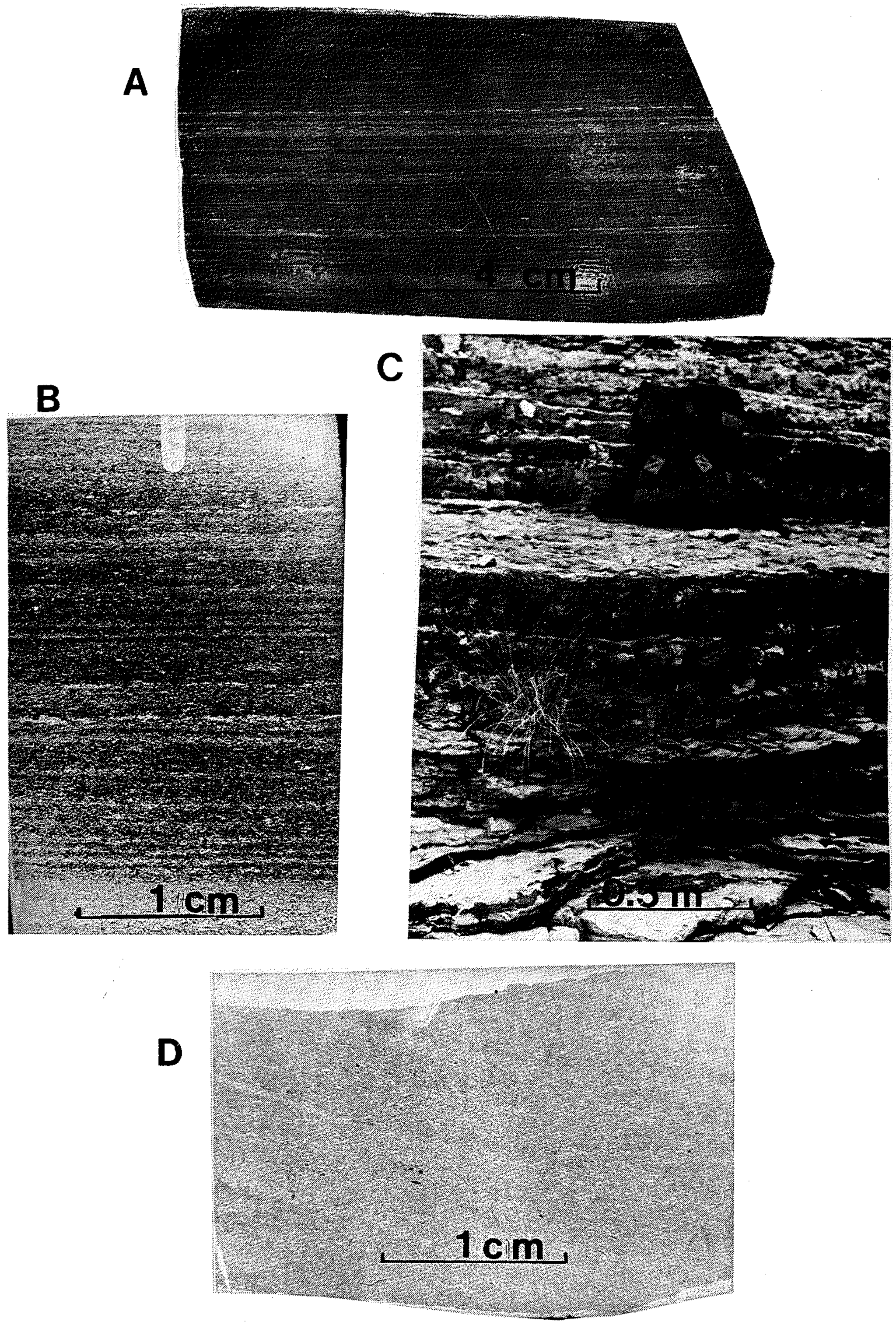

A
4 cm
B
1 cm
C
0.5 m
D
1 cm

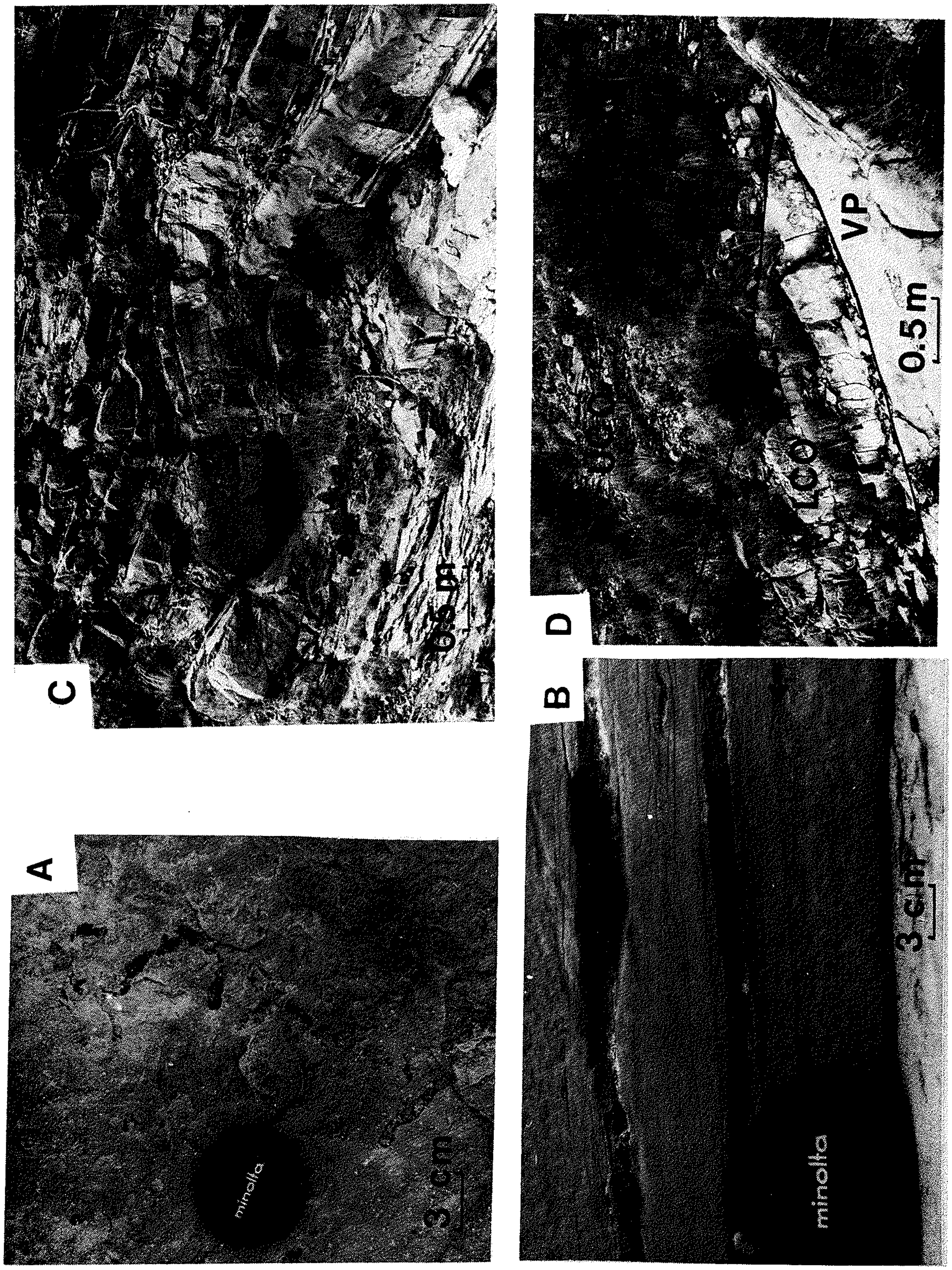
Figure 13: Features associated with black, cherty lime mudstone.

A. Flattened, horizontal burrows which occur in rare horizons in the basin area. Field photograph from above, section B, 140' level.

B. Burrows as in B. Side view, field photograph, section B, 124' level. Horizon with burrows indicated by arrows.

C. Small fold at basin edge believed due to submarine slump. Fold affects 3 meters of strata. Field photograph, section B, 48-54' level.

D. Truncation of black, cherty lime mudstone of the lower cutoff Formation (LCO) by the intra-cutoff unconformity. Lower Cutoff strata fill a channel cut into the Victorio Peak Formation (VP) along the pre-Cutoff unconformity. Strata overlying lower Cutoff and Victorio Peak strata are upper Cutoff lutites (UCO). Field photograph, south wall of South Shumard Canyon (shelf margin), 5-15 meters east of section H.


A
3 cm
minolta
B
3 cm
minolta
C
0.5 m
D
LCO
VP
0.5 m

disrupt bedding. These appear to indicate soft sediment deformation very soon after deposition because the upper surfaces are sharply truncated with undisturbed bedding above. The position of the folds near the base of a submarine slope and their similarity to the slump folds described by Lowery and Cooper (1970) lead to the conclusion that these are slump folds formed nearly contemporaneously with deposition. Above the lower 17 meters the well laminated texture is replaced by a mixture of lamination styles: laminae which are irregular or bumpy due to horizontal burrows, non-laminated texture, and well laminated texture. This mixture of lamination styles is not found in the rest of the study area but this may be due to the removal of lateral equivalents beneath the intrformational unconformity between the lower and upper Cutoff.

<u>Interbedded lime mudstone-shale</u>

The interbedded lime mudstone-shale consists of three rock types: thinly laminated lime mudstone, siliceous shale, and scattered minor amounts of siltstone (Fig. 14). The mudstone and shale locally alternate in centimeter thick intervals but normally one lithology occurs vertically for several meters. The mudstone and shale look alike and can only be distinguished with certainty by testing with dilute hydrochloric acid. The shale typically contains carbonate concretions (about 0.3 meters across) which are

Figure 14: Interbedded lime mudstone and siliceous shale.

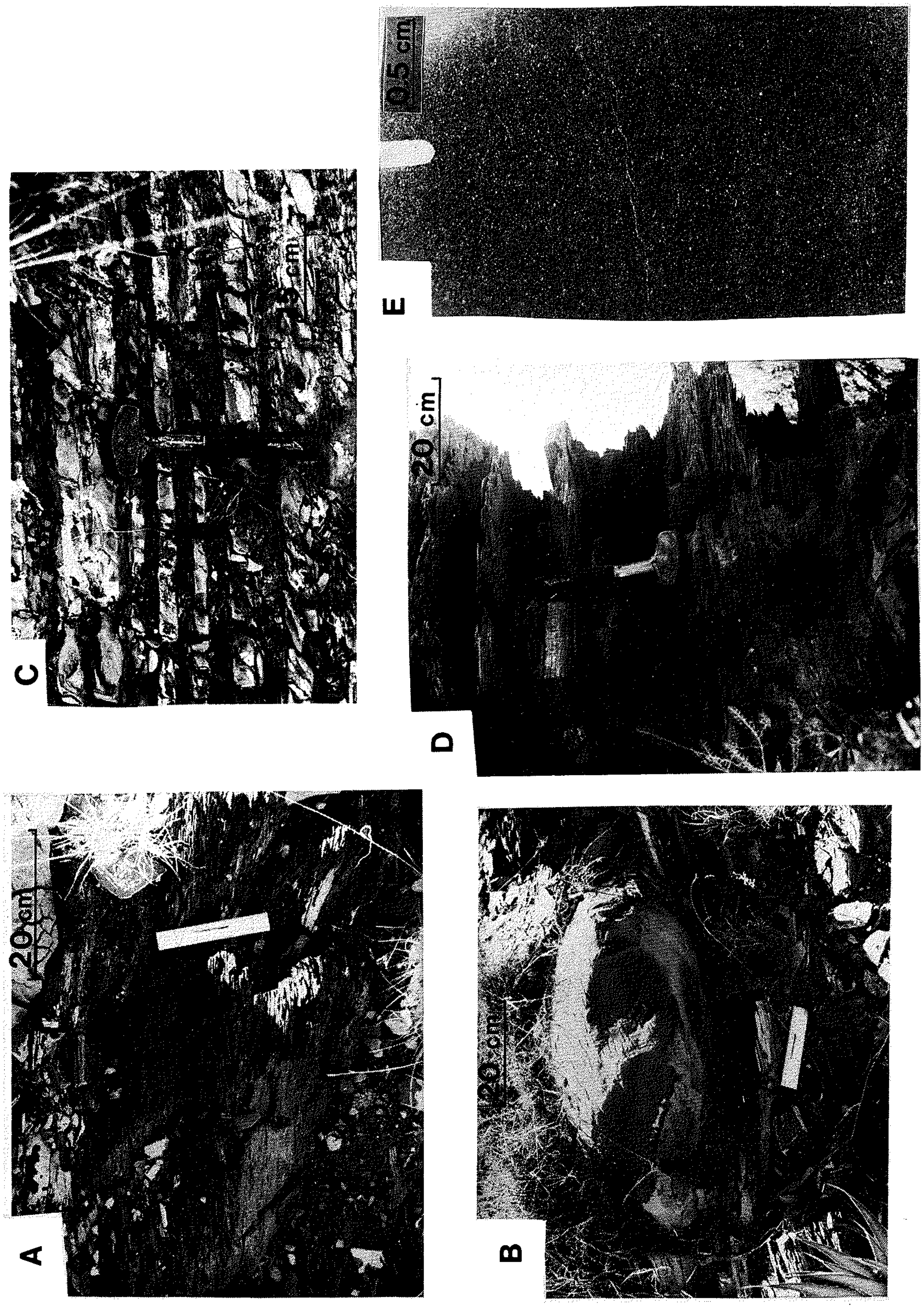
A. Typical bedding style, where exposed, of interbedded mudstone-shale. Field photograph, section D, 20' level.

B. Carbonate concretion in siliceous shale. Field photograph, section D, 20' level.

C. Differentially weathered regularly alternating, interbedded lime mudstone (thicker, more resistive beds) and siliceous shale. Field photograph, section H, 16' level.

D. Interbedded lime mudstone and siliceous shale. Weathered profile reflects amount of carbonate; move calcareous sections are more resistive. Field photograph, section A, approximately at 75' level.

E. Fine siltstone, locally interbedded in shale. Thin section, section H, 12' level, specimen U.W. 1719/4.


A
B
C
D
E
20 cm
20 cm
20 cm
0.5 cm

generally lacking in the lime mudstone, but this relation is not universal. In other aspects (color, laminations, fissility) the two rock types are identical. They occur together with no detectable lateral or vertical order. I suspect the compositional difference has been enhanced by diagenesis which concentrated the carbonate content of the shales into concretions.

This interbedded lime mudstone-shale occurs in all areas and weathers to form recessive intervals. It generally comprises most of the lower portion of the upper Cutoff; in most of the shelf and shelf margin, it is the basal unit of the Cutoff Formation. The shale is probably the major reason the Cutoff was termed the "Cutoff shale".

Thinly laminated, fissile lime mudstone

This rock type is dark gray to black, lime mudstone. It is thinly laminated, and unfossiliferous. Typically it is slightly siliceous and shaley partings cause its fissility. Generally interbedded with shale, the thinly laminated mudstone is distinguishable by the strong positive reaction to HCl and its general lack of concretions.

Siliceous shale

This rock type is dark gray to black, siliceous shale. It is thinly laminated, unfossiliferous, and fissile. Locally weakly calcareous, it is generally interbedded with very thinly bedded lime mudstone. In places it contains ellipsoid carbonate concretions up to 0.3 meters across. Around the concretions the shale exhibits squeezing effects indicating the concretion formed prior to the bulk of the compaction of the shale.

Dark brown to tan siltstone

This rock type is unfossiliferous, thinly laminated, very thin to thin bedded siltstone. It occurs as scattered beds in the siliceous shale. In the type section one interval of siltstone contains evaporite molds of secondary gypsum.

Thinly laminated, medium bedded lime mudstone

This rock type is dark gray, thinly laminated, lime mudstone (Fig. 15). It is medium bedded and contains shaley partings. A sparse fauna (predominantly brachiopods) occurs in thin laminae within the beds. The skeletal structure is generally well preserved. This lithology is widespread in the shelf margin and basin areas. In the basin area it makes up most of the upper half of the upper Cutoff, but elsewhere it is a minor portion of the section.

Faintly laminated to non-laminated, medium bedded lime mudstone

This rock type is dark gray, medium bedded lime mudstone (Fig. 16). It contains shaley partings, and faint laminations or none at all. A sparse, well-preserved fauna (brachiopods) occurs in thin laminae within the beds. This lithology is widespread, being found from shelf to basin.

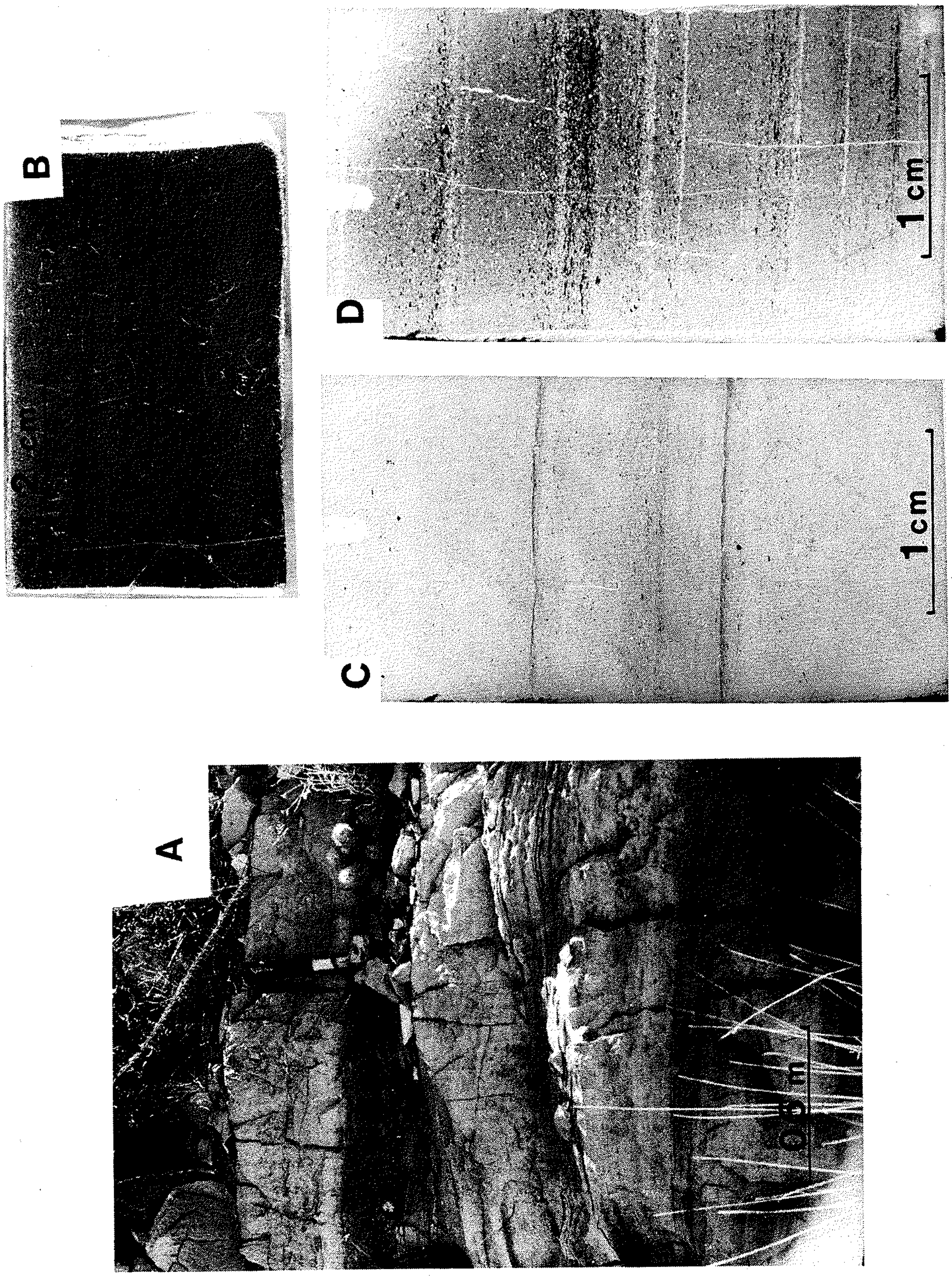
Figure 15: Thinly laminated, medium bedded, lime mudstone.

A. Typical exposure. Field photograph, section E, 39' level.

B. Thinly laminated texture. Polished slab, section B, 202' level, specimen U.W. 1719/5.

C. Thin section of slabbed sample in B. Specimen V.W. 1719/6.

D. Only occurence of grading and compositional banding in lutites, possibly due to turbulent flow. Small white dots are cross sections of sponge spicules. Sample from basal mudstone bed of uppermost channel fill (Figure 26) in upper Cutoff Formation, 70 meters east of section E, south wall of Bone Canyon. Thin section, specimen U.W. 1719/7.


A
0.5 m
B
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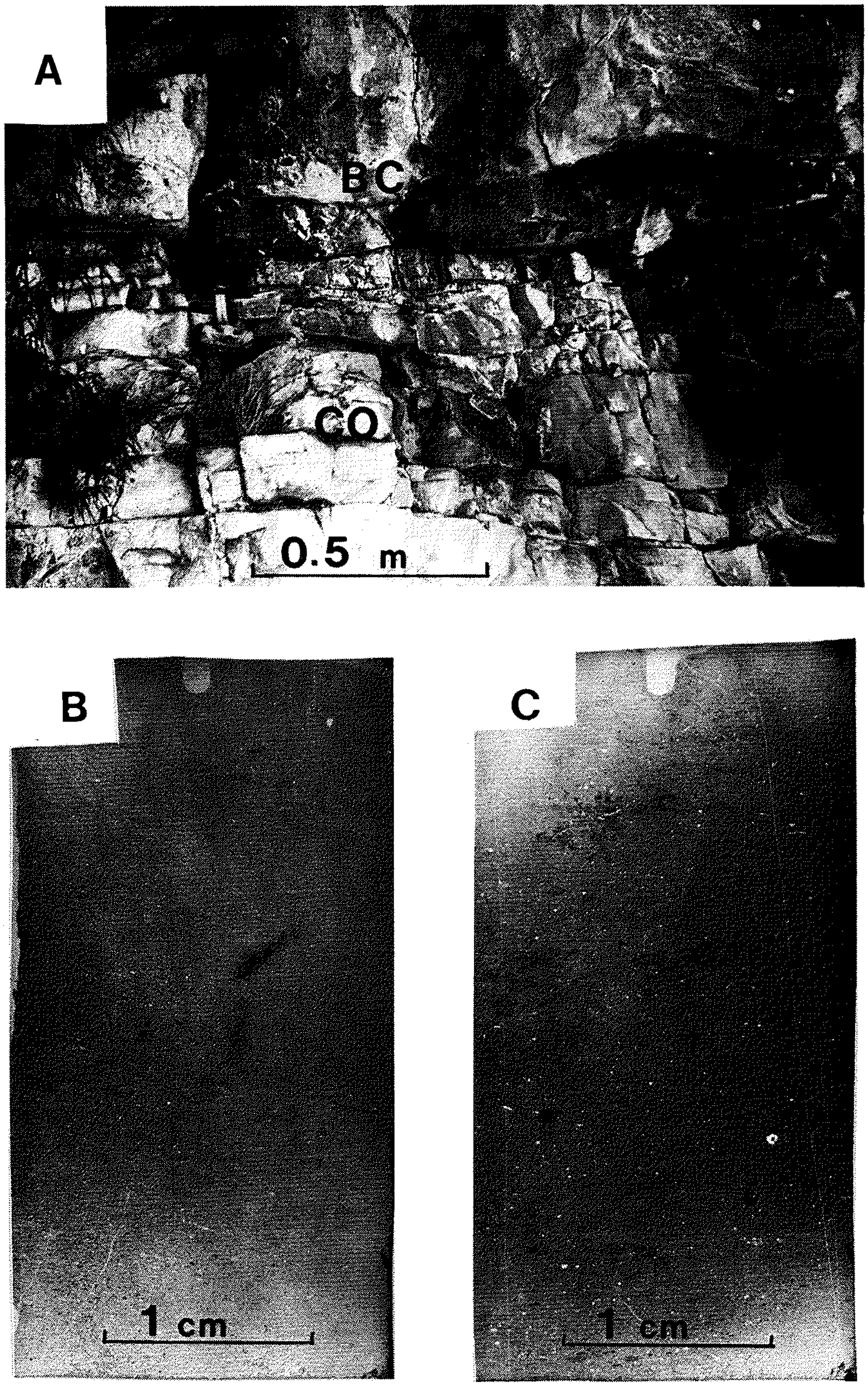
1 cm
D
1 cm

Figure 16: Faintly to non-laminated, medium bedded, lime mudstone.

A. Mudstone, in a typical exposure, forming uppermost Cutoff strata (CO) with basal sandstone of Brushy Canyon Formation (BC) above. Field photograph at top of section D, edge of basin area.

B. Faintly laminated texture. Thin section, section D, 76' level, specimen U.W. 1719/8.

C. Non-laminated texture from shelf margin area with mottling suggestive of burrowing. Thin section, section J, 150' level, specimen U.W. 1719/9.


A
BC
CO
0.5 m
B
1 cm
C
1 cm

It is the uppermost rock type and is generally only a few meters thick in the shelf margin and basin edge areas. In the shelf area it occurs below the medium gray mudstone. On the outer shelf (Bartlett Peak, section M) the faintly laminated to non-laminated mudstone is 26 meters thick and makes up to 3 meters of the upper half of the upper Cutoff at Cutoff Mountain (section N). To the north it thins and is largely replaced by medium gray, lime mudstone.

Medium gray, lime mudstone

This rock type is medium bedded, non-laminated, medium gray lime mudstone (Fig. 17). It contains scattered skeletals. In places the beds may contain vugs and/or light colored chert nodules. This lithology is limited to the shelf where it is the uppermost rock types within the Cutoff.

Medium gray, lime wackestone

This rock type is medium gray wackestone with skeletal grains of various types. It forms thin layers within the medium gray mudstone of the type section (Fig. 17). The layers have sharp, even lower surfaces and irregular, sharp upper surfaces. The occurrence of this lithology as layers within the mudstone and the sharp (erosional?) bases are suggestive that these layers are the result of current reworking and winnowing of the lime mud. The irregular upper surfaces suggest post-depositional burrowing activity. The

Figure 17: Medium gray, lime mudstone and wackestone.

A. Medium gray, lime mudstone from shelf area with chert-lined vugs. Shelf area, about 100 meters northeast of section L, where unit 5 is truncated by the upper unconformity. Polished slab, specimen U.W. 1719/10.

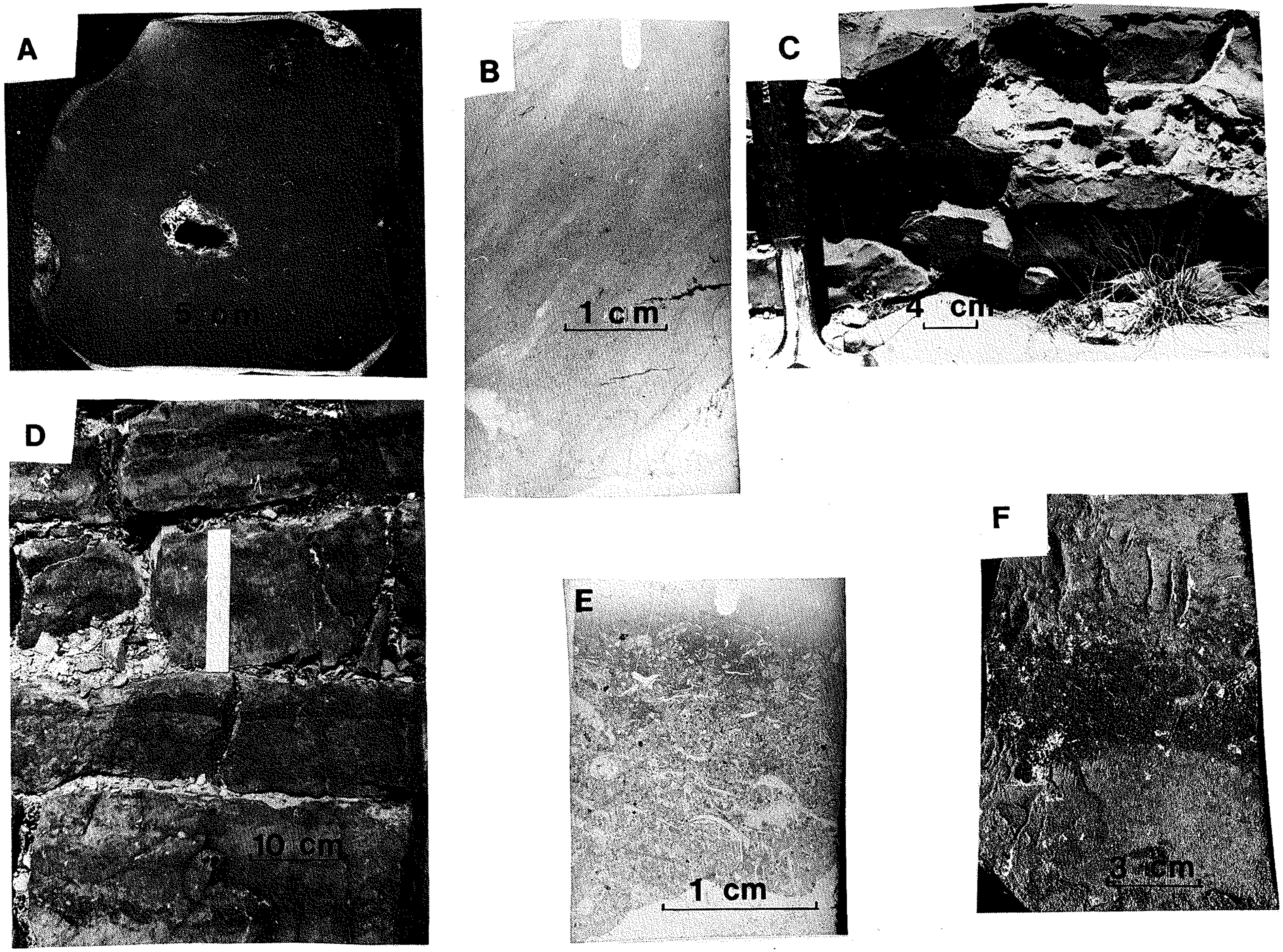
B. Medium gray, lime mudstone, without laminations. Thin section, section M 36' level specimen U.W. 1719/11.

C. Medium gray, lime mudstone with chert-lined vugs. Field photograph section M, 161' level.

D. Medium gray lime wackestone layers in medium bedded, medium gray, lime mudstone. Wackestone layers (weather darker) have sharp bases and uneven, borrowed upper surfaces. Field photograph section N (Cutoff Mountain, type section), 134' level.

E. Thin section of wackestone (locally packstone) layers shown in D. Section N, 134' level, specimen U.W. 1719/12.

F. Field slab of wackestone layer shown in E. Section N, 134' level, specimen U.W. 1719/13.


A
5 cm
B
1 cm
C
4 cm
D
10 cm
E
1 cm
F
3 cm

location of this rock type, only in the most shelfward and probably shallowest water area of the shelf in the study area is compatible with the evidence of more turbulence than in the margin and basin areas.

INTERPRETATION OF LUTITES

Origin, transport, and deposition of lutites

Despite the variety of rock types it is important to recognize that the Cutoff strata is comprised predominantly of lime mud. Clay is important in shales and argillaceous limestones and terrigenous silt is a minor component. Thus nearly all rocks are lutites.

The source of the clastic siliceous material is not well established. Two sources for terrigenous material in the Delaware Basin are indicated. During Leonardian time a clastic source to the north is suggested by a high proportion of sandstone in the northern portion of the Delaware Basin. To the south in the Glass Mountain region, coarse sandstone and conglomerate are present (King, 1948; Oriel *et al*., 1967). Hills (1972) favors the northern source for the Guadalupe Mountains area. The presence of some shelf sands in the Victorio Peak Formation of the Guadalupes, the transport to the southwest of sands of the basal Brushy Canyon Formation, and the study area's location on the Northwest Shelf clearly implies the northern detritus source.

The source of the lime mud is problematical. The lime mud may have formed in the surface waters of the basin or be derived from any of the neighboring shelves to the west or north. Lime mud might have formed on the sea floor in the area of deposition but this seems unlikely. More likely autochthonous biota are the siliceous sponge spicules (0.025 millimeters, or 25 microns, in diameter). The origin of the lime mud cannot be determined petrographically. The spicules suggest that biotics are the source of the fine carbonate material. The draping geometry of the laterally continuous, near constant thickness lutite beds over the bottom topography suggests these beds are largely suspension deposits, but some beds thicken slightly into minor paleotopographic lows of a few centimeters. These thickness variations imply some current activity, in addition to simple settling. The small scale features (few centimeters) are evidence for reworking of the muds by weak bottom currents. The cutting of channels up to 30 meters in depth is evidence for episodic strong bottom currents.

The lime mud, as well as the clay, may have been transported into the basin from the shelf. In her study of the Lamar Limestone (Guadalupian) L. Babcock (1974) concluded that shelf-derived lime mud was transported into the basin, but this was based upon the constant thickness decrease away from the shelf edge. By contrast the pre-erosional thickness of the Cutoff strata remains nearly constant from shelf to basin.

The lime mud appears to be the result of a pelagic rain of carbonate material. The source of this pelagic material is uncertain but it was deposited over the entire study area. The Northwestern Shelf is a possible source area because this is the source for the terrigenuous clastics.

Currents provided a mechanism of transport into the basin competent enough to transport quartz silt at some times. These silts have the same draping geometry as the muds and clay, and presumably were also deposited from suspension. Harms (1974) suggested density current interflows as the transport mechanism to carry silts with a similar depositional geometry in the Delaware Mountain Group and in Harms and Pray (1974) this was suggested for the Cutoff Formation and Delaware Mountain Group. This depositional model will be discussed after consideration of the channel-filling rock types within the Cutoff.

<u>Ideal succession of correlation units</u>

My field study shows that the lutites occur in a consistent vertical succession of "correlation units". They are called correlation units because the primary use of these units is for correlation. The succession of correlation units is present in all areas of this study and can be identified in all stratigraphic sections. It has not been previously recognized. It consists of:

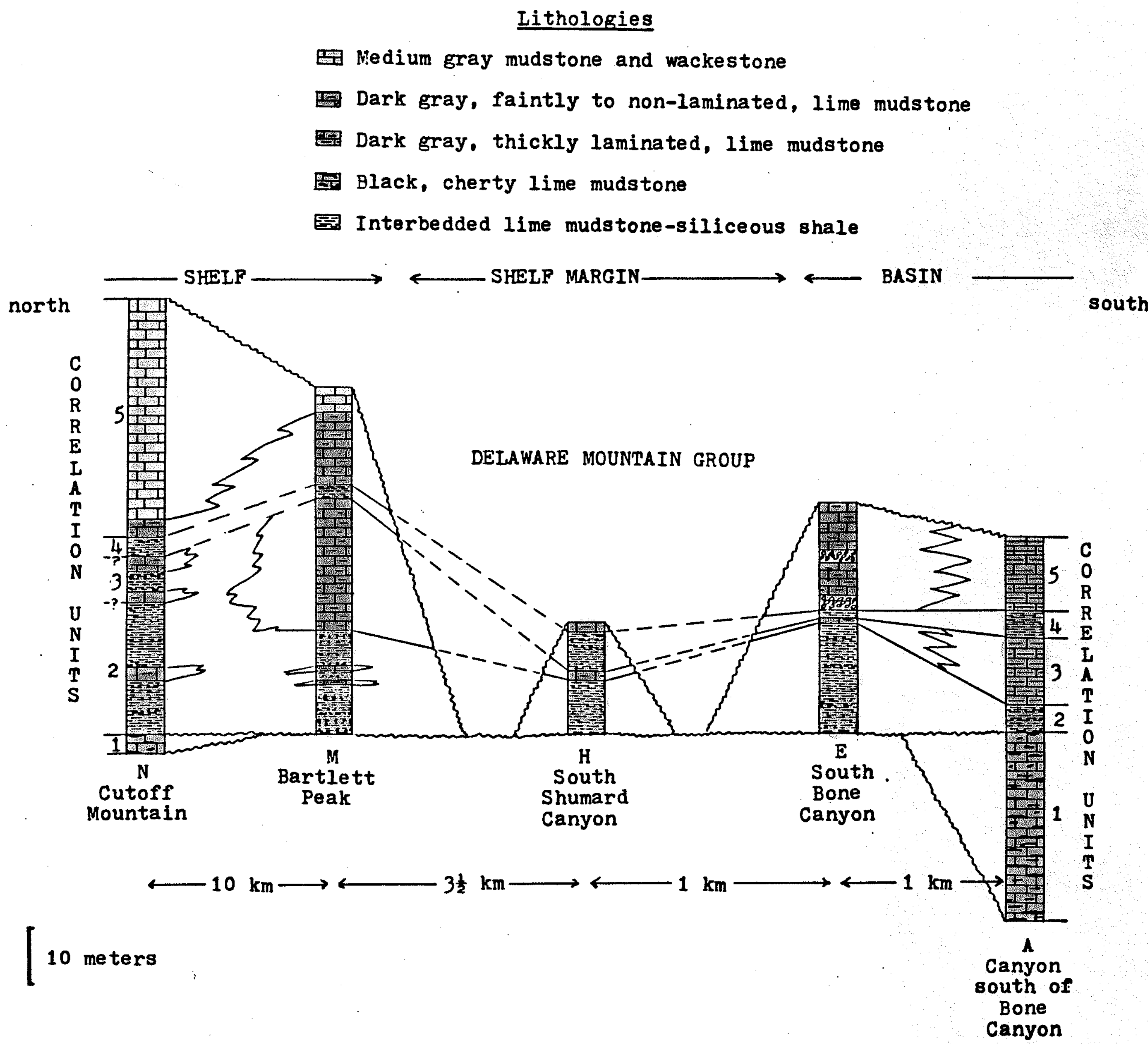
unit 5:	dark to medium gray mudstones with discontinuous beds	
unit 4:	interbedded lime mudstone-shale	upper Cutoff
unit 3:	dark gray mudstone with continuous beds	
unit 2:	interbedded lime mudstone-shale	
unit 1:	black, cherty mudstone	Lower Cutoff

The recognition of this succession is essential for interpreting the Cutoff: 1) It provides a key for resolving the correlation disagreements of previous workers. 2) This internal stratigraphy within the Cutoff allows more precise correlation of the depositional and erosional events in Cutoff time. 3) The rock types which make up these units and the sedimentary structures contained within them are the raw data of environmental reconstructions. In particular, the distribution of the various limestone lithologies are best explained by a detailed anoxic basin model which focuses on the oxygen content of the water. This model also leads to speculation about basin-wide events.

Correlation from shelf to basin

The entire succession of alternating limestone and shaley units within the Cutoff strata can be recognized in all areas except the type section, located well back on the shelf, where unit 3 cannot be recognized with assurance (Fig. 18). In the critical area from shelf edges to basin

Figure 18: Selected sections showing lateral persistence of correlation units.



the succession can be followed from section to section (Plate 15), except where the Cutoff is truncated or removed by erosion. The consistency of the succession is the key to correlation across the intervals where the Cutoff strata has been removed because the pattern is maintained. With the correlations thus established, how can the diverse correlations of previous woerks be interpreted?

King (1942, 1948) recognized that the discontinuous nature of the Cutoff made a direct physical correlation impossible. He defined the Cutoff on the shelf and recognized the shelf margin equivalents. As the correlative basin units he suggested a sequence of limestones, shales, and sandstones at the base of his mapped Brushy Canyon Formation, exposed to the south of El Capitan. These strata appear to be above the Cutoff and include the "Pipeline shale" (Warren, 1955) which is in the basal Brushy Canyon Formation (Newell _et al_., 1953). In the basin area King recognized as Cutoff correlatives strata within 15 to 30 meters of the lower-most Brushy Canyon sandstone beds and above a black limestone bench (his Bone Spring Limestone) which makes the series of low hills west and south of El Capitan.

In the basin Newell, in Newell _et al_. (1953), identified strata of my correlation units 2, 3, and 4 as Cutoff. The black limestone which forms the bench south of El

Capitan (my correlation unit 5) was considered by Newell to (see his Figure 10) be an "Upper Bone Spring Limestone" and of post-Cutoff age. Newell traced the Cutoff "shales" (units 2 and 4) as they disappeared into the subsurface of the Delaware Basin.

McDaniel and Pray (personal communication) correctly identified the basin Cutoff (units 1-5) in the mid 1960's based upon stratigraphic position and lithologic similarity.

Recognition of the vertical succession of correlation units from shelf to basin resolves these differences. As shown in plate 15, the succession is less clear north of the shelf edge at the type section, but southward from the Barlett Peak section (M) the pattern can be traced into the shelf margin area. This confirms King's shelf to shelf margin correlation. In the basin the succession is recognized in Bone Canyon and can be followed southward as the Cutoff thickens basinwards. The strata suggested by McDaniel and Pray as basin Cutoff are confirmed as such by this analysis.

The lower unit (#1) appears 0.4 kilometers south of Bone Canyon and thickens to 31 meters in a distance of 0.4 kilometers (section B) (see Fig. 18 and Plate 15). The upper unit roughly doubles in thickness (from 40 to 93 meters) over a distance of 2 kilometers south of Bone Canyon (section E to section A). Despite this thickening the upper surface of the Cutoff is horizontal and nearly planar due to truncation of beds by post-Cutoff erosion. From about 1 to 2 kilometers south of Bone Canyon, correlation units 1,2,3, and 4 successively disappear from view into the subsurface. Unit 5 thickens by stratigraphic addition of beds below the post-Cutoff unconformity to make up the low-lying hills of black mudstone south of El Capitan, long considered to be Bone Spring limestone (King, 1948; Newell el al., 1953; and other workers and guidebooks).

In summary, recognition and tracing of the vertical succession of correlation units has clarified the shelf to basin correlation of the Cutoff.

Rock types in the correlation units

The units are not the same as rock types. Each unit includes some variation of lithologies within it, and the same rock type may appear in more than one unit. The distribution of rock types is summarized in table 2. Plate 15 shows the details of this distribution.

Unit. 1: The lower Cutoff consists of one major lutite rock type, the black cherty mudstone. Examination of specimens reveals a variation in the quality of laminations from shelf to basin. The cherty mudstone of the shelf and shelf margin is only faintly laminated or non-laminated but the basin equivalents are well laminated (Fig. 12). Vertical changes are only recognized in the basin section B,

Table 2: Distribution of rock types

Correlation Unit	Shelf	She
5	medium gray, lime mudstone and wackestone faintly laminated to none-laminated, medium bedded lime mudstone	faintly la laminate lime mud
4*	thinly laminated, fissile lime mudstone + si	
3	faintly laminated to non-laminated, medium bedded lime mudstone	faintly lan laminatec lime muds
2*	thinly laminated, fissile lime mudstone + si	
1	faintly laminated to non-laminated, black, cherty lime mudstone	faintly lam laminated lime muds

*Units 2 and 4 are the same in all areas.

on of rock types in correlation units from shelf to basin.

	Shelf margin	Basin
ınd	faintly laminated to non-laminated, medium bedded lime mudstone	faintly laminated to non-laminated, medium bedded lime mudstone thinly laminated, medium bedded, lime mudstone
ime mudstone + siliceous shale + siltstone		
	faintly laminated to non-laminated, medium bedded lime mudstone	faintly laminated to non-laminated, medium bedded lime mudstone thinly laminated, medium bedded, lime mudstone
ime mudstone + siliceous shale + siltstone		
	faintly laminated ato non-laminated, black, cherty lime mudstone	thinly laminated, black, cherty lime mudstone

ıs.

probably because elsewhere the lower unit has been drastically thinned by later erosion.

Unit 2: The interbedded lime mudstone-shale contains several rock types but is remarkably uniform from shelf to basin. No consistent lateral or vertical lithologic changes were noted in this study but the fissile nature of these rock types makes the unit non-resistive and hence could obscure any changes present.

Unit 3: This is a 1-6 meter thick unit of lime mudstone which is characterized by its bedding style. Beds are laterally continuous for up to 10+ meters, about the maximum extent of good exposures. In some places however the same bed can be followed for over 100 meters.

Two rock types are present which differ in quality of laminations. In the basin thinly laminated, medium bedded lime mudstone makes up this unit. On the shelf margin this lithology is replaced by the faintly laminated to non-laminated, medium bedded lime mudstone. This lithology continues onto the shelf. At the Barlett Peak section unit 3 is thickest. Unit 3 cannot be clearly distinguished at the type section (N) at the New Mexico border because two thin mudstone beds occur within the strata correlated with units 2 and 4 at the expected stratigraphic position of unit 3. The mudstones are composed of the faintly laminated to non-laminated, medium bedded lime mudstone, and either or both may be correlative with unit 3 to the south.

Unit 4: The interbedded lime mudstone-shale lithologies make up unit 4. The non-resistant, fissile nature obscures any variations, as with unit 2.

Unit 5: The uppermost Cutoff unit contains the greatest variety of rock types. The major differences are in color, lamination quality, and amount of skeletals. The most basinward sections (see section B) are made up of thinnly laminated, medium bedded lime mudstone. South of Bone Canyon, this is replaced by the faintly laminated to non-laminated, medium bedded lime mudstone. This extends from basin edge to the shelf. Across the shelf this lithology grades into the medium gray lime mudstone and wackestone. At the Bartlett Peak section (M) the medium gray mudstone makes up the upper 3.7 meters of this unit but at the type section (N) the medium gray limestone dominates this unit (the upper 39 meters of the total 42 meters).

In contrast to unit 3, the individual beds in unit 5 are not laterally continuous; they generally pinch out within 5-10 meters. This is interpreted as being due to scouring on the sea floor prior to deposition of the next bed.

Unit 5 has been affected by the post-Cutoff unconformity more than any other unit because it is the uppermost Cutoff unit. Locally unit 5 is missing where the other units are still present (section C). The bedding along the upper surface is sharply truncated by the unconformity. Due to this truncation, the original thickness of unit 5 is uncertain. The maximum thickness observed is 42 meters at the type section (N).

Summary: Eight different types of lutites are recognized in the Cutoff strata. These were mostly deposited by suspension from a pelagic rain, with a lesser amount deposited by interflows (silts certainly). The eight rock types occur in a vertical succession of five correlation units. These units permit unambiguous correlations from shelf to basin areas.

Lens and Sheet deposits

The Cutoff strata contains rock types which are coarser-textured than the lutites already discussed. The geometry of these coarse-textured deposits is of two types: channel-filling lenses and sheet-like masses. These rock types are limited to shelf margin and basin areas. Vertically they are distributed throughout the Cutoff strata but about half are along the basal unconformity surface. The coarser-textured rock types are generally only a minor portion of the section (less than 5%).

The channel-filling lithologies (in decreasing abundance) are: intraclastic rudstone and megabreccia, lutites (lime mudstone and shale), skeletal rudstone, and fine-grained quartz sandstone. Intraclastic rudstone and megabreccia sheets are limited to the shelf margin area (North to East Shumard Canyon).

The lenses appear to occupy channels. The basal surfaces of the lenses are erosional scours which are roughly spoon-shaped in cross section. The erosional scours range in size from over 100 meters wide and 30 meters deep, to about one meter in width, and a few centimeters in depth. In contrast, the upper surfaces are nearly planar and conformable with the overlying beds. These aspects will be more fully discussed in the section on erosional phenomena.

The channel-filling lenses composed of megabreccia were first noted by King (1948). He interpreted them as reefs but noticed the channel-shaped bases. Newell et al. (1953) interpreted them as patch reefs which grew on the upper Bone Spring surface. Pray and Stehli (1963) reinterpreted these rock bodies as channel-filling megabreccias lenses because of the clastic texture and chaotic orientation of clasts as determined from geopetal fabrics. They recognized these lenses as bodies of allochthonous material with blocks of lithified rock over 10 meters across.

The megabreccia blocks are more richly fossiliferous than the enclosing lutites and formed the source for many of the paleontologic collections of King and Newell, and later Wilde. Newell believed the megabreccia lenses were in-place reefs. King also collected fossil material from the skeletal rudstone lenses in the basin area. The fauna collected was considered to be contemporaneous with the surrounding strata until recognition of the allochthonous nature of the megabreccia lenses. It is uncertain now which fauna are of Cutoff age and which fauna are reworked from earlier Leonardian strata. More aspects of this problem will be discussed in the paleontology section.

The observed occurences of rudites are listed in table 3.

ROCK TYPES

Intraclastic rudstone and megabreccia

The coarsest-textured of the lens and sheet deposits are composed of intraclastic rudstone and megabreccia (Fig. 19). Rudstone was defined by Embry and Klovan (1971) as a rock type which contains greater than 10% of components greater than 2 millimeters in size and in which these coarse components form the supporting framework. Cook *et al*. (1972) defined megabreccia as "a deposit in which angular clasts larger than 1 meter are conspicuous components and which may contain some clasts many meters

Table 3: Rudites

Location section	Location interval	Rock type	Clast type[1]	Texture[2] clast sup.	Texture[2] matrix full	Strat. Position[3] over	Strat. Position[3] under	Mosaic key[4]
A	10	rudstone	IC,SK	Y	Y	4	4	IR 1
A	16	rudstone	IC	Y	Y	5	5	IR 2
A	18	rudstone	IC,SK	Y	N	5	5	IR(V) 3
B	1	rudstone	SK,IC	Y	N	BS	1	SR(V) 1
B	3	rudstone	IC,SK	Y	N	1	1	IR(V) 4
B	19	rudstone	IC,FU	Y	Y	4	5	IR 5
B	21	rudstone	IC,FU	Y	Y	5	5	IR 6
Between sect. C & D		rudstone	IC	Y	Y(?)	BS	1	IR 7
D	0	megabreccia	IC	Y	Y	BS	2	MB 1
Between sect. D & E		megabreccia	IC	Y	Y	BS	2	MB 2
Between sect. D & E		megabreccia	IC	Y	Y	BS	2	MB 3
E	13	rudstone	IC	Y	Y	4	5	IR 8
E	15	rudstone	IC	Y	Y	5	5	IR 9
Between sect. E & F		rudstone	IC	Y	Y	3 & 2	BC	IR 10
G	8	rudstone	SK,IC	Y	N	4	5	SK(V) 2
Between sect. H & I		megabreccia	IC	Y	Y	1	2	MB 4
J	1	rudstone	IC	Y	Y	VP	1	IR 11
Between sect. J & K		rudstone	IC	Y	Y	VP	1	IR 12
Between sect. J & K		rudstone	IC	Y	Y	2	3 & BC	IR(S) 13
Between sect. J & K		rudstone	IC	Y	Y	3	BC	IR(S) 14
K	0	megabreccia	IC	Y	Y	VP	2	MB(S) 5
K	3	rudstone	IC	Y	Y	2	2	IR 15

Symbols:

Clast type: IC=intraclasts, SK=skeletals, FU=fusulinids

Stratigraphic position: numbers=corrilation units, BC=Brushy Canyon Formation, BS=Bone Spring Limestone, VP=Victorio Peak Formation

Mosaic Key: IR=intraclastic rudstone, SK=skeletal rudstone, MB=megabreccia, (V)=depositional void space, (S)=sheet shaped body

Notes:

1: Clast types are listed in decreasing abundence.

2: Clast support by components coarser than sand size. Matrix (sand size and finer) fills all available space.

3: Strata the rudite overlies and underlies.

4: Key for the stratigraphic sections and photo mosaics (ex.: Figure 25).

Figure 19: Intraclastic rudstone and megabreccia.

A. Intraclastic rudstone largely composed of dark gray lime mudstone clasts. Clasts derived from upper Cutoff strata of upper shelf margin; sample from rudstone sheet, IR(S)-14, between unit 3 and Brushy Canyon strata in the south wall, East Shumard Canyon (shelf margin). Polished slab, specimen U.W. 1719/14.

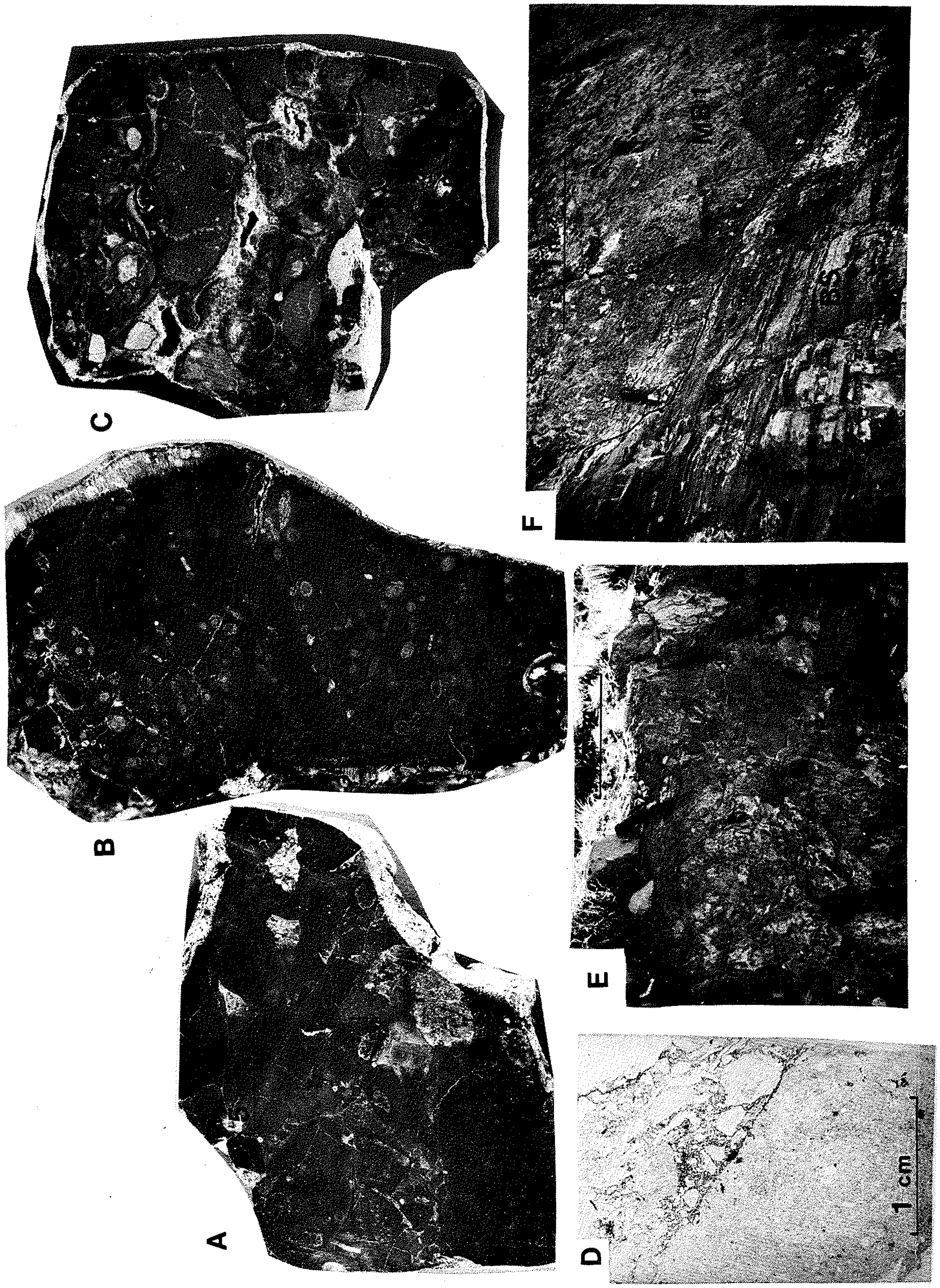
B. Intraclastic-fusulinid rudstone from the basin, IR-5. Polished slab, section B, 166' level, specimen U.W. 1719/15.

C. Intraclastic rudsotne with primary voids, IR(V)-4. Polished slab, section B, 5' level, specimen U.W. 1719/16.

D. Intraclastic rudstone with "matrix" filling all interparticle space; from rudstone lens IR-12 at base of lower Cutoff strata, northeast of section J, Shumard Canyon (shelf margin). Thin section, specimen U.W. 1719/17.

E. Sheet of intraclastic rudstone which caps megabreccia #1, 150 meters south of the mouth of Bone Canyon. Field photograph.

F. Lower surface of megabreccia #1 showing erosional truncation of underlying Bone Spring Limestone (BS). Field photograph, 150 meters south of Bone Canyon.


A
B
C
D
E
F
1 cm

across." Megabreccias are rudstones, where the clasts form a supporting framework, but the term megabreccia will be used for such to call attention to the large size of the clasts.

In the Cutoff strata lenses of intraclastic rudstone and megabreccia are widespread in the shelf margin and basin areas (table 3). The megabreccia lenses range in thickness from about 3 to 35 meters but the intraclastic rudstone lenses are less than 3 meters thick. Sheet-like bodies of intraclastic rudstone and megabreccia are limited to the shelf margin (Shumard Canyon). The sheets occur on a paleoslope of 10°±2°, dipping to the south or southeast. A 10-20 meter thick sheet of megabreccia forms the basal Cutoff strata for much of the northern portion of Shumard Canyon (over a distance of 0.8 kilometers). Two thinner intraclastic rudstone sheets, less areally extensive, occur in the middle part of the canyon.

Texturally both the intraclastic rudstones and megabreccias within the Cutoff are poorly sorted. Clasts larger than sand size form a clast-supported framework. With few exceptions, fine material ("matrix") pervasively fills all interclastic space. The body of the deposit is not size graded but at least one of the rudstone sheets is graded (IR(S)14) (Symbols refer to rudite composition, texture, and location. See Table 3 for explanation.) In places the largest clasts occur at the base (MB1) but generally this was not observed. The upper surface of some lenses is mound-like (MB1-4, IR10). In places thin graded caps (few centimeters thick in IR10) or 1-3 meters of conglomerate beds (MBI) occur above the main rudite lens, but generally such features are absent.

The larger than sand sized clasts of the rudstones and megabreccias are lithified carbonate rock. Black to dark gray lime mudstone and wackestone, light gray packstone and grainstone are all abundant, and less common lime boundstone also occurs (Pray, personal communication). The rock types of many clasts are very similar to the Cutoff mudstones, Bone Spring mudstone and wackestone, and Victorio Peak packstones and grainstones. All of these formations may have been sources for the clasts. However, it is also possible that the clasts are all derived from the Cutoff or contemporaneous shallow shelf environments. The occurrence in some lenses of boundstone clasts (reef-like and Tubiphytes-rich rock) which do not resemble Bone Spring, Victorio Peak or Cutoff rock types, suggests the source of the clasts was a different type of bank or shelf edge which involved "patch reefs". Because the upslope area to the north-northwest is unavailable for study due to Cenozoic downfaulting and erosion, neither of the two possibilities for the source area can be eliminated.

I believe that the underlying strata (Victorio Peak, Bone Spring) were sources for some of the clasts because of the distribution of different clast types.

In the shelf margin exposures in East Shumard Canyon, the Cutoff overlies the Victorio Peak Formation. Several rudites occur: a rudstone lens (IR12), two rudstone sheets (IR(S)13 and IR(S)14), and a basal megabreccia sheet (MB(S)5). The relative proportions of clast lithologies in the basal rudites differs from the proportion in the rudites higher up in the section. The basal rudites (IR12 and MB(S)5) contain light gray limestone clasts similar to those in the Victorio Peak Formation. In contrast the clasts in the rudstone sheets are predominantly dark gray lime mudstones with light gray limestone lithologies as only a minor component. One explanation is that the light gray limestone clasts were derived from lithified Victorio Peak strata exposed upslope along the shelf margin. The absence of dark mudstone clasts in the basal rudites probably is because the Bone Spring Limestone is the subcrop beneath the Cutoff Formation only to the south (basinwards) of this area. Later in Cutoff time the dark gray mudstones of the Cutoff largely covered the Victorio Peak strata. The Cutoff mudstones must have had some early lithification because these served as a major source for clasts for the later, Cutoff-age rudites. Apparently the Victorio Peak was also locally exposed as a minor clast source.

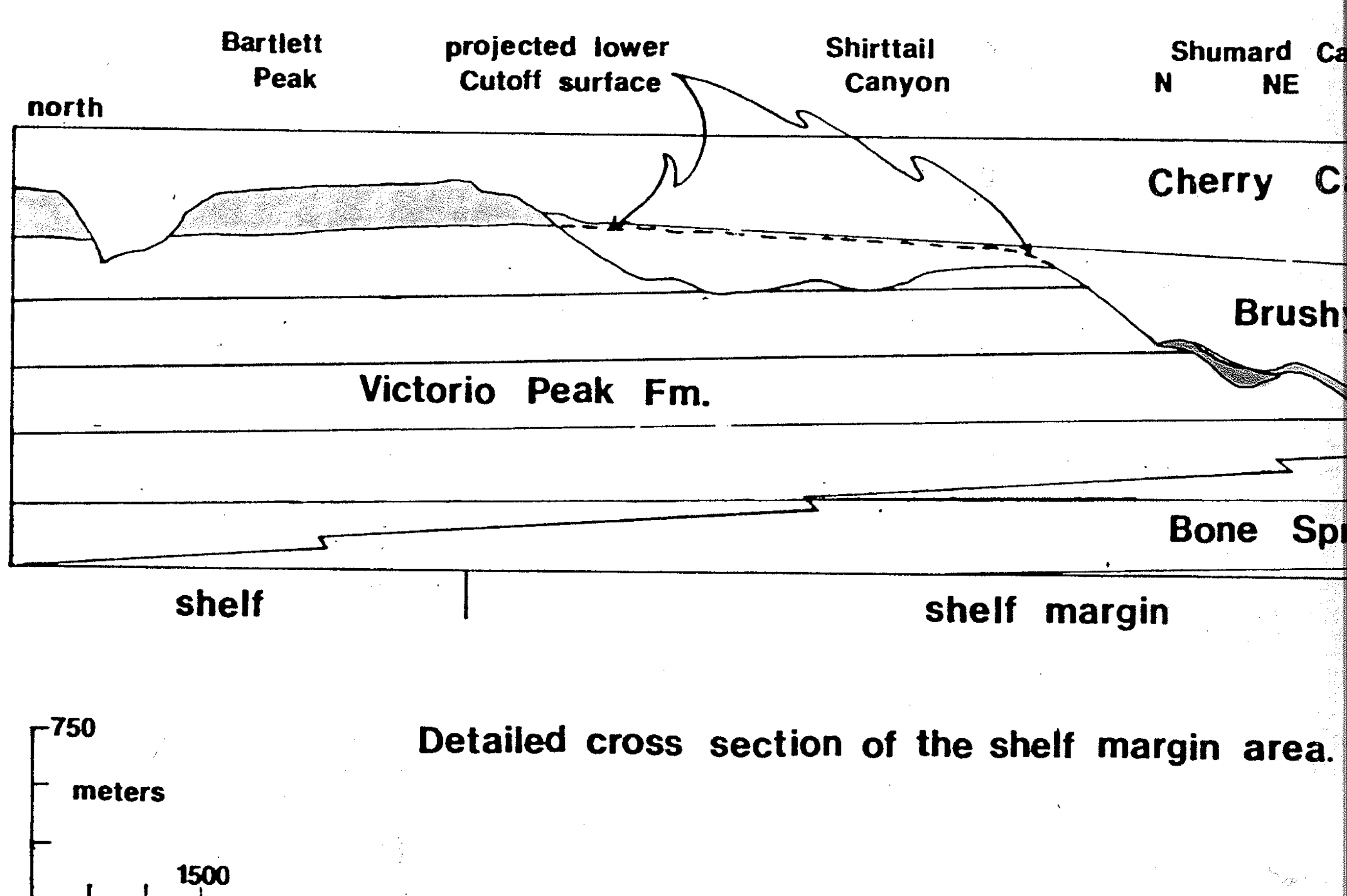
The situation in Bone Canyon is similar to that in Shumard Canyon, namely an upsection shift in clast source from Victorio Peak - Bone Spring strata to a predominantly Cutoff source. However, the contrast of clast lithologies is less dramatic because the Bone Spring Limestone and Cutoff mudstones are both possible sources and cannot be distinguished in the clast population. Based upon unpublished data of Pray and my observations, the basal megabreccia lenses (MB1, 2, and 3) include clasts similar to the entire range of Bone Spring - Victorio Peak lithologies. Intraclastic rudstones (IR8, 9) in correlation unit 5 contain clasts of light gray limestone (very similar to lithologies high on the Victorio Peak bank) and dark mudstone (very similar to Cutoff or Bone Spring lithologies). I suggest the shift of clast types occured because the Victorio Peak and Bone Spring were largely covered by Cutoff strata. The Cutoff and a limited portion of the Victorio Peak served as clast sources at the end of Cutoff deposition.

An alternative interpretation for the upsection shift of clast types in the Cutoff rudites is that contemporaneous shelf-derived material was supplied into the Cutoff strata. This supply decreased with time perhaps due to changes in patterns of sediment dispersal. I consider this alternative less likely because of the sharp decrease upsection of the light gray limestone clasts. This seems to be best explained by the covering of the Victorio Peak bank deposits by the Cutoff strata.

The reef-like boundstone, found as clasts in some lenses, is the best evidence for a source other than the Victorio Peak. This rock type does not occur along the pre-Cutoff surface or any regional equivalent. However, the reefs which were sources of these clasts may have been present in portions of the Victorio Peak bank, or in equivalent shelf environments.

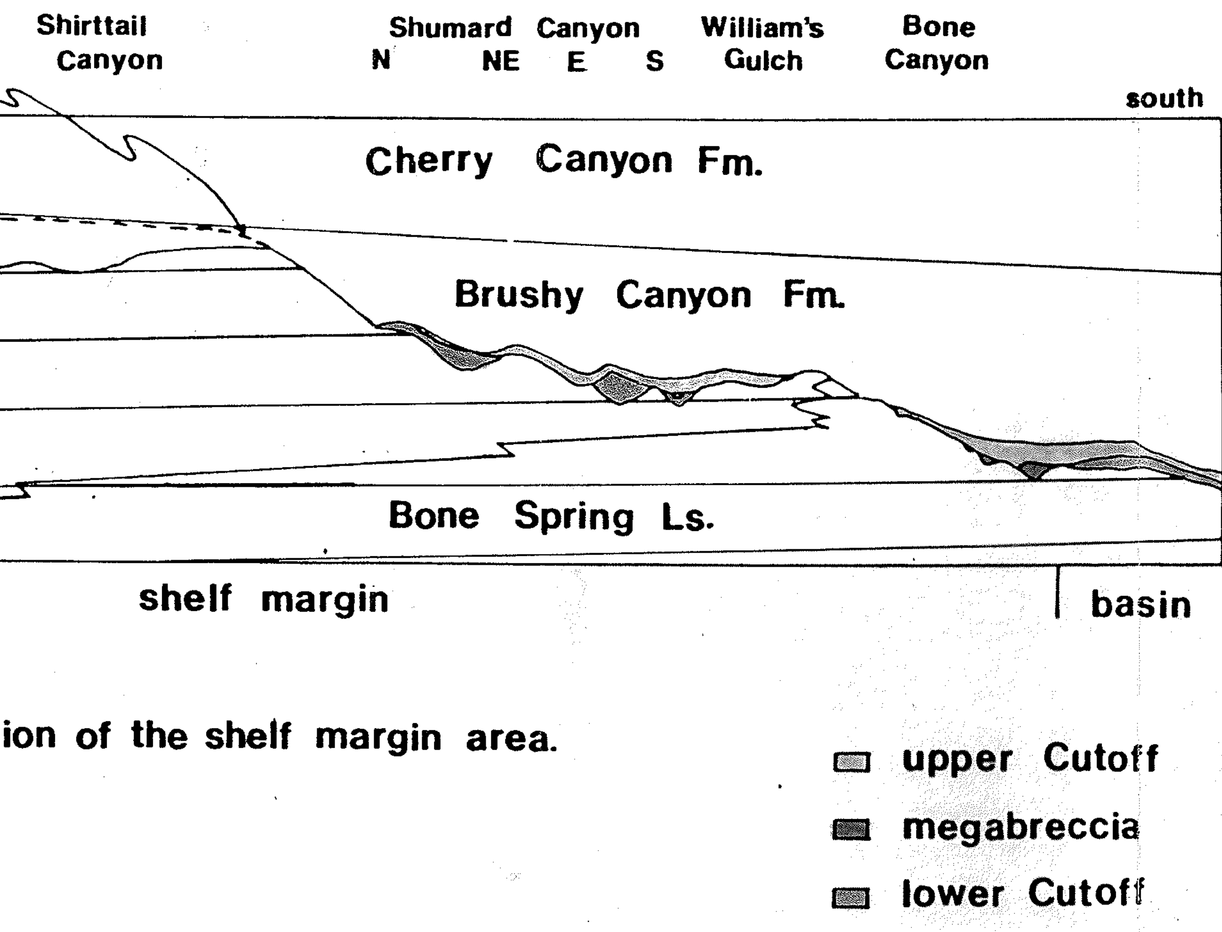
The interpretation of Victorio Peak derived clasts gains plausability if the possible source area is considered. The upper shelf margin is the area from the north edge of Shumard Canyon northwards (upslope) to the appearance of the shelf Cutoff 0.8 kilometers north of Shirttail Canyon. In this area the Cutoff is missing and the Victorio Peak strata are deeply truncated to form a recessive step in the shelf profile (Fig. 20). The upper shelf margin appears to have been an area of continued erosion and retreat to the shelf edge throughout Cutoff deposition. I suggest that this could be the source for the clasts (Cutoff and Victorio Peak) in the upper rudites.

Figure 20



Detailed cross section of the shelf margin area.

Figure 20



ion of the shelf margin area.

Lutites

Lutites are the second most abundant channel-filling rock type. Any of the lutites (mudstones or shale) previously described may fill channel-shaped scours. The beds of the lutite may thicken slightly into the scours, but generally the bed thickness is nearly constant over both scours and adjacent surfaces.

Generally the lutite lithologies fill broad, nearly flat bottomed scours. These lutite-filled scours are often difficult to detect because the scours are cut into lutites as well. In places a sharp lithology contrast (north wall of South Shumard Canyon, see figure 29) or an exceptional exposure (south wall of Bone Canyon, see figure 25) make the lutite-filled channels more readily visible.

Skeletal rudstone

This rock type is a rudstone in which the predominant type of clasts are a variety of invertebrate skeletals and a lesser amount of lithified carbonate intraclasts (Fig. 21). The clasts range in size from 0.2 to 10 millimeters with an average size of about 0.5 millimeters. They are in grain support and only a minor amount of mud is present. The cement is carbonate but both the cement and the skeletals have been partially silicified. This contrasts with the well-preserved and unsilicified fauna in the mudstones. This contrast is probably caused by a difference in the

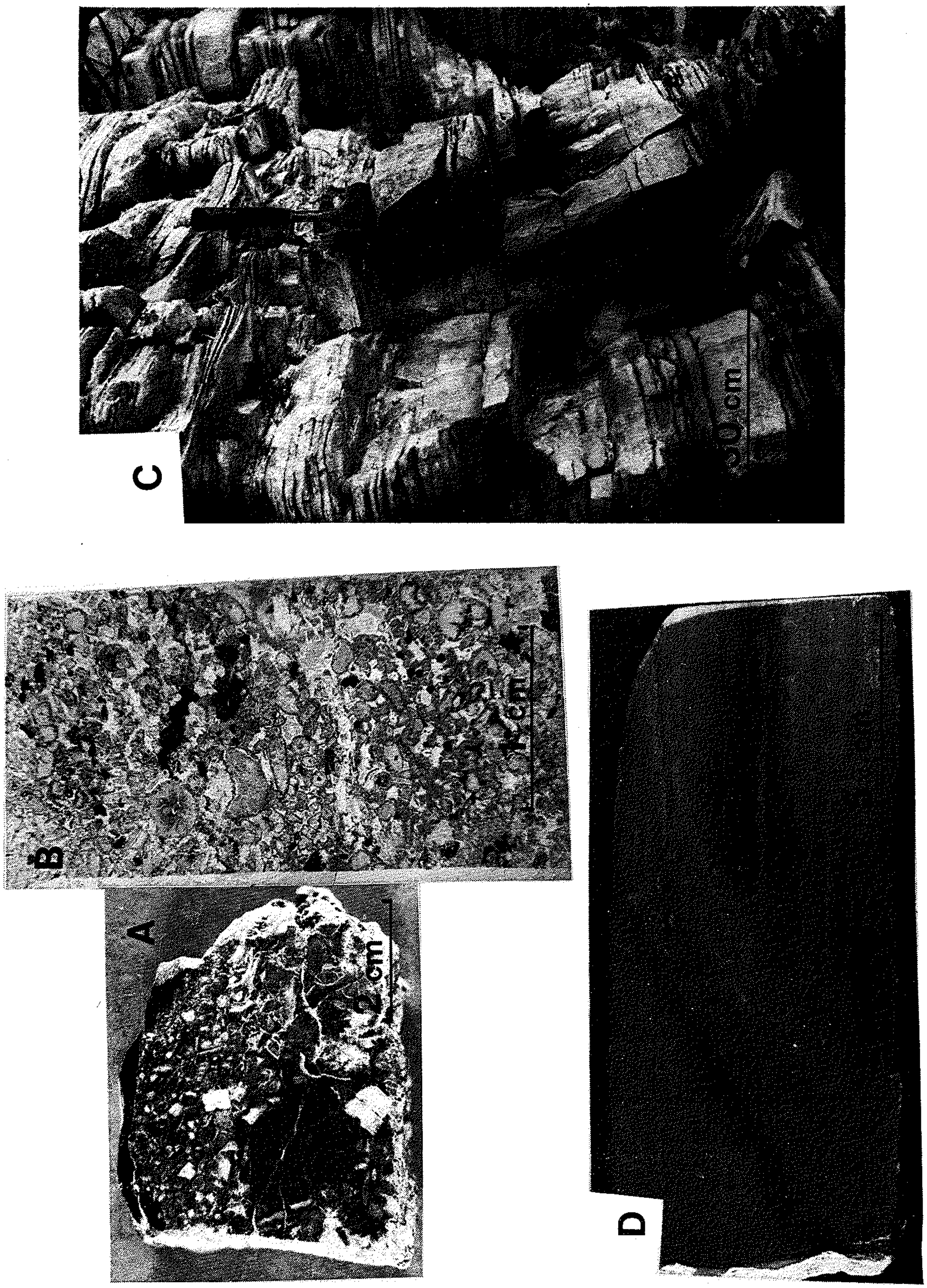
Figure 21: Skeletal rudsotne and sandstone.

A. Skeletal rudstone, SK(V)1. Polished slab, section B, 1' level, specimen U.W. 1718/18.

B. Skeletal rudstone, SK(V)2. Thin section, section G, 40' level, specimen U.W. 1719/19.

C. Quartz sandstone, lower Cutoff Formation, initial channel fill, northeast of section J, Shumard Canyon. Filed photograph.

D. Same as C. Polished slab, specimen U.W. 1719/20.


C
B
A
D

permeability of the lithologies. The siliceous fluids were able to move through the porous rudstones but not the mudstone.

This rock type is limited to small channel fillings, generally less than 1 meter in thickness and 10 meters in width. Several occur in the basin and one is in the shelf margin area (Williams Gulch, section G).

Tan, thinly laminated sandstone

This rock type is tan, thinly laminated, thin-bedded, fine-grained quartz sandstone (Fig. 21). It is only present within the Cutoff at the bottom of the Shumard Canyon channel. This channel is largely filled by the lower Cutoff mudstone but two meters of this sandstone forms the initial channel-filling deposit. It is exposed on the west side of the channel on both the north and south walls of South Shumard Canyon. The sandstone beds are truncated and overlain by lenses of intraclastic rudstone (IR11, 12) and beds of mudstone. The sandstone may have originally extended across the entire 100-meter width of the base of the channel.

INTERPRETATION OF LENS AND SHEET DEPOSITS

The rudstones, megabreccias, and sandstone in the Cutoff are located in the shelf margin and basin area. They are composed of material apparently derived from the shelf and upper shelf margin. These deposits are subaqueous gravity flows (Cook *et al.*, 1972; Mountjoy *et al.*, 1972). Dott (1963) recognized four classes of such flows: rockfalls, slumping and sliding, mass flows, and turbidity flows. The latter two have been divided by Middleton and Hampton (1976) into debris flows, turibidity currents, fluidized flows, and grain flows. Harms (1974) considers the additional transport mechanism of density interflows for coarse silts.

Crawford (in progress) considered similar thin deposits with a coarser sand size in the Goat Seep Formation (Guadalupian). These deposits are also at a toe-of-slope at the shelf margin of the Delaware Basin. Crawford concluded that debris flows, fluidized flows, and density interflows were the major depositional mechanisms. From both field evidence and theoretical considerations he was able to show that the debris flows were of two types: turbulent and laminar. Turbulent behavior was favored by steeper slopes and thicker flows.

Before speculating about possible mechanisms it is worthwhile to consider what possibilities can be eliminated. Grain flows were proposed by Bagnold (1956) as a transport mechanism for sand. This proposal has been discussed at length in literature. Most recently Lowe (1976) has argued that grain flows can only flow at angles near the angle of repose, and that grain flow deposits are normally less than 5 centimeters thick. If correct, the angle of slope (5-10°) and the thickness (1-30 meters) of the rudstones and megabreccias are evidence against a grain flow mechanism. Turbidity flows are not believed important because graded beds are essentially absent from the Cutoff. One bed about 20 centimeters thick containing several graded sequences occurs in the southeast wall of Bone Canyon. This is the only example observed of graded bedding of the type predicted by the turbidity current model. Fluidized flows appear unable to transport material in a subaqueous setting because the supporting pore fluids are quickly dissipated (Middleton and Hampton, 1976). No evidence of rockfalls or slumping and sliding are recognized. All these mechanisms are believed to be of minor importance for the transport of material into the basin during Cutoff deposition.

Both the sandstone and those rudstones which lack pervasive fine material in the interparticle position between grain-supported clasts are sorted channel deposits. The process of transport did not involve a major amount of muddy material. Turbulent bottom-currents appear responsible for these deposits and the cutting of their channels. The bottom-hugging currents may have been density-driven underflows, as suggested by Harms (1974) for the transport of channel-filling sands in the Delaware Mountain Group.

The clast-supported megabreccias and rudstones with a pervasive matrix are problematical because their texture cannot be understood by any present model of depositional processes. The texture is most similar to the texture of a debris flow but there are some differences. Textural features in common are: 1) pervasive fine material fills all spaces, leaving no voids between the clasts, 2) seriate texture, 3) disorganized, ungraded position of the clasts, 4) general lack of any internal stratification, and 5) bumpy or mound-like upper surface due to local protruding of clasts from some deposits. These features support the inference that the megabreccias and matrix-rich rudstones are the deposit of a debris flow.

Differing sharply from the debris flow model are two features which suggest turbulent flow: 1) the clast-supported texture, and 2) the erosional, channeled bases of the megabreccias and rudstones. The clast-supported texture suggests turbulent flow but this texture could conceivably result from post-depositional settling of clasts through the less dense matrix of a liminar debris flow; however, this seems unlikely. The erosional bases of the lenses vary widely in shape. Some are steep-sided (10-20^{o}) and completely filled with rudite (MBI-4, IR10). I suggest that the channel cutting and filling are closely related and that this relationship may be the result of common origin from a turbulent flow. Other scours are broad features with flatter sides ($<10^{o}$) in which the rudite is not the dominant fill. Two examples are present on the south wall of Bone Canyon (IR8, 9). The broad channel of the shelf margin containing the lower Cutoff in Shumard Canyon is another such feature. Here it can be clearly shown that the rudite was not the initial channel fill. One to two meters of the remnants of sandstone beds beneath the rudite indicate that sandstone was an earlier channel fill. The sandstone fill was later truncated and overlain by intraclastic rudstone lenses (IR11, 12). The rudites may be related to the truncation of the sandstone but they are separate from the channel-cutting event.

The amount of turbulence associated with those rudstones with a pervasive matrix and the megabreccias is uncertain. These rudites all overlie erosional surfaces but may or may not be related to the cutting of the channels. The persistent association of these rudites with erosion surfaces is suggestive that these deposits are the result of turbulent flows which eroded material.

Debris flows are normally inferred to be laminar gravity flows. Winn and Dott (1979) found evidence of turbulent behavior associated with debris flow deposits, as did Crawford (in progress). Crawford also demonstrated that turbulent debris flows are possible from fluid mechanics theory. Turbulent behavior is favored by steeper slopes and thicker flows. I suggest that the rudstones with a pervasive matrix and megabreccias are debris flows. Some of these may have been turbulent as well, the megabreccias in particular, but for most of these rudites the presence or absence of turbulent flow cannot be determined.

Above the rudite lenses two types of caps are observed. A thin, graded cap (Cook et al., 1972) a few centimeters thick occurs above an intraclastic rudstone lens (IR10) on the north wall of Bone Canyon. This thin cap is probably the final deposit of the (debris?) flow, a tail of finer-grained material settling behind the body of the flow. Other rudites such as the megabreccia lens south of the mouth of Bone Canyon (BM1) are capped by 1-3 meters of conglomerate beds. These beds appear due to either: 1) the reworking and/or winnowing of the uppermost portion of the deposit by latter currents, or 2) later channelized flow.

The lutite deposits are suspension deposits as discussed above. The depositional style (and presumably depositional process) is little affected by the bottom topography. The bedding thickens only slightly into paleotopographic lows which range in depth from a few centimeters to 40 meters.

In summary a variety of depositional processes are inferred for the lens and sheet deposits in the Cutoff strata. Mud-lean intraclastic rudstones and skeletal rudstones are inferred to be the channel deposits of density-driven bottom currents. The mud-rich intraclastic rudstones and megabreccias are probematical but a mechanism analogous to a debris flow (possibly turbulent) is suggested. The lutite channel-fills are suspension deposits.

Depositional processes-which model?

The variety of rock types indicate a variety of depositional processes for Cutoff strata. The relationship of fine-grained material to channel fills are quite similar to features within the deep-water deposits of the overlying Delaware Mountain Group: draping lutite beds and coarser channel deposits (Harms and Pray, 1974). To date two contrasting models of depositional processes and setting have been proposed for the Delaware Mountain Group. A review of these models may help in interpretation of the Cutoff.

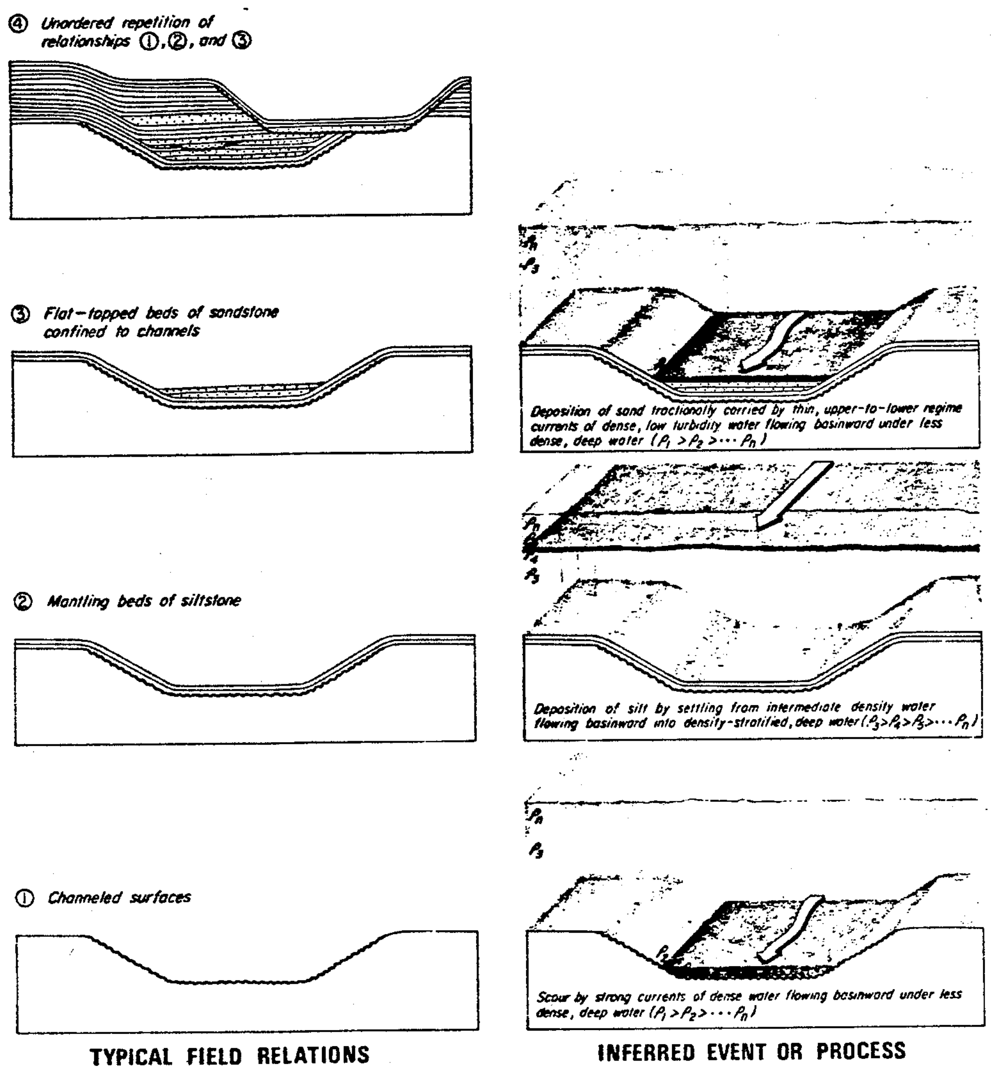
Delaware Mountain Group models

Turbidity currents and deep-sea fans: The model proposed by Jacka and his co-workers (Jacka et al., 1968; 1969) relies upon analogy with modern continental slopes. They proposed that the Delaware Mountain Group is composed of a complex of prograding and recessional deep-sea fans. This interpretation is based on: 1) the vertical sequence of lithologies which fill the channels, 2) presence of turbidite deposits, and 3) proximal to distal changes of lithology. These features were considered similar to modern deep-sea fans, leading Jacka and co-workers to a straightforward analogy. Large scale variations were identified, tied to cyclic shelf models, and finally inferred to be related to glacial sea level fluctuations.

Density currents and draping silts: Harms and Pray (1974) and Harms (1974) proposed a depositional model which differs in both observations and interpretations. In his detailed analysis of the Delaware Mountain Group, Harms (1974) recognized the lateral continuity of channel fillings. The features noted were in contrast to the observations of the Jacka group: 1) lutite (predominantly silt) beds which drape over both channel features and interchannel areas, 2) sand deposits which are limited to the channel filling deposits, and 3) lack of graded beds or any proximal to distal changes. Based on depositional geometry the lutites were interpreted as suspension deposits and the sands as traction load deposits (Fig. 22).

Harms and Pray (1974) and Harms (1974) inferred a density stratified basin with density currents spilling off the shelf. These density currents were turbulent and driven by salinity and/or temperature contrasts. They can account for the observed sedimentation features in

Figure 22



Typical bedding relations in Brushy Canyon Formation and their interpretations.

Harms' (1974) model of deep-water sedimentation for the Brushy Canyon Formation (Guadalupian) the Delaware Mountain Group. Dense bottom-hugging flows erode channels and deposit the channel-filling sands. Interflows along surfaces of density contrasts carry the draping silts far out over the basin. Density currents were not limited to a fan network but spread over the slope and basin. These currents were also suggested as the erosional agents of unconformity formation. The slope margin area was also believed affected by episodic phenomena such as debris flows, slumps, or deep wave action.

Recent studies of the Delaware Mountain Group have supported this interpretation (Bozanich, 1979; Williamson, 1979).

Cutoff depositional model

The two models of deep water sedimentation in the Delaware Basin differ in both depositional mechanism and resulting deposit. Draping beds from interflows differ from graded turbidite beds. Within the Delaware Mountain Group the draping silt beds have supported the density current model. But what is the case in the Cutoff?

The depositional geometries in the Cutoff are well described by the density current-draping silt model, as first suggested by Harms and Pray (1974). The general lack of graded beds is strong evidence against turbidity current deposition, especially in the carbonate deposits that have a wide range of particle sizes. The absence of any apparent proximal-distal variations is also evidence against the existence of a deep-sea fan.

The strata are predominantly draping lutite beds, including broad channel fillings. These are inferred to be suspension deposits. Other channel deposits include: 1) traction deposits from bottom currents (mud-lean rudstones and sandstones), and 2) debris flows or some similar process (mud-rich rudstones and megabreccias). The shelf margin and basin edge are areas of erosional activity. These are all features which favor the application of the density current model to Cutoff deposition.

In comparison with the Delaware Mountain Group, there are differences. In the Cutoff: 1) carbonate predominates 2) silt-sized sediment is less abundant because the lutites are chiefly comprised of clay-sized particles, 3) traction deposits (sand-size or greater) are less abundant, and 4) debris flow deposits are more common.

In the Cutoff a combination of suspension and traction deposition is indicated. The relative abundance of each may differ from that in the Delaware Mountain Group but the depositional geometries are similar. The predominance of draping lutite layers indicates a large amount of deposition from suspension. The near constant thickness of lutites from the shelf far into the basin suggests that the fine particles were actively carried out into the basin prior to settling or that the particles originated on the surface waters of the basin. Because silt is not normally carried in suspension far into a basin, the presence of silt in the basinal Cutoff also suggests active transport. Harms' suggestion (1974) of density-driven interflows for transporting silt into a basin is one possible solution. Turbulent interflows could transport large amounts of clay and lime mud into basin waters away from the shelf. The suspended clay-size material may provide the density contrast needed for flow movement. Temperature and salinity contrasts could also be responsible, as suggested by Harms for the Delaware Mountain Group (which lacks shale or any clay-sized material).

The effects of bottom-hugging traction currents are abundant. Channel erosion and bed scour indicate currents were probably moving down the shelf margin and across the basin. The bottom-hugging currents eroded broad (in places over 100 meters in width), low relief channels at the toe of the shelf margin slope (see next section). In Bone Canyon (Fig. 25) these lenticular channel fills make up half to two-thirds of the upper Cutoff strata. These channels are predominantly lutite-filled, but the low abundance of deposits coarser than silt-size may reflect a low supply of coarse material rather than a lack of currents competent enough to carry them. Sand size material in contemporaneous

Permian strata (San Andres) is generally restricted to the backshelf. The only available coarse materials were clasts of lithified carbonate or material derived from shelf edge failure (slump, etc.) resulting in debris flow (cf. Radar, see Newell et al., 1953). Much of this material was carried down the shelf margin by debris flows (turbulent?) in channels or in sheet-like bodies.

In summary, the depositional geometries within the Cutoff indicate primarily suspension deposition and a lesser amount of traction deposition. Turbulent bottom-currents were active in eroding channels. A system of density currents (both interflows and bottom flows) driven by density contrasts due to suspended fine material, salinity and/or temperature contrasts best explains the pattern of deep-water sedimentation. I have recognized no evidence for a deep-sea fan system, where major introduction of material is in a channel system with distal distributaries. Instead it appears as if channels were more randomly distributed along a depositional slope and that major deposits mantled all of the shelf margin, as also inferred for the Delaware Mountain Group by Harms and Pray (1974) and Harms (1974).

EROSIONAL PHENOMENA

"If she give ought,
she deals it in small parcels
That she may take away
all at one swoop."
Webster

Introduction

Evidence of erosional removal of material is abundant in the Cutoff Formation. The erosional surfaces associated with the channel and sheet deposits are mute testimony to this. More subtle but more extensive are the widespread erosional surfaces which occur at the base of the Cutoff, between lower and upper Cutoff, and at the upper contact with the Brushy Canyon Formation (King, 1948; Pray, 1971; Pray *et al.*, 1980). These surfaces are laterally extensive and can be traced throughout the 16 kilometers of the study area. I consider these erosional surfaces unconformities because of the angular relationship of strata above and below the surfaces, and because of the lateral extent of the surfaces from shelf to basin. The origin of these unconformity surfaces will be discussed below.

Channels within the Cutoff strata are abundant in the shelf margin and basin areas, but absent in the shelf area. Up to 10-30 meters of underlying strata may be locally removed along these erosional features. On a smaller scale erosional surfaces may truncate only one or more beds of strata (one meter or less).

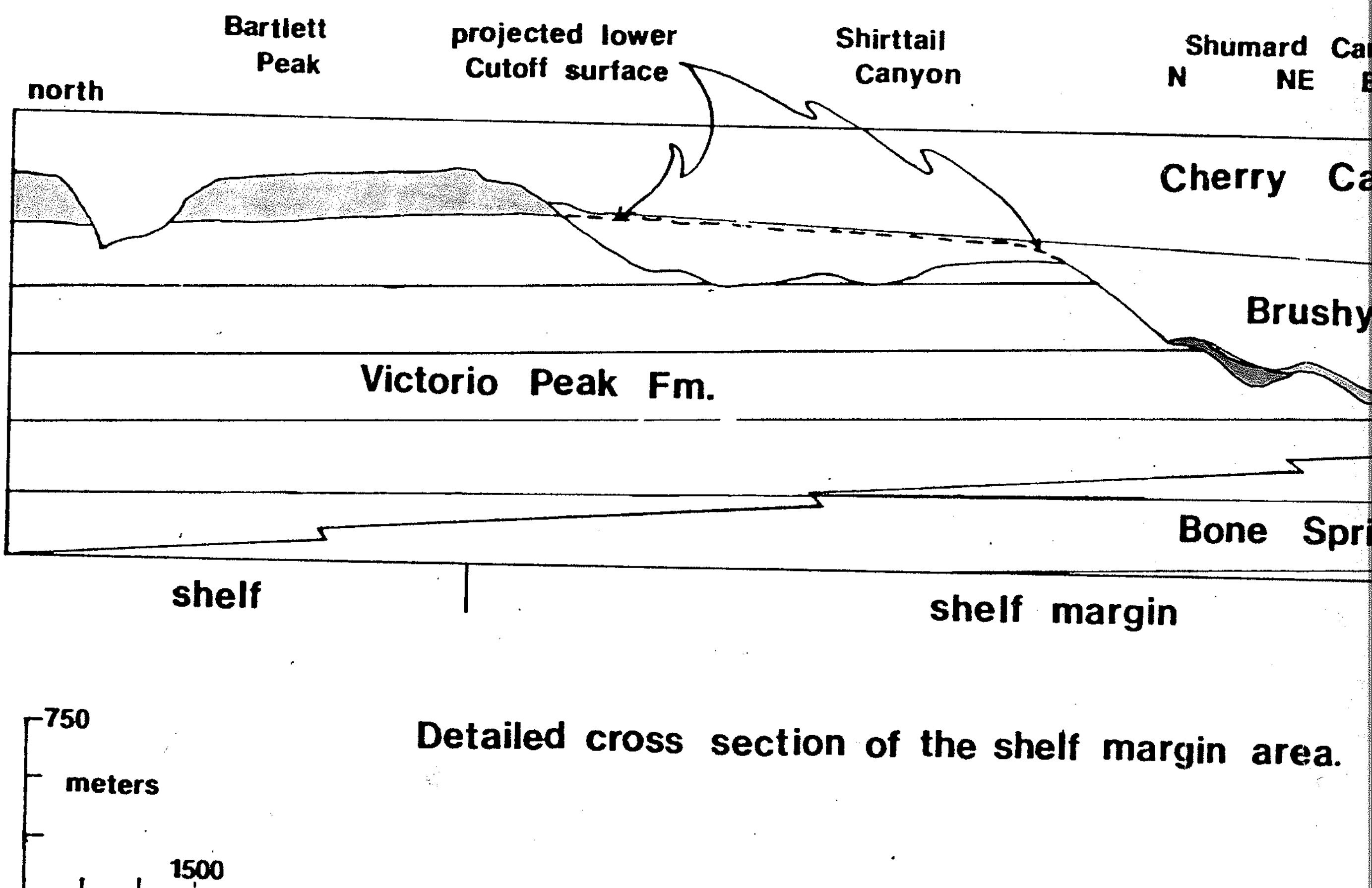
A bottom-current system of varying strength appears to have been operative at least during some of Cutoff time. Generally the effects are negligible but occasionally erosion increased to carve 30 meter deep channels and form the unconformities from shelf to basin.

Examples of erosion surfaces

Erosion surfaces are concentrated along the shelf margin (Shumard Canyon) and basin edge (Bone Canyon). The stratigraphic relationships in this area are complex, due in part to the erosional events (Fig. 4, 23). Before presenting the details of these exposures, the following discussion provides a useful outline.

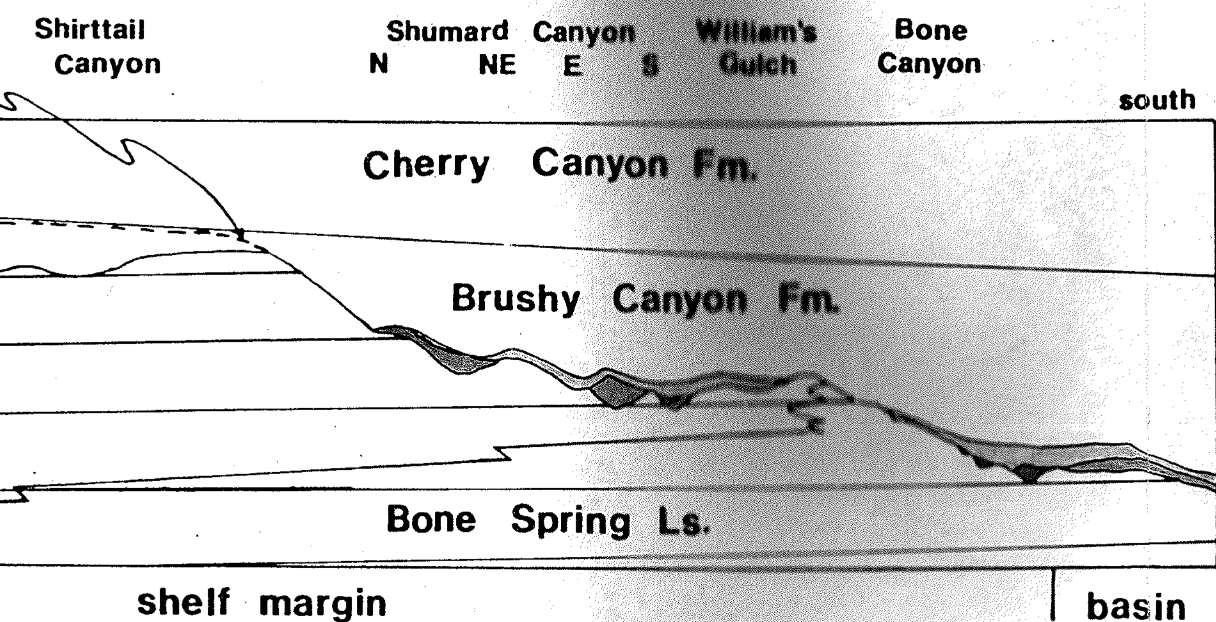
Both the lower and upper Cutoff Formation occur in the basin, underlain by the Bone Spring Limestone and overlain by the Brushy Canyon Formation. The lower Cutoff strata from the basin are erosionally truncated 0.4 kilometers south of Bone Canyon. The upper Cutoff strata persists northwards to the toe of the sloping bank margin, located in Bone Canyon. The south wall of this canyon exposes a complex pattern of broad (100+ meters wide) channels within the Cutoff Formation, with both lutite and intraclastic rudstone fills. The contact with the underlying Bone Spring Limestone is an erosional unconformity along which two channel lenses of megabreccia occur (a third is exposed just

Figure 23



Detailed cross section of the shelf margin area.

Figure 23



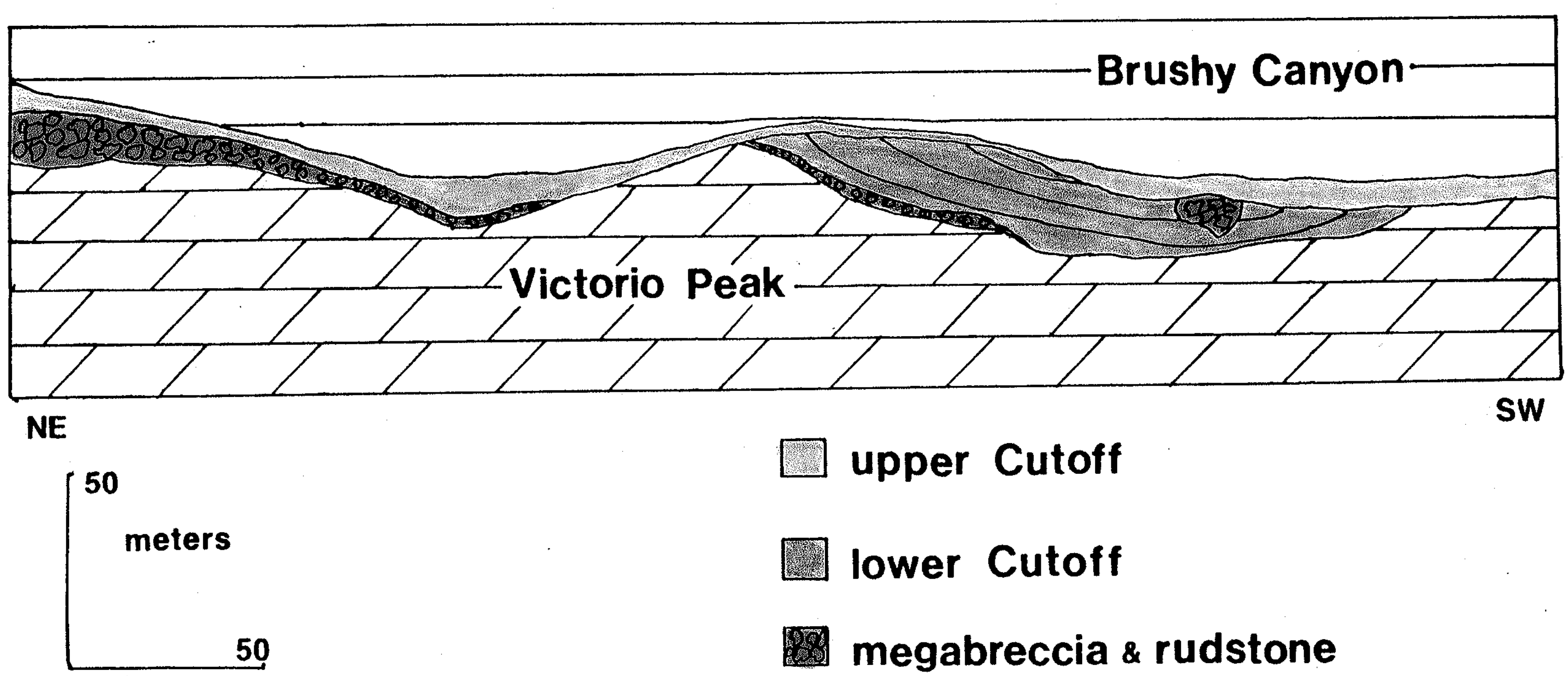
ion of the shelf margin area.

south of the canyon mouth). The contact with the overlying Brushy Canyon Formation is also an erosional unconformity. The basal Brushy Canyon strata are composed of onlapping beds of conglomerate (King, 1948). The north wall of Bone Canyon reveals similar unconformable relationships except the post-Cutoff unconformity truncates the Cutoff Formation in the center of the north wall. The stratigraphic relationships in Bone Canyon were detailed by King (1948) and Newell et al., (1953). However, it was the later work of Pray and Stehli (1963), Pray (1971), and Harms and Pray (1974) which recognized the importance of the erosional surfaces.

The shelf margin exposures of the Cutoff Formation occur in Shumard Canyon and Williams Gulch (the informal name for the draw between Bone and Shumard Canyons, originally used by McDaniel and Pray; see figure 3). The upper Cutoff strata occur in Williams Gulch, 400 meters north of the pinchout of basin Cutoff in Bone Canyon. From here it can be traced to the northern truncation of shelf margin Cutoff 1.5 kilometers to the north in North Shumard Canyon (Fig. 4, 23). The upper Cutoff strata contain channels filled with intraclastic and skeletal rudstone. The lower Cutoff Formation fills the most spectacular channel of the shelf margin area (Fig. 24). This occurs in South Shumard Canyon, and cuts 30 meters into the Victorio Peak. It was

Figure 24

View towards SE Shumard Canyon



first mapped by King (1948). The channel filling is predominantly lutite but includes megabreccia, intraclastic rudstone, and sandstone. The surface between upper and lower Cutoff Formation is an erosional unconformity which truncates the lower Cutoff strata. Throughout the shelf margin area the Cutoff Formation is underlain by the Victorio Peak Formation and overlain by the Brushy Canyon Formation. The interformational contacts are erosional surfaces which dip basinwards (Pray, 1971). The origin of these surfaces is not well understood (Pray _et al_., 1980), as discussed below.

Shelfwards (to the north) these erosion surfaces rise both stratigraphically and physically (Fig. 23). North of the northern (shelfwards) pinchout of shelf margin Cutoff strata, they merge together. The upper Cutoff Formation occurs 1.6 kilometers to the north in a shelf position, as mapped by King (1948). The pre-Cutoff unconformity flattens abruptly, but the post-Cutoff unconformity continues to rise another 70 meters to the top of the Cutoff strata. The morphology of the truncation surface at this shelf edge is that of a "half-channel", as discussed below. The Brushy Canyon Formation onlaps about 300 meters of Victorio Peak Formation and 10 meters of shelf Cutoff strata along the post-Cutoff surface over a distance of 2.5-3 kilometers (Fig. 4, 23), as described by King (1948). The

Brushy Canyon strata pinch out 10 meters above the base of the shelf Cutoff. Above this the Cherry Canyon Formation onlaps the remaining 60 meters of the truncated Cutoff strata. Shelfwards the Cutoff Formation does not contain any internal channel features, but it is cut by a major channel of post-Cutoff age which occurs 0.3 kilometers north of Bartlett Peak. This channel (termed the Bartlett Channel because of its proximity to Bartlett Peak) was first discovered by McDaniel and Pray (1967) and illustrated by Harms (1974). It cuts through 70 meters of Cutoff strata and 30 meters of Victorio Peak strata, and is filled by Cherry Canyon Sandstone. It is the only large erosional feature on the shelf except for the very low angle truncation of the underlying Victorio Peak.

With this summary as a framework, the following sections discuss the evidence of erosional phenomena in specific parts of my study area. The discussion begins in the basin and works northwards across the shelf margin to the shelf. Figure 23 should be consulted as a guide in this discussion in addition to the individual canyon wall mosaics presented.

Basin edge (Bone Canyon)

The exposures on the walls of Bone Canyon are the clearest examples of erosional phenomena within the Cutoff Formation. Erosional features on a variety of scales are present. Bone Canyon is located at the basin edge and is the most accessible portion of the study area.

The Cutoff strata in Bone Canyon were first recognized by Newell _et al_., (1953). Their "patch reefs", now interpreted as channel-filling megabreccias (Pray and Stehli, 1963), occur in this area.

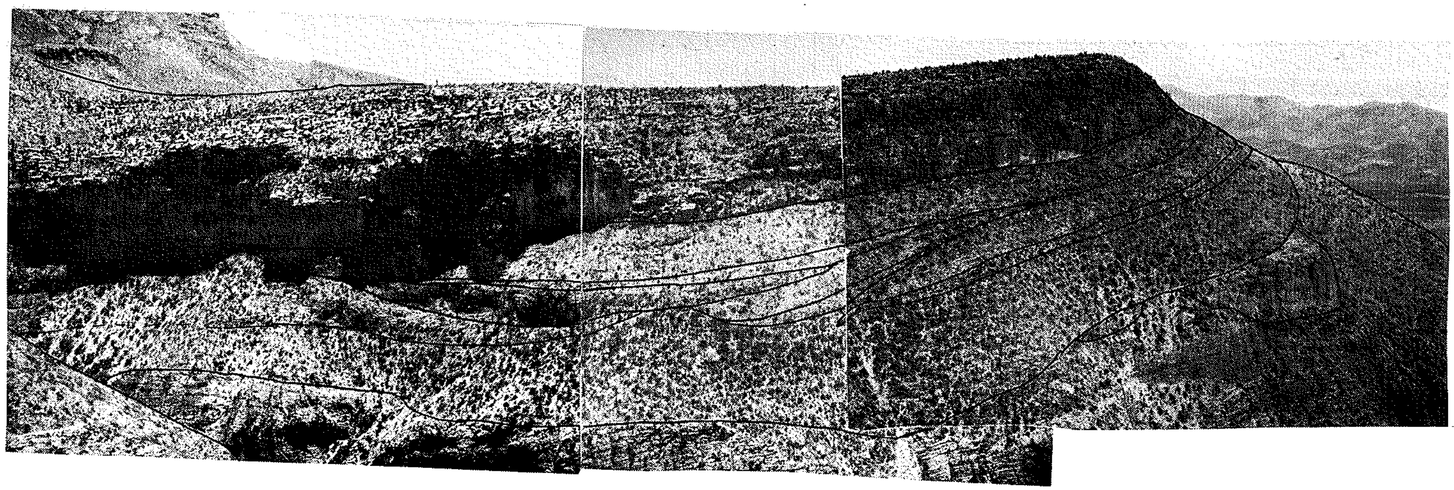
South wall: The south wall of Bone Canyon (Fig. 25) exposes about 300 meters of strata of three rock units: Bone Spring Limestone, upper Cutoff Formation, and Brushy Canyon Formation. The lower steep cliffs of black limestone are the Bone Spring and the upper cliffs are the Brushy Canyon, sandstone with a basal conglomerate. The less resistant strata between are the Cutoff.

The upper surface of the Bone Spring Limestone is the basal Cutoff unconformity. It is visible due to the undulating low-angle truncation of the bedding in the Bone Spring Limestone. The upper surface of the Cutoff is a basin sloping erosional surface (unconformity) which is capped over most of the east-west exposure by basal conglomerate beds of the Brushy Canyon (King, 1948). These two unconformity surfaces are the two most laterally extensive erosional features visible in Bone Canyon. They serve to vertically bound the Cutoff strata.

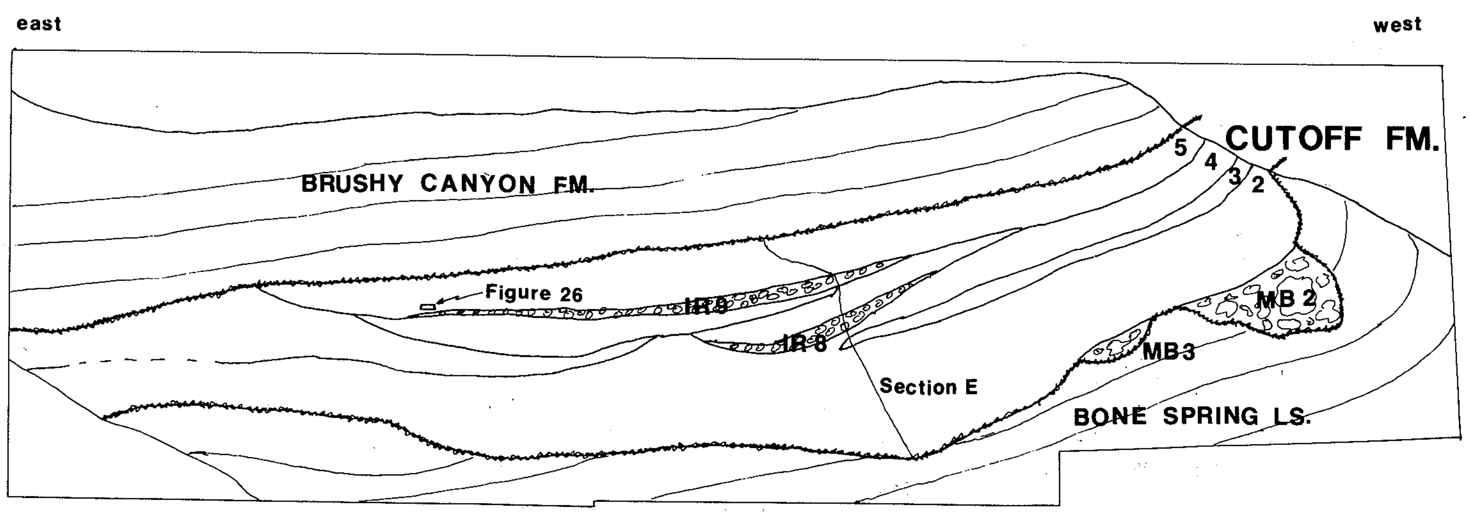
Two megabreccia channel lenses (MB2 & 3) occur along the lower unconformity towards the west end of the canyon.

Figure 25: South wall of Bone Canyon

Three formations are exposed in the south wall of Bone Canyon. From canyon bottom upwards, they are: Bone Spring Limestone (lower cliffs), Cutoff Formation (recessive slope), and Brushy Canyon Formation (upper cliffs). The formations are seperated by erosional unconformities (incicated by cross-hatched lines in the sketch) which truncate underlying strata. Smaller scale erosional phenomena occur within the Cutoff strata. At the western edge of the canyon wall, all units (2-5) of the upper Cutoff strata occur, and can be traced basinwards (south) from Bone Canyon. Unit 3 (lime mudstone) is erosionally truncated east of the canyon mouth, and the interbedded lime mudstone-siliceous shale of units 2 and 4 merge. In the center of the canyon wall, the three 100-200 mter wide channels with flat sides occur in unit 5. In two of these broad channels, intraclastic rudstone lenses (IR 8 and 9) form the basal channel fill. Two smaller, channel-filling lenses of megabreccia (MB 2 and 3) occur along the basal Cutoff surface.



South wall of Bone Canyon

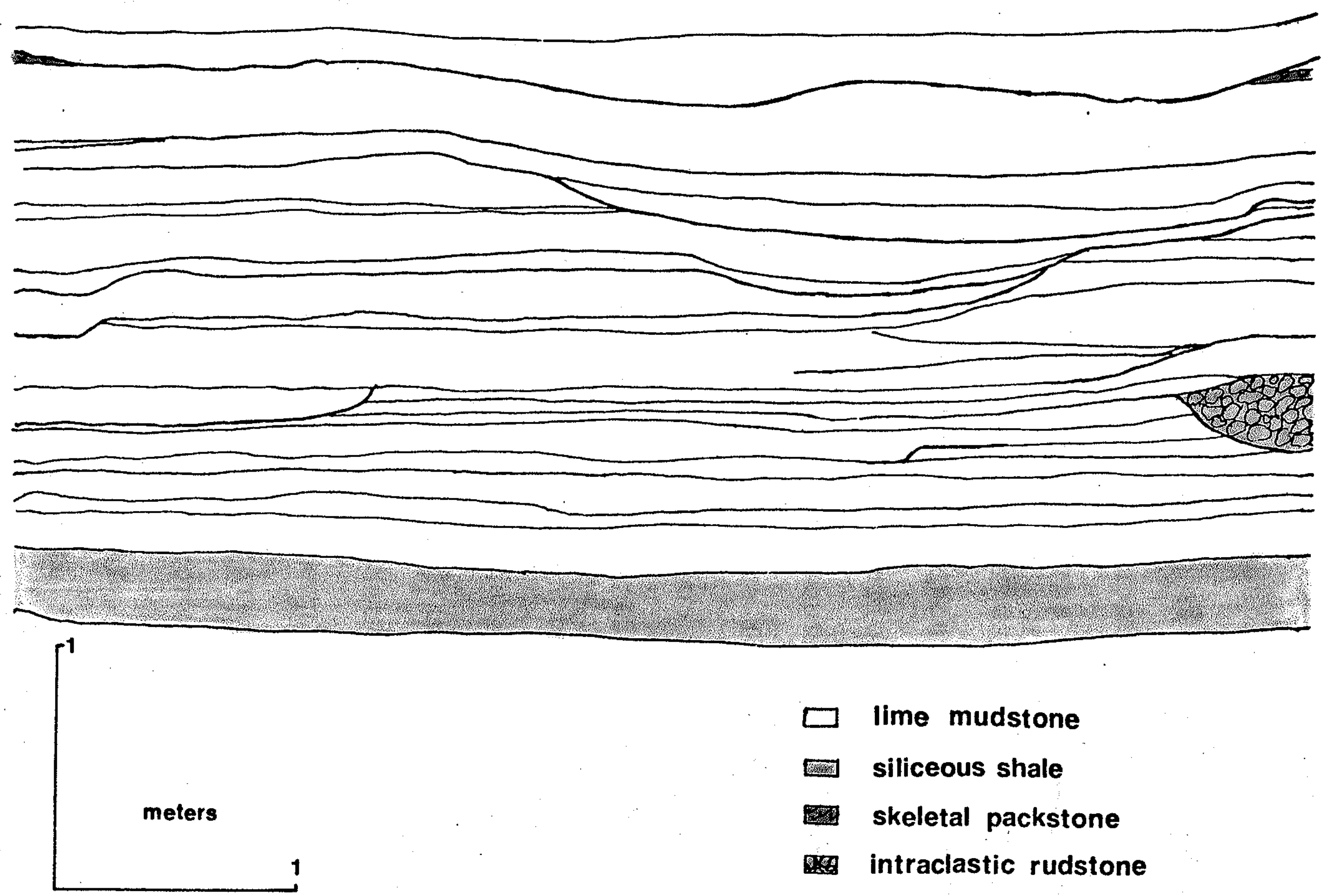


A third lens of megabreccia (MB1) occurs 0.4 kilometers south of the center of Bone Canyon. Less obvious but laterally more extensive features are the broad, 30 to 100 meter wide channel scours within the Cutoff strata with sides which rise at a low angle. Intraclastic rudstone lenses (IR8 & 9) occur at the bases of two of these channels. The resulting complex of erosion surfaces indicates that stratigraphic removal along each broad channel was on the scale of about 10 meters each.

On the scale of individual beds, scours of several centimeters are abundant in the discontinuously bedded mudstone of correlation unit 5. To show this relationship a detailed sketch was made of a portion of the filling of a 45 meter wide channel in southeast Bone Canyon (Fig. 26). At the base of the channel filling is a bed of very thinly laminated siliceous shale. The bulk of the channel fill is nonlaminated, medium bedded lime mudstone. Laterally the individual beds are discontinuous due to scour. This discontinuity is well illustrated by the thin layer of skeletal packstone which is absent across most of the sketch due to a 1/4 meter deep scour. A rudstone lens fills a small (1/3 of a meter) scour. Above this are the only two beds which contain graded sequences, except for "graded caps" of some rudites, observed in the Cutoff strata. On this fine scale the relationships duplicate

Figure 26

Detail of bedding in upper limestone unit in southeast Bone Canyon



the larger scale pattern found on the canyon wall: bed truncation, channeling, draping lutite beds, and rudite-filled channel lenses.

North wall: The shelfward pinchout of the basin Cutoff strata is exposed in the center of the north wall of Bone Canyon (Fig. 27) beneath the onlapping beds of the Brushy Canyon Formation. A channel lens at the top of the Cutoff, composed of interclastic rudstone (IR10), occurs 60 meters southeast of the pinchout. The sharp truncation pattern at the pinchout implies the same sequence of events as indicated on the south wall, namely: deposition of the Bone Spring Limestone followed by erosion, deposition of the Cutoff Formation followed by a second major erosional episode, and finally deposition of the Brushy Canyon Formation.

Shelf margin (Williams Gulch-Shumard Canyon)

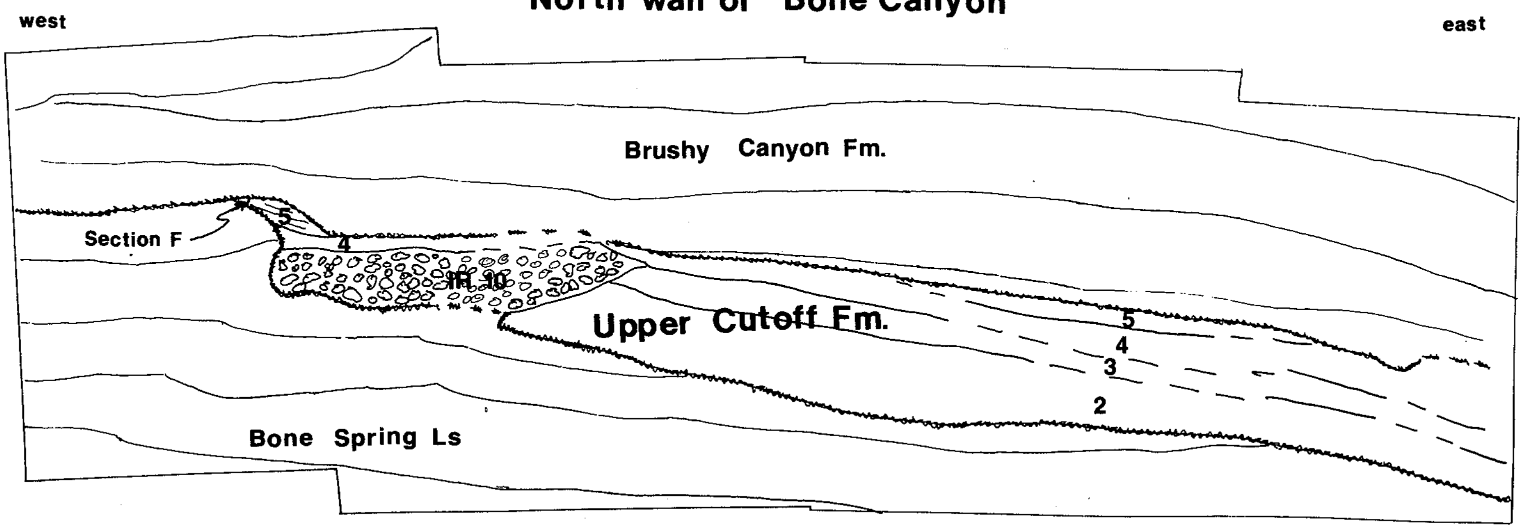
The most interesting, varied, and informative examples of erosional features are present in the shelf margin exposures of the Shumard Canyon complex and Williams Gulch (the draw between Bone and Shumard Canyons). Shumard Canyon branches into four major canyons 0.5 kilometers east of the mountain front (Fig. 3).

The upper and lower Cutoff strata in Shumard Canyon and Williams Gulch were first recognized and accurately mapped by King (1948).

Figure 27: North wall of Bone Canyon

The pinchout of the basinal Cutoff Formation (units 2-5) occurs at the base of the shelf margin. It is exposed in the north wall of Bone Canyon. The Cutoff strata is bounded by erosional unconformities above and below. Units 2 and 3 are erosionally truncated in an upslope (north-west) direction by a channel filled with intraclastic rudstone (IR 10). Just west of this lens, unit 4 onlaps the pre-Cutoff unconformity surface. Unit 5 is eroded above the rudstone lens but reappears locally to the west. It onlaps the pre-Cutoff surface and is, in turn, truccated by the post-Cutoff unconformity at section F.

North wall of Bone Canyon



Williams Gulch: In the north and south forks of Williams Gulch the upper Cutoff Formation occupies a shallow, 150 meter wide scour cut into the Victorio Peak Formation. The Cutoff strata are sharply truncated by the post-Cutoff, pre-Brushy Canyon unconformity, creating the southern pinchout of the shelf margin Cutoff. This occurs on the south wall of Williams Gulch (Fig. 4 and 28). The preserved Cutoff strata can be traced across the gullies into South Shumard Canyon. In the north arm of Williams Gulch a thin lens (1 meter) of skeletal rudstone (SK(V)2) occurs in section G at the base of correlation unit 5.

The orientation of the broad (150 meter wide) scour that the Cutoff strata occupy in Williams Gulch is uncertain. It appears to be approximately east-southeast. The continuation of the scour may be at the pinchout of the basin Cutoff in the north wall of Bone Canyon, 400 meters to the southeast. In both places the base of the Cutoff strata, draping over the scour surface, rises sharply to the west and is abruptly truncated by a nearly horizontal erosion surface beneath the Brushy Canyon Formation.

South Shumard Canyon: Both the upper and lower Cutoff Formation occur in South Shumard Canyon. The lower Cutoff appears as a channel-filling which is exposed on both the north (Fig. 29) and south walls of the canyon. This occurrence was first noted by King (1948). The

Figure 28: South wall of Willians Gulch

The basinwards (southern) truncation of the shelf margin Cutoff Formation occurs in the south wall of Williams Gulch. Units 2-4 onlap the pre-Cutoff unconformity surface, a broad channel cut into the Victorio Peak Formation. Units 4-5 are truncated by the post-Cutoff unconformity and are onlapped by the sandstones of the Brushy Canyon Formation.

South wall of William's Gulch

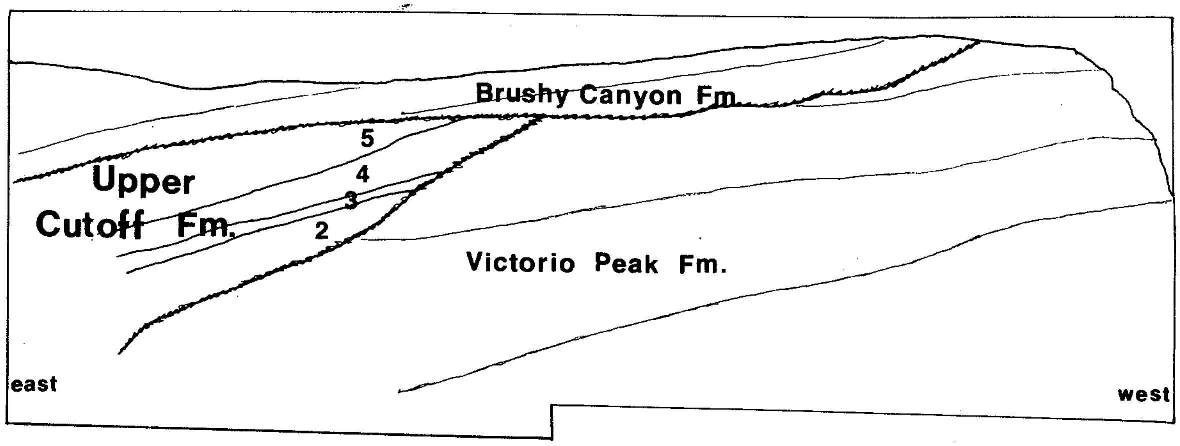
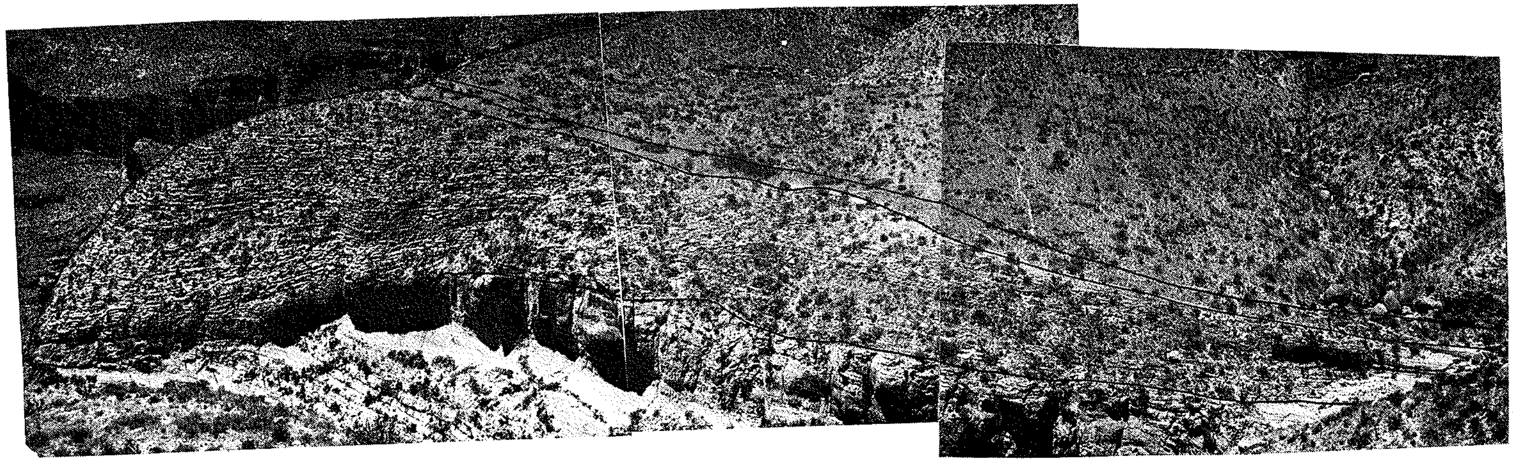
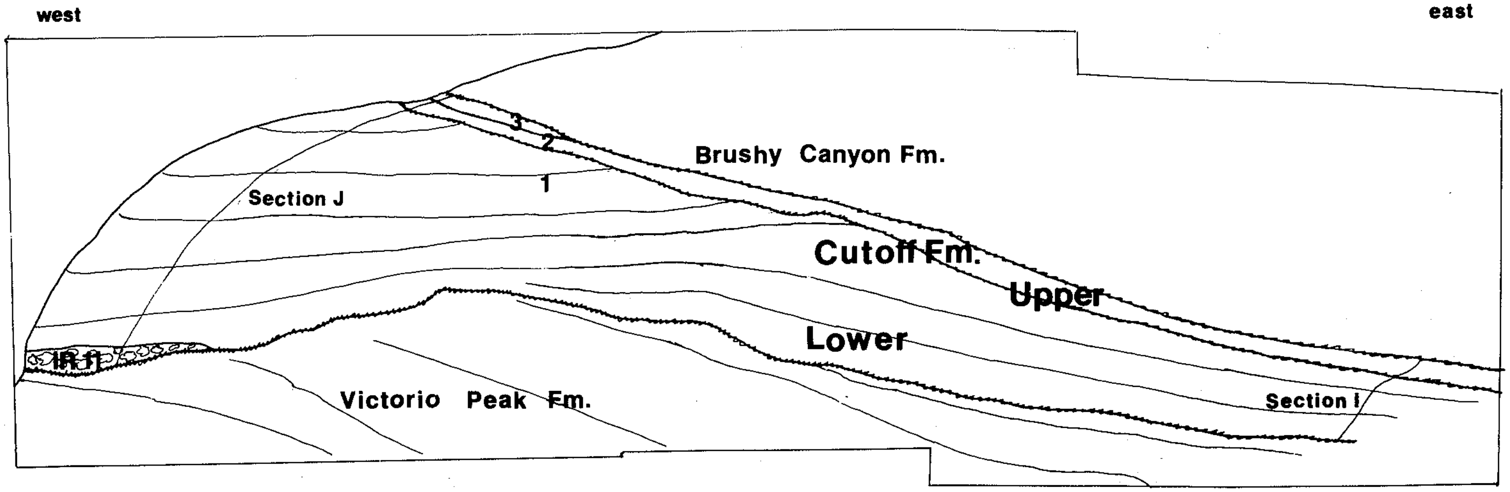


Figure 29: North wall of South Shumard Canyon

In the shelf margin area the lower Cutoff Formation occurs as a large lens which fills a channel cut into the underlying Victorio Peak Formation. At the base of the channel fill is a 3.5 meter thick lens of intraclastic rustone (IR 11). Above is a 2 meter thick shale bed, but the bulk of the channel fill (40 meters) is black, cherty lime mudstone. On the west-facing exposure of this channel (out of this view), the earliest channel fill, 2 meters of quartz sandstone, occurs with a second intraclastic lens (IR 12) and black, cherty lime mudstone as later fills. The lower Cutoff strata is truncated by the intraformational unconformity. This surface is covered by upper Cutoff strata (units 2 and 3) which are eroded along the post-Cutoff unconformity, and onlapped by Brushy Canyon sandstones.



North wall of South Shumard Canyon



channel filled by the lower Cutoff has a maximum depth of about 40 meters. The lower surface is a smooth scour cut into the Victorio Peak Formation. The channel appears oriented slightly west of north and transport is inferred to have been southward into the Delaware Basin. Within the channel a variety of fillings occurs. The sequence of fillings is different in the exposures on the north and south walls. The south wall fillings are about 30 meters thick and are successively: 1) a few beds of thinly laminated, very fine grained quartz sandstone (1-2 meters thick at the west side of the channel), 2) black, cherty mudstone which forms the bulk of the channel fill, and 3) a megabreccia lens (MB4) above the center of the channel (Newell's patch reef number 4). The 40 meter thick sequence of channel-fillings in the exposure on the north wall is: 1) 1-2 meters of the initial thinly laminated, very fine grained quartz sandstone, 2) two intraclastic rudstone lenses (IR11, 12) up to 2 meters thick, 3) a thin (1 meter thick) shale drape, and 4) black, cherty mudstone which fills the rest of the channel. All of the channel-fillings are bounded by erosional surfaces, indicating an alternation of erosional and depositional events. The lack of continuity of the rudstone and megabreccia lenses across the canyon (a distance of only 150 meters in a north-south direction) implies these bodies are lenticular in a down channel direction as well.

The upper surface of the channel fill is a relatively flat erosional surface which truncates the lower Cutoff strata (Fig. 29, 24). This unconformity has removed the lower Cutoff strata in the shelf margin area, except where these strata are preserved in the channel scour.

The erosional unconformity (basal Brushy and Canyon Formation) which cuts the top of the upper Cutoff strata also sharply truncates bedding of the Cutoff and Victorio Peak strata. Within South Shumard Canyon the thickness of the upper Cutoff strata varies between 18 and 2 meters (sections H and J respectively).

East, Northeast, and North Shumard Canyon: The upper Cutoff Formation is exposed in these three canyons. From East to North Shumard Canyon the proportion of rudite sheets increases from about 15% of the section to nearly 90% at the northern pinchout of shelf margin Cutoff in North Shumard Canyon (Fig. 24). Three sheet-like bodies occur. A megabreccia (MB(S)5) of up to 10 meters in thickness forms a basal sheet in the Cutoff strata from the bottom of East Shumard Canyon to the pinchout. At the pinchout itself the megabreccia makes up almost the entire Cutoff section and the lutites above it are reduced to only a few meters. Two intraclastic rudstone sheets (IR(S)13, 14) occur on the south wall of East Shumard Canyon. Each sheet is about 1 meter thick and exposed over 150 meters in the northeast-southwest direction. These rudstones contain dark mudstone clasts believed to be from the Cutoff strata farther shelfward.

The lutites of the upper Cutoff strata thin shelfward (north-northwest) as the overlying erosional surface, the upper unconformity, cuts deeper. North of the Cutoff pinch-out the unconformity truncates the Victorio Peak Formation. This surface is probably the result of the cutting of both upper and lower unconformities. The erosional surface is concave-upwards, and truncates at least 100 meters of underlying strata.

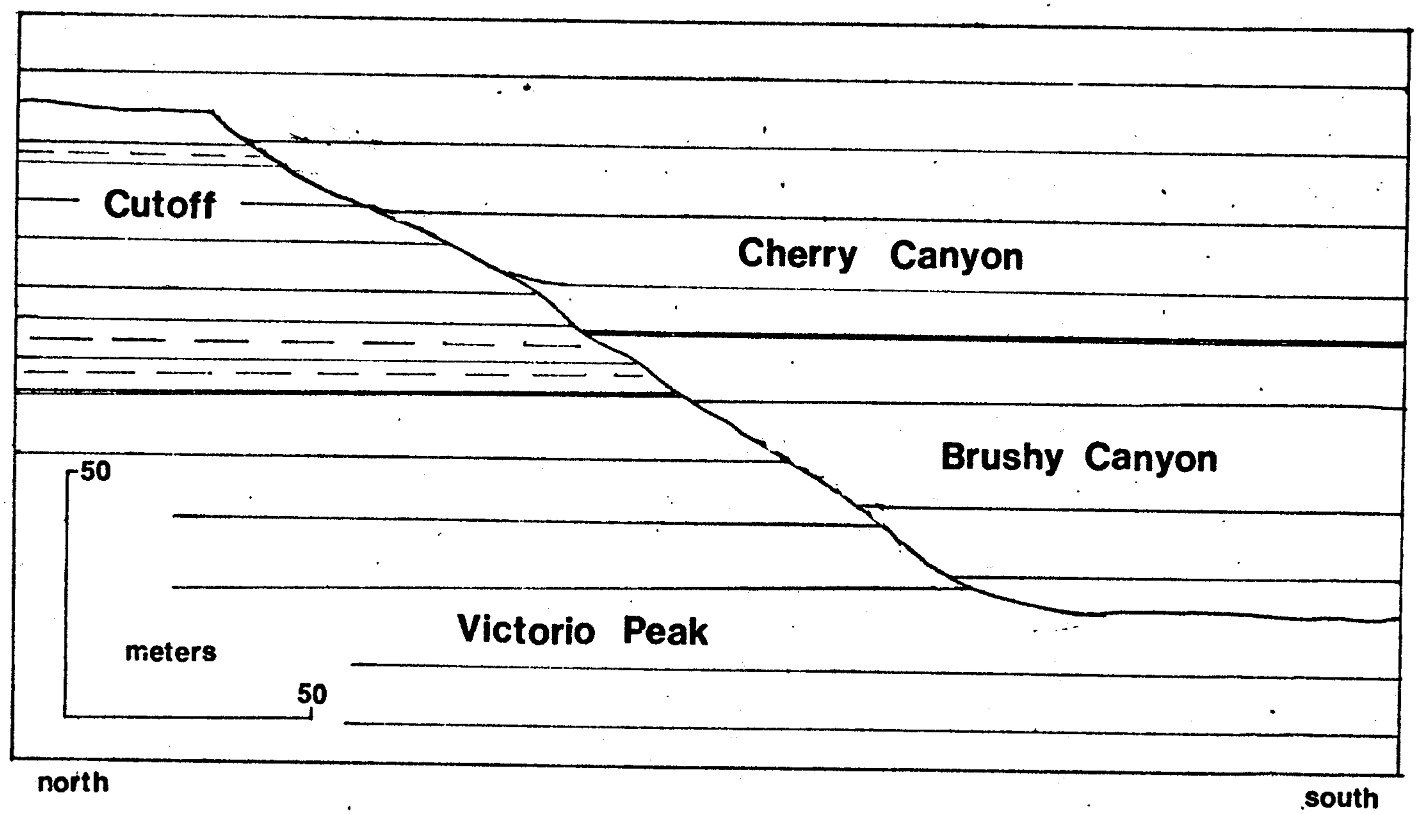
Shelf (Shirttail Canyon to Bartlett Peak)

North of the shelf edge the Cutoff Formation can be traced almost continuously for 10 kilometers to the type section at Cutoff Mountain, at the Texas/New Mexico line. A further 9-13 kilometers northward the Cutoff grades into the lower San Andres Formation through a transition zone (Boyd, 1958).

The shelf area generally lacks any channel phenomena. The two major features involving Cutoff erosion are: 1) the basinward (southward) pinchout of the shelf Cutoff strata north of Shirttail Canyon, as first mapped by King (1948), and 2) a deep channel scour northwest of Bartlett Peak which cuts completely through the 70 meters of Cutoff strata and 30 meters into the Victorio Peak Formation. This feature was first recognized by McDaniel and Pray (1967).

Pinchout of shelf Cutoff Formation: The southernmost limit of the Cutoff Formation of the shelf coincides with the northern limit of the Brushy Canyon Formation. The shelf Cutoff strata are truncated 1.2 kilometers north of Shirttail Canyon. The erosion surface that truncates the Cutoff strata strikes about east-west and dips 22° to the south. The abrupt truncation of 70 meters of Cutoff strata occurs over a distance of 200 meters. Below at least another 30 meters of Victorio Peak strata (Fig. 30) is also truncated. The morphology of this post-Cutoff unconformity is that of a "half-channel" (Pray *et al.*, 1980). The surface is smooth and concave-upwards. Its shape is similar to one side of a channel trending roughly west-northwest to east-southeast (a very oblique angle to the basin edge), but no corresponding opposite channel wall occurs. The problem of the origin of this feature will be discussed below. The unconformity is the depositional surface for the onlapping uppermost Brushy Canyon and Cherry Canyon sandstones.

Bartlett Peak channel: North of the shelf pinchout, the Cutoff strata continues at a rather constant but poorly exposed 70-80 meter thickness, as demonstrated by field



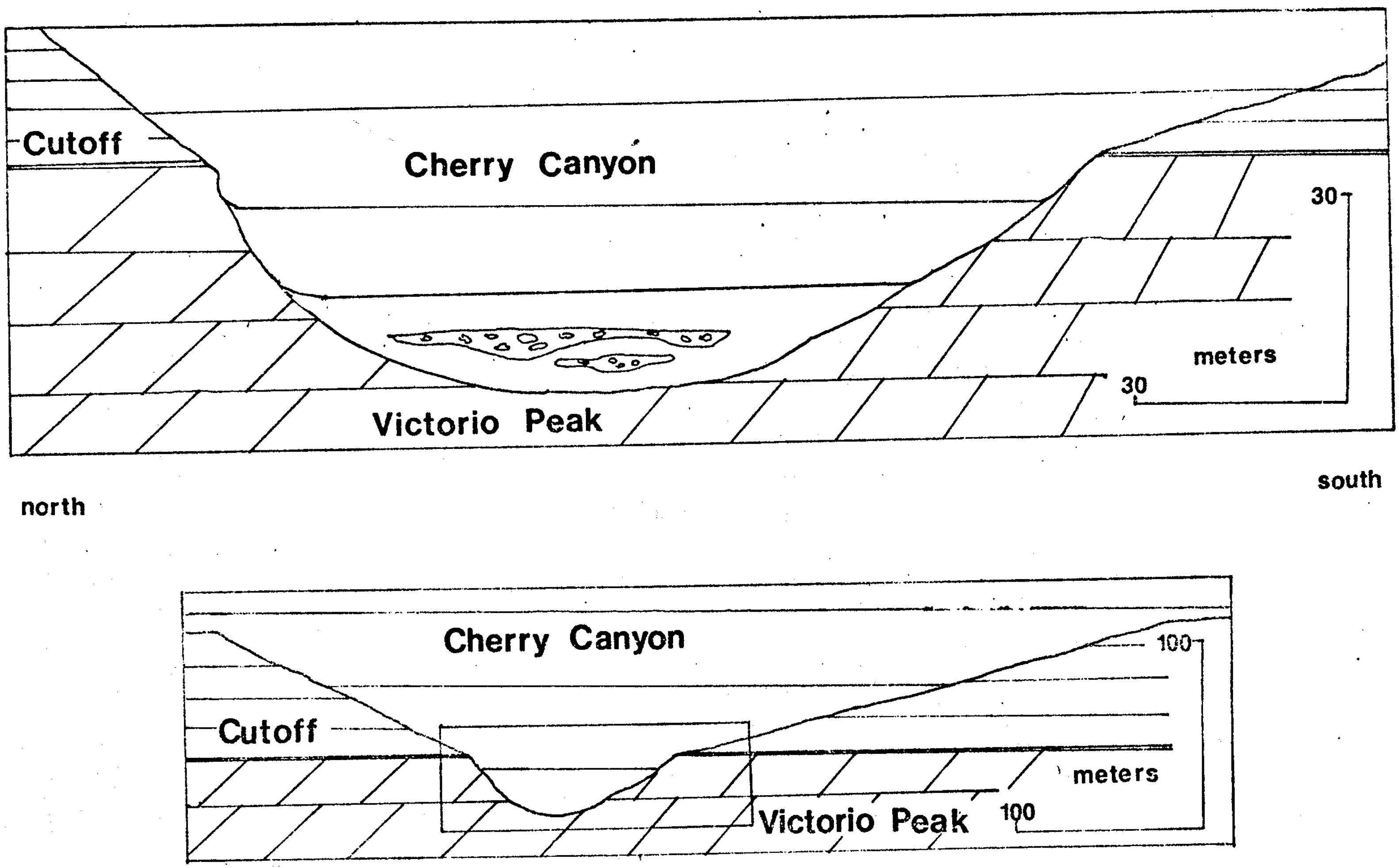
Cross Section of Brushy Pinchout

Figure 30 From original by Kirkby for Pray et al. (1980).

tracing and section work (King, 1948 and this report). This monotony is broken by a large channel feature 0.3 kilometers northwest of Bartlett Peak which cuts through 70 meters of Cutoff and 30 meters of Victorio Peak strata (Fig. 31). The channel's cross section appears U-shaped in the Victorio Peak and more broadly V-shaped in the Cutoff. The Cutoff strata are truncated at an angle of about 10° but this angle steepens to 40° and steeper (locally the north wall is vertical) where the channel cuts into the Victorio Peak Formation. Probably the Victorio Peak was more lithified at the time of channel formation than the Cutoff strata.

The Bartlett channel formed after deposition of the Cutoff strata, as did the erosion surface at the pinchout of the shelf Cutoff strata. Based on the very fine grain size and thin bedding, the sandstone which fills the channel is Cherry Canyon sandstone, an interpretation first made by Harms (1974). This suggests a younger age for this channel (or at least its filling) than for the truncation of the shelf Cutoff strata at the pinchout (which is partially onlapped by Brushy Canyon sandstones).

This channel is the best exposed and largest channel of this size (100 meters deep) which has been recognized leading into the Delaware Basin in the west escarpment Guadalupe Mountains area (Pray, personal communication).



Cross section of Bartlett channel

Figure 31 From original by Kirkby for Pray _et al_.(1980).

The channel trends S65-70^{o}E, either at about right angles or at an oblique angle to the inferred edge of the basin in Leonardian and Guadalupian time. It almost surely served as a major point for introducing sand into the basin.

Major unconformities

The two major erosion surfaces at the top and base of the Cutoff, considered unconformities by Pray (1971), and the possibly equally important erosion surface separating the lower and upper Cutoff, are the most persistent erosion surfaces in the sequence studies. I infer that all three extended across the entire study area, but are locally superimposed. The nature of the shelf profile is profoundly affected by the truncation and removal of strata along these surfaces. These major surfaces are here all considered unconformities, though they may differ but little in process of formation from the less persistent erosional breaks within the upper Bone Spring, Cutoff and Brushy Canyon (Harms and Pray, 1974).

The pre-Cutoff ("lower") unconformity is responsible for the majority of the removal of earlier Leonardian strata. Truncation of nearly 300 meters of Victorio Peak and Bone Spring strata is indicated. The angular unconformity between upper and lower Cutoff ("middle") largely involves removal of the lower Cutoff strata from much of the shelf margin area, as evident from the presence of discontinuous remnants of the lower Cutoff strata in the shelf, shelf margin, and basin. Where these strata are missing the middle unconformity may have modified the lower unconformity surface. In particular their effects in the shelf margin area cannot be distinguished except at the 40 meter deep channel filled by the lower Cutoff strata. This feature indicates that cutting of the lower unconformity surface included some major channeling.

The post-Cutoff ("upper") unconformity represents primarily another episode of removal of Cutoff strata. In two areas the removal of Cutoff strata was total. At the base of the shelf margin a gap 400 meters wide separates the Cutoff Formation of the shelf margin from the basin equivalents. The unconformity surface intersects a high spot on the pre-Cutoff surface to reach older strata (Fig. 24). On the upper shelf margin the lateral gap between Cutoff strata of the shelf margin and shelf is 1.6 kilometers. Because Cutoff strata is missing, it is difficult to reconstruct the exact shelf profile in this area during deposition of the Cutoff strata. During Cutoff deposition the upper shelf margin area was probably the source of Cutoff and Victorio Peak clasts for the intraclastic rudstones, as discussed above. This area of the upper shelf margin appears to have experienced episodic removal of material interspersed with depositional events. The overall concave-up profile is broken at the upper shelf margin by a recess in the area of Shirttail Canyon (Fig. 24). I believe this recess was due to continued erosional retreat to the northwest of the uppermost shelf margin. The original profile in early Cutoff time may have been steeper in this area and the shelf edge further to the south (Fig. 24). The present unconformity is the result of all three unconformities, the upper one shaping the present profile after the continued retreat of the surface.

The erosion of the upper unconformity removed less strata in shelf and basin than along the shelf margin, but still the question of how much strata has been removed on the shelf needs to be considered. Is the shelf section complete or is this the much reduced remnant of a greater thickness? Based on sedimentation rates and known ages, I argue that the shelf section has been only slightly affected. The Leonardian stage is approximately 17my. in duration and is represented by 900-950 meters of strata in the Delaware Basin, for an average sedimentation rate of 54m./my. The Cutoff Formation is merely the latest episode of carbonate deposition in the basin. At this sedimentation rate the 80 meters of preserved Cutoff strata would represent 1-2 my. The faunal overlap of the Leonardian and Guadalupian fossils also suggests the Cutoff strata represents a relatively brief span of time, because it is at the limit of faunal resolution. If the sedimentation rate for this preserved Cutoff strata (40-80 m./my.) is similar to, or slightly above the rate for the Leonardian as a whole (54m./my.), how does this compare with modern sedimentation rates? The estimated rates are similar to the sedimentation rates on modern continental rises (60-80m./my.), exceed abyssal plain rates (20m./my.), and fall at the low end of shelf rates (0-4,000 m./my.) (data from Olsen, 1978). This pattern is not unexpected because the Cutoff and Bone Spring represent sedimentation in a basin largely starved of terrigenous clastic material. The Cutoff Formation is not a normal deposit even where it overlies normal shelf deposits.

Formation of erosion surfaces

Alternatives for environment of formation

Erosion surfaces can form subaerially or subaqueously. The subaqueous alternative is favored for the Cutoff surfaces because of the lack of features associated with vadose, subaerial, or shallow marine environments (Pray, 1971); the basinal nature of the overlying Cutoff deposits; and the similarity of erosional surfaces and depositional processes to those in the overlying, more readily interpretable, deep-water deposits of the Delaware Mountain Group (Harms and Pray, 1974; Harms, 1974). The erosional surfaces (both unconformities and smaller) in the Cutoff strata are sharp, angular, and smooth without any karst or soil phenomena. The subaerial alternative for the formation of the Cutoff unconformities can not be directly disproven. For example the lower unconformity surface may have been formed by subaerial erosion followed by a minor amount of planation in a submarine setting. I believe that all the unconformity surfaces formed in a subaqueous setting for five reasons: 1) The similarity of morphology of the erosion surfaces, ranging in size from the unconformities to scouring of individual beds. The small channels are certainly of subaqueous setting, and duplicate the channel shapes and fills associated with the unconformity surfaces. 2) The post-erosional unconformity surfaces are quite steep for a subaerial erosion surface. Maximum removal occured at the base of the slope, not at the top where it would be expected if due to subaerial processes. 3) Consideration of the regional correlatives suggests that the lower unconformity surface formed at a time of shelf subsidence. 4) If the surface formed in a subaerial setting there is no evidence of such exposures. 5) The upper Victorio Peak indicates a shift toward increasing water depth below the lower unconformity (Kirkby, in progress).

Subaqueous unconformities can be due to non-deposition (hardgrounds), gravity sliding (slumping), or erosional removal (channeled or non-channeled). The removal of nearly 300 meters of Victorio Peak strata at the shelf margin clearly eliminates nondeposition as a possibility. The other two may be difficult to distinguish.

Process of erosion: Slumping or erosional removal?

Although different processes, the results of these removal mechanisms may be very similar. Davies (1977) considered intraformational truncation surfaces in the deep-water carbonates of the Sverdrup Basin, Canada. He listed eight criteria he used to infer these features to be the soles of gravity slides in preference to an erosional origin for the surfaces. Slightly rearranged, these criteria are listed in table 4 with my evaluation based on observations of the Cutoff Formation and the Bone Springs Limestone. A revised list of criteria for the origin of truncation surfaces is presented in table 5. The major differences concern the criteria for gravity slide mechanisms. Arguing by analogy with information from modern shelves, Davies lists large scale, listric geometry (spoon-shaped, concave-upward), and lithologic similarity as limited to slumping phenomena. I believe this incorrect.

The evidence from the rock record in the Permian strata in the Guadalupe Mountains is quite different (Pray *et al.*, 1980). The basal Cutoff surface has channel features with

Table 4:

Davies (1977) criteria for origin of truncation surfaces and my evaluation of them

Davies's criteria	My evaluation: Useful?	My evaluation: Comments
A. Erosional Removal		
1. Coarse breccia or conglomerate along the surface.	yes	This sediment type is typically either a current deposit or channel fill.
2. Discontinuous tabular beds contained within truncation structure.	yes	Depositional sediment geometry due to bottom currents.
3. Channel or erosional irregularities along the sharp, regular truncation surface.	yes	Indicates current removal of strata.
4. Large U-shaped channel cross section.	varies	Cross section depends on the relative orientation of channel to the plane of view.
B. Gravity slide mechanisms		
1. Large size ($\geq$ kilometer?)	no	Erosional unconformities may be any size or shape.
2. Listric geometry of surfaces.	no	These features may characterize slumps but may also occur on erosional surfaces. Thus they can not be used to distinguish origin.
3. Similarity of lithologies above and below surface.		
4. Abundant on modern continental margins.	no	Origin needs to be proven in the rocks themselves.

Table 5:

Revised list of criteria for the origin of truncation surfaces as applied to the Cutoff Formation

	Cutoff examples?
A. Erosional removal	
1. Coarse breccia or conglomerate above the surface.	yes
2. Discontinuous tabular beds contained within truncation structures.	yes
3. Channel or erosional irregularities along the truncation surface.	yes
4. Variety of lithologies above the surface.	yes
B. Gravity slide mechanisms	
1. Step-like fault scarp.	not recognized
2. Large slump rolls and folds.	not recognized
3. Lacks channel irregularities.	channels occur

breccia fillings which imply erosional activity. However the surface lacks any large-scale slump features such as step-like normal faults. The larger channel features are similar to erosional surfaces within the Cutoff strata. The interformational channels are clearly subaqueous erosion features because they are cut into and filled by deep-water sediments. A similar subaqueous erosion origin appears likely for the channels along the unconformity which are similar in morphology and fillings.

The early lithification of the eroded strata also supports an erosional origin over slumping. The major evidence of early lithification prior to formation of the unconformity is that the clasts in the rudites appear to be derived from the Victorio Peak strata. These were clastic sediments and require cementation to form the clasts. Early lithification of carbonates in a submarine environment has long been suspected from ancient examples (Pray, 1960) and more recently demonstrated in modern settings (for example: Bricker, 1970; Matter, 1974). The lithification of the substrata would hinder slope failure by slumping.

The most likely explanation for the truncation surfaces (unconformities and channels) in the Cutoff Formation is by erosion, not slumping. The listric geometry is a problematical feature tied to the question of channel size and orientation and erosional process, as discussed below.

Channels

Channels form portions of the unconformities bounding the Cutoff strata and are also contained within the Cutoff. They are the primary evidence for current removal of strata and their orientation is an indication of current orientation.

The channel forms can be divided into major size groups: 1) medium to small channels with a maximum depth of about 50 meters. The upper limit on observed width is about 200 meters. These are typically spoon-shaped channel sections with orientations into the basin, where orientation can be determined. 2) Large channel and possible "half-channels" which truncate 100 meters or more of underlying strata. These range in size from several 100's of meters in width to an unknown upper size. The half-channels have a listric profile downslope which is similar to the shape of one side of a large channel. This profile also resembles slump scars. The strikes of the erosion surfaces are roughly northeast-southwest, and range from nearly parallel to oblique to the basin edge. The features are not well understood (Pray *et al.*, 1980).

Medium to small channels

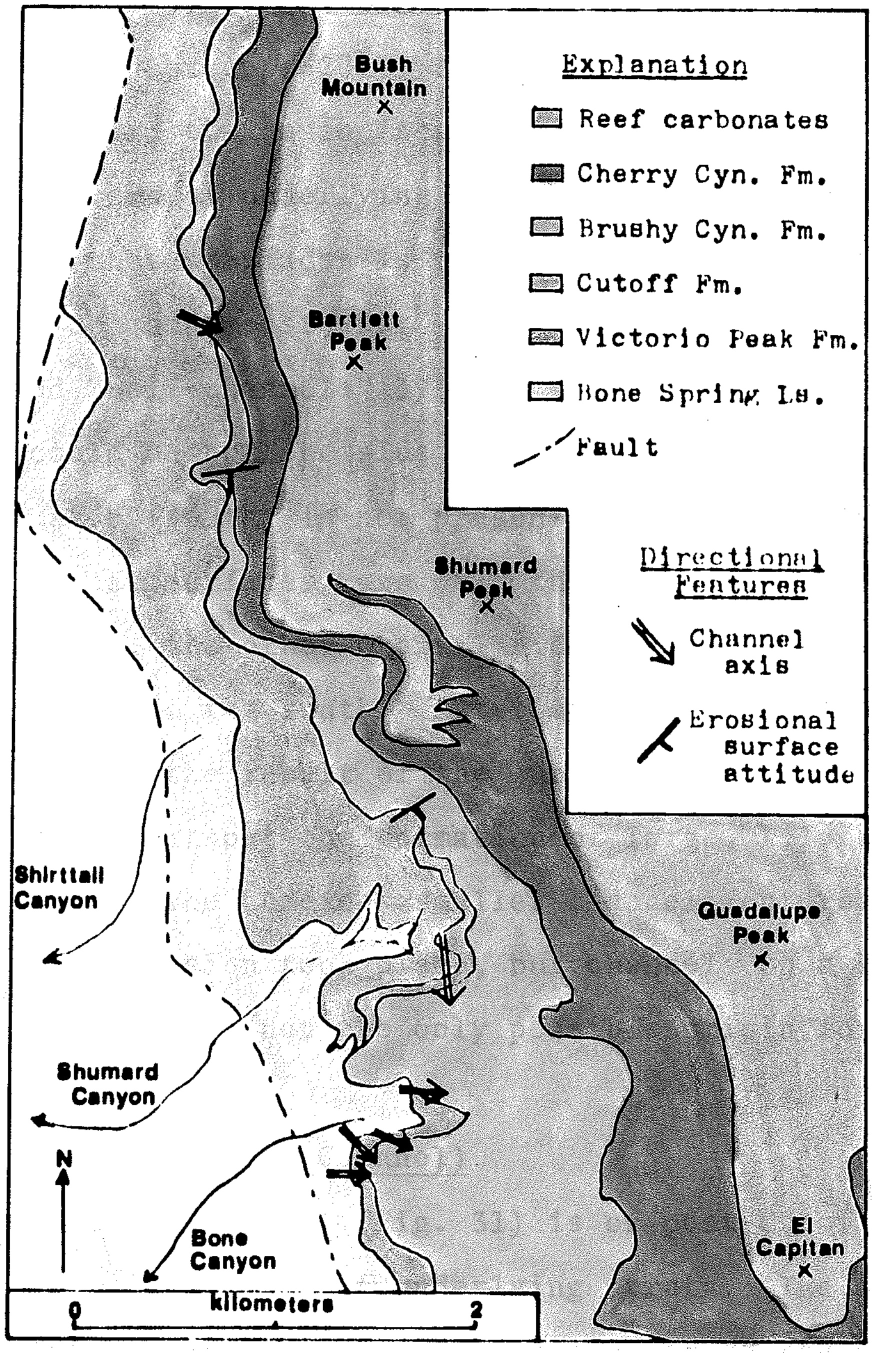
These channels are ubiquitous features in the shelf margin and basin areas. They are evidence of strong bottom-current activity both at the time of unconformity formation and episodically during lutite deposition.

The channels vary in shape and size. The two end members of the distribution are: 1) narrow (<30 meters) steep-sided (>10^{o}) channels which are roughly V to U-shaped, for example the megabreccia lens south of Bone Canyon (MB1), and 2) broad (100-200 meters) features with flattened sides (<10^{o}) with the morphology of a very flattened U, for example the broad channels (Fig. 25) on the south wall of Bone Canyon. While these are only the end members of the distribution of channel forms, most channels are close to one of these two types.

Directional data is difficult to find. Within the lutite channel fills the only structures are horizontal laminations. Where exposures are favorable the orientation of the channel itself can be determined. The lower Cutoff channel in Shumard Canyon has an orientation of slightly west of north. Other channel orientations cannot be so well determined but there is a general sense of northwest to southeast orientation, based on six examples (Fig. 32). This is roughly perpendicular to the inferred trend of the basin edge. It appears the channels were cut by currents which flowed basinward down the shelf margin.

Figure 32:

Directional features associated with the Cutoff Formation



"Half-channels"

The lower unconformity in North Shumard Canyon and the upper unconformity at the pinchout of the shelf Cutoff strata are both steep (>20^{o}), listrically-shaped surfaces which dip toward the basin (southward) and truncate at least 100 meters of underlying shelf strata. The orientation of these surfaces is uncertain but the strike appears to be about east-west (Fig. 32). These surfaces were termed "half-channels" by Pray et al., (1980) because surfaces could be but one side (north) of a major channel. The other side (south) is not present in outcrop. If these erosional surfaces were only the north sides of two large channels, the other channel side may have been a kilometer away to the south. Alternatively these erosion surfaces may be the result of the submarine erosion of lithified strata without the formation of large, kilometer-wide channels. The numerous smaller channel features are evidence that erosion took place, but channels on a kilometer wide scale are not the only possible origin for these enigmatic features.

Large channel (Bartlett Channel)

The Bartlett channel (Fig. 31) is of post-Cutoff age and truncates 100 meters of underlying strata. The sides of this channel have a listric shape similar to the half-channels. The orientation of the Bartlett channel is

N67^{o}W, an oblique angle to the shelf edge. This is intermediate between the inferred east-west orientation of the half-channels and the basinward orientation of the smaller channels. The reason for this variation in channel and erosion surface orientation is not understood.

Summary of erosional phenomena

Removal of strata is concentrated on the shelf margin (or adjacent (∿ 1 km.) shelf top and basin floor) at three unconformities: pre-Cutoff, between upper and lower Cutoff strata, and post-Cutoff. These unconformities are interpreted as subaqueous erosional features. The mechanism of formation of some of the large features (half-channels) remains enigmatic.

Erosional features on the shelf margin are not limited to the unconformity surfaces. The upper shelf appears to have been an area of continental erosion and retreat of the shelf edge. Channels cut by basin-directed currents flowing down the shelf margin are prevalent. Small scale bed scour and sediment redistribution attest to frequent weak current activity.

PALEONTOLOGY AND AGE

"Life's but a walking shadow, a poor player,
That struts and frets his hour upon the stage,
And then is heard no more..."
Shakespeare

Paleontology

The Cutoff Formation contains a sparse biota. The fossils are invertebrate skeletals with minor amounts of algae. Most of this material is allochthonous. Most previous workers have sampled the fossiliferous clasts of the megabreccias or the fossils forming grains in the rudstone lenses. These lenses are the only rock bodies in the Cutoff strata with abundant fauna. The megabreccia clasts are reworked pieces of older strata or lithified sediment of contemporaneous age. Unfortunately for the utilization of the fossil collections, collectors generally did not recognize the allochthonous nature of the specimens but instead considered them to be in-place.

Invertebrate skeletals are sparse to rare in the lutites of the shelf margin and basin. The medium gray mudstone contains scattered invertebrate skeletals. The extent of transport of these skeletals is uncertain, but they are likely to be the least transported of the Cutoff fauna (except for pelagic foraminifera and sponges).

In this study no attempt was made to systematically collect specimens of the Cutoff fauna, except for fusulinids. I looked for fossils in all lithologies to determine their distribution and abundance. Special attention was taken to note all trace fossils and to collect fusulinids.

Previous work

King (1948) recognized the sparse occurrence of fauna in the Cutoff strata. The brachiopod-dominated fauna was examined by G. H. Girty (reported by King, 1948). One genera of brachiopods was found abundant several miles north of the New Mexico line. Ten species were identified in the intraclastic rudstone (IR11) at the base of the lower Cutoff in South Shumard Canyon. A large (40 species) fauna was identified in the Cutoff exposed in Brushy Canyon, in the Delaware Mountains a few kilometers south of the study area. King also collected fauna from the black limestones of the Bone Spring Limestone. These collections appear to have come from the Cutoff Formation as recognized in this report. King (1948) obtained most of his specimens in the low hills of dark limestone south of El Capitan "In a few layers, which are generally lenticular or nodular, and somewhat more granular than the rest of the rock . . .". These appear to be skeletal rudstone lenses in unit 5, based on his description and map location. (Collection locations of King (1948) which appear to actually be in the Cutoff Formation include U.S.G.S. localities 2920, 2967, 7413, 7691, 7720, and 8596.) The "Bone Spring" fauna listed by King is actually a Cutoff fauna. The fauna's occurrence in the channel lenses and the nature of the biota and clasts suggests that it was transported into the basin from the shelf or shelf margin. Because of the erosional evidence discussed above, the actual age of this fauna may be Cutoff and/or earlier Victorio Peak-Bone Spring.

Newell et al., (1953) increased the known Permian fauna in the Guadalupe Mountains area but made few additions to the sparse Cutoff fauna. In the Cutoff strata they only sampled the clasts in the megabreccia lenses ("patch reefs"). Boyd (1958) greatly increased the recognized fauna in the Cutoff strata of New Mexico. He recognized several genera and species previously unreported.

Fauna

The macrofauna of the Cutoff Formation is dominated by brachiopods, with over 40 species reported. Other groups are but sparsely represented: ammonites, nautiloids, pelecypods, gastropods, bryozoans, crinoids, fusulinids, corals, and dasycladacian algae (King, 1948; Newell et al., 1953). In this study a conularid of the genera Conularia was observed at the Cutoff type section. The most recent taxonomic assignments, faunal lists, and locality lists for the brachiopods can be found in Cooper and Grant's monographs (1972-77) on the brachiopods of West Texas. It must be used with care because several of the localities for the Bone Spring Limestone are actually in the Cutoff Formation. In addition to King's locations noted above, the American Museum of Natural History (Newell group) locations numbered 658, 660, and 661 are in the Cutoff Formation. The fusulinid occurrences are discussed below.

The only widespread fauna in the lutites are sponge spicules. They are locally recognizable in the dark mudstone rock types. These needle-like spicules are siliceous and have diameters in the silt-size range. Most of the rock is carbonate mud but scattered sponge spicules occur in some thin sections studied in laboratory. The medium gray mudstone is generally lacking any clearly identifiable spicules.

Trace fossils

Trace fossils are useful for environmental interpretations. It was hoped at the start of this study that they would provide such information. However in the Cutoff strata trace fossils are only notable by their near total absence. Two examples were found. In the upper portion of unit 1 (lower Cutoff) flattened horizontal burrows were noted in section B (basin area). Due to post-Cutoff removal and truncation of this strata, the original lateral extent of these traces could not be determined. In unit 3 a few faint horizontal traces were observed in section C (basin edge) at one horizon. These were not observed elsewhere.

Interpretation of distribution of fauna and trace fossils

The general lack of in-place fauna or trace fossils in the dark gray mudstones is reflective of the paleoenvironment. I believe that the basin waters were deficient in oxygen, inhibiting life. The greater abundance of skeletals in the medium gray mudstones of the shelf area reflects more normal marine conditions which appear to have existed on the shelf in later Cutoff time. This argument will be considered more fully below.

The lenses of skeletal rudstone in the basin are probably derived from contemporaneous shelf areas and not reflective of the location where they are deposited.

Fusulinids

The Cutoff Formation has been believed to be youngest Leonardian, oldest Guadalupian, or transitional between the Leonardian and Guadalupian. The fusulinid data of the Cutoff strata is important as the fusulinids are widely used for age determination in the Permian rocks of West Texas.

Adams *et al*. (1939) established the standard Permain stages for North America. The Leonardian stage was named after exposures in the Glass Mountains and the Guadalupian stage from Guadalupe Mountain outcrops. Fusulinids were used to recognize the stages regionally. The Bone Spring Limestone (including the Cutoff strata) and its fauna was recognized as Leonardian age (Blanchard and Davis, 1929; Adams et al., 1939, King, 1948). The Cutoff, then considered a member in the Bone Spring Limestone, was likewise believed to be of Leonardian age.

In 1955, Hollingsworth and Williams (cited in Boyd, 1958) recognized Guadalupian fusulinids in the shelf Cutoff strata. Further fusulinid studies by Wilde (Wilde and Todd, 1968) led him to consider the Cutoff strata to be of Guadalupian age, as defined by fusulinids. By this time King's (1965) elevation of the Cutoff to formation status had separated the Cutoff strata from the Bone Spring Limestone, which is of Leonardian age. The fauna in the Cutoff Formation is predominantly a Leonardian fauna (King, 1948) because the collections of "Bone Spring, Leonardian age" fauna (from the Guadalupe Mountains) are actually from the Cutoff basinal strata. To try to untangle these paleontologic problems is beyond the scope of this report. The problem is further complicated by the uncertainty about the amount of transport and reworking prior to final burial.

I have collected fusulinid specimens from the Cutoff strata in various areas of this study, despite these interpretive difficulties. In the basin area fusulinid specimens are available from an intraclastic rudstone lens in section B (unit 5). They occur as individual grains between the intraclasts and are considered contemporaneous with the unit, rather than older as rock clasts may be. In the shelf margin area (South Shumard Canyon) a loose block of mudstone from unit 5 yielded fusulinids. At the type section fusulinids occur as scattered specimens in unit 5.

Age of Cutoff Formation

Previous work of Wilde (Wilde and Todd, 1968) has shown that some of the fusulinids in the upper Cutoff Formation are of Early Guadalupian age. The lower Cutoff strata lacks fusulinids, so its age is uncertain. Because it cannot be lithologically distinguished from the underlying Leonardian-age Bone Spring Limestone, I include the lower Cutoff Formation in the Leonardian series. This places the series boundary in the western Guadalupe Mountains between upper and lower Cutoff strata. While somewhat arbitrary, the boundary is a widespread and persistent erosional surface which is easily recognized. Black, cherty mudstone of the lower Cutoff Formation of Bone Spring Limestone, or the light colored carbonates of the Victorio Peak Formation,is below the surface and contrasts with the shaley mudstone and shale of the upper Cutoff Formation above. Also, Guadalupian fusulinids have not been found in lower Cutoff strata because all fusulinid collections by myself and previous workers are from the upper Cutoff strata. In effect, the series boundary suggested is placed at the first laterally persistent (erosional) surface below the lowest occurrence of Guadalupian age fusulinids.

CONCEPTUAL SEDIMENTATION MODELS

"The time has come," the Walrus said
"To talk of many things;
Of shoes-and ships-and sealing wax-
Of cabbages-andkings-
And why the sea is boiling hot
And whether pigs have wings."
Carrol

The Permian rocks of West Texas have long been a mecca for model makers. Interpretations of the Guadalupian-age reef complex have spawned a large number of sedimentologic models, most of them involving cyclicity (see Elam and Chuber, 1969). The source of the shelf strata cyclicity has been considered as related to fluctuating sea level (some glacially induced) (Meissner, 1972; Jacka et al., 1968, 1969) or to episodic shelf edge subsidence without much sea level fluctuation (Pray, 1977).

The following sections will examine the few cyclic sedimentation models (Silver and Todd, 1969; Meissner, (1972) which have been extended downward to include Leonardian strata. The application of these regional models to the Cutoff Formation leads to contradictions with the results of this study. Other more detailed models which consider parameters of water quality (salinity, oxygen content) are more compatable with this study. These have been given little attention until now, but have been involved in interpreting bank-basin deposits of Leonardian age (McDaniel and Pray, 1967). Finally an anoxic basin model will be presented which appears to fit best with the observations of this study.

In discussing and evaluating these conceptual sedimentation models, they will be considered relative to the Cutoff strata. Fortunately. the relative positions of shelf, shelf margin, and basin sections in Cutoff time is known because the strata are but little disturbed by later deformation. The critical area from the edge of the shelf (Bartlett Peak) to the edge of the basin (south of Bone Canyon) lacks any evidence of faulting or folding. The relationships which led King (1948) to postulate the "Bone Spring flexure" are better explained by submarine erosion along the shelf margin (Pray, 1971). The entire Delaware Basin and neighboring shelves were subsiding as the Permian section of 1000's of meters accumulated. It is possible that differential subsidence leading to tilting may have occurred. If so, some details of the following discussion may need modification but the basic pattern and its interpretation would remain the same. The apparent lack of any later deformation except for the interpretable Cenozoic block faulting and uplift allows this confidence of reconstruction.

Cyclic models

Many cyclic sedimentation models have been applied to the Guadalupian strata. Few of these have been extended to treat the Leonardian series. Meissner (1972) treated the Leonardian strata in a broad sense. Silver and Todd (1969) consider detailed correlations of both Leonardian and Guadalupian strata in terms of cyclic models. Both models are derived from subsurface studies.

The models of Meissner and Silver and Todd both use the concept of "reciprocal sedimentation" (Wilson, 1967, 1975) to explain the cyclic basin and shelf strata of the Guadalupian series. Low stands of sea level are tied to contemporaneous deposition of terrigenous clastics (primarily sand) in both the shelf and basin areas, and by passing at the shelf margin. High sea level stands are inferred to be represented by carbonates in both the shelf and basin strata. Both models use this concept of sedimentation to guide correlation of shelf and basin strata. This sedimentation model was questioned by Pray (1977) who suggested that sandstone represent high stands of sea level and that carbonates represent low stands.

The concept of equating terrigenous influx with shallow water conditions does not appear applicable to the Cutoff Formation. This study indicates that the influx of terrigenous siliciclastics during Cutoff deposition followed a rapid subsidence of the shelf. As Cutoff strata accumulated in shelf, shelf margin, and basin areas a shift to pure carbonate deposition occurred. Because of this association of siliciclastics with an episode of shelf subsidence, the application of a "reciprocal sedimentation" model to the Cutoff strata (Meissner, Silver and Todd) is questionable.

While both Meissner (1972) and Silver and Todd (1969) use similar concepts of sedimentation, the resulting shelf-to-basin correlations differ from each other, and also from Boyd's (1958) surface correlations. This variation is due to two factors: 1) The type sections of the shelf units are in north central New Mexico. The correlations, especially in the northern Guadalupe Mountains region are part inference. 2) The subsurface units studied by Meissner and Silver and Todd may not be strictly equivalent to surface units with the same name. For example, the Glorieta Formation is considered by some workers to be equivalent to the upper Yeso Formation, by others to the lower San Andres, and by still others to be a separate unit between the Yeso and San Andres Formations.

The immediate shelf equivalent of the Cutoff Formation was determined by surface tracing in New Mexico by Boyd (1958) to be what he considers the lower San Andres Formation. This appears to be correlative with the Glorieta Formation in the shelf to the north (Wilde and Todd, 1968). It is less clear what is the subsurface equivalent of the Cutoff Formation. Meissner (1972) suggested the upper San

Andres Formation, Silver and Todd (1969) suggested the upper Yeso Formation. The subsurface correlative is uncertain (Wilde and Todd, 1968). This problem needs to be re-examined because of the apparent nonapplicability of the reciprocal sedimentation concept which has guided most previous correlations.

In summary the cyclic sedimentation models developed for the Guadalupian strata do not appear applicable to the Cutoff Formation. Correlations to the shelf strata are problematical but it appears surface equivalents of the Cutoff are the lower San Andres and Glorieta Formations. Subsurface correlatives are uncertain.

Salinity and early anoxic models

The patterns and associations of lithologies in the Permian strata of the Delaware Basin region have led previous workers to propose various models of depositional environment. These models generally concern the regional distribution of rock types (such as evaporites or black mudstones) due to the effect of water parameters such as salinity and oxygen content.

Lang (1937) proposed a salinity model for a restricted basin to explain the distribution of evaporites in the Delaware Basin region. Subsequent workers (King, 1948; Newell *et al.*, 1953; McDaniel and Pray, 1967) proposed that the

Delaware Basin was an anoxic (or euxinic or pontic) basin due to restricted circulation. This was based on the general appearance (dark, thin bedded) and lack of fauna in the basinal strata. Hills (1972) combined the salinity and anoxic models in a large-scale consideration of the entire Texas, New Mexico, and Oklahoma region throughout the Permian Period.

These models and suggestions are all valuable. Although I believe that the major control on the Cutoff's lithology was oxygen concentration, not salinity, the concept of sediment types being affected by water quality originates in Lang's work. This study reveals the Cutoff Formation is largely an anoxic basin deposit. I believe that the details now recognized in the Cutoff strata allow the application of a more detailed basin model than that used by previous workers. This detailed anoxic basin model derives from a general sedimentologic model which has been largely developed over the last decade. I will apply it to the Cutoff Formation in this study.

Anoxic basin model

History

The concept of anoxic or euxinic basins and their effect on sediment appearance has been in the geologic literature for several decades. The classic area is the Black Sea (Pontus Euxinus) from which the term euxinic (and pontic) was derived. More recently Rhodes and Morse (1971) presented a detailed ecologic model which was expanded by Byers (1977) in his study of black shales of the Devonian of New York. This model will be used for interpretation of the Cutoff Formation.

The terminology of oxygen deficient basins has long resisted standardization. In recent work some agreement has been achieved. The term "anoxic" is generally used for the basin as a whole even though the surface waters may not be oxygen-deficient. The different zones within it (and the resulting sediment types) are termed "aerobic, dysaerobic, and anaerobic" in order of decreasing oxygen concentration.

The anoxic model uses the water parameter of dissolved oxygen concentration to explain variations of biota and sediment texture. Studies of modern examples of restricted basins (Black Sea, Gulf of California) demonstrated that oxygen concentration controlled the biota. Rhodes and Morse (1971) described three zones: aerobic (1.0 ml./l.*), dysaerobic (1.0-0.1 ml./1/), and anaerobic (0.1 ml./l.). Byers (1977) dsicussed in more detail the sedimentologic aspects and the usefulness of these zones on reconstructing restricted basins. He also suggested several rock bodies,

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*Figures are in milliliters of dissolved oxygen/liters of water.

including the Cutoff Formation, which might reveal anoxic variations.

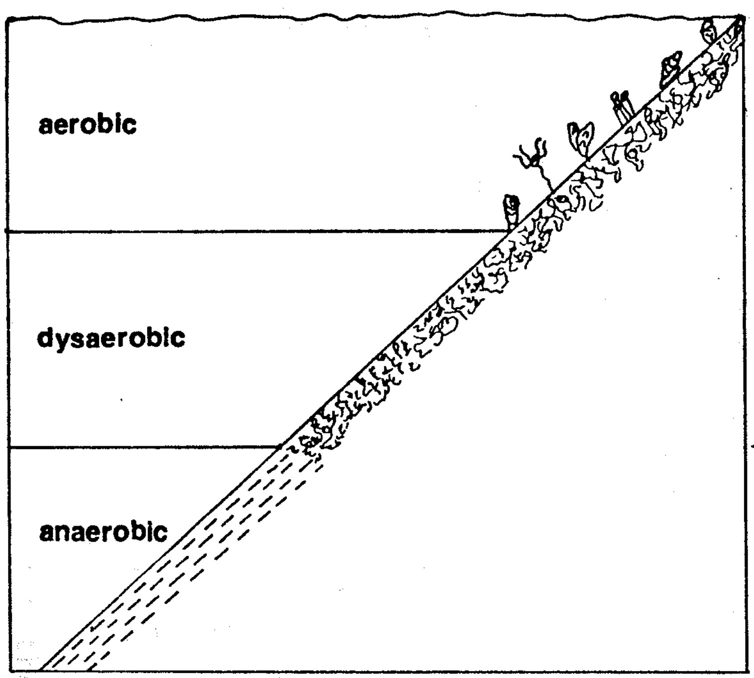
Theory

The anoxic basin model describes a restricted basin which is layered into three zones (Fig. 33). These zones are defined in terms of the concentration of dissolved oxygen (see above). The boundaries are oxygen levels which appear to be threshold values for different types of biotic activity. A distinct sediment type may occur in each oxygen zone because of the differences in the biota. Because the oxygen concentration actually decreases in a gradational manner with depth, the boundaries between the resulting sediment types are also gradational.

The aerobic zone is the normal well-oxygenated marine environment. A shelled invertebrate pelagic and benthonic fauna is present and the sediment is bioturbated and oxygenated. The result is a light colored, non-laminated sediment with calcareous body fossils of invertebrate skeletals. The dysaerobic zone is an intermediate layer with a low oxygen level which excludes benthonic calcareous fauna. Soft-bodied infauna can survive, disrupting the sediment through bioturbation. The resulting sediment is dark in color, faintly laminated or non-laminated, and lacking in calcareous benthonic skeletals. The lowermost zone, anaerobic, lacks oxygen and benthonic fauna is absent. No

Figure 33

ANOXIC MODEL (after Byers,1977)



Terms	Pictorial	Biologic Evidence	Cutoff Lithologies
aerobic		bioturbation & shelled epifauna	medium gray mudstone & wackestone
dysaerobic		bioturbation	dark gray faint to non-laminated mudstone
anaerobic		laminations	dark gray thinly laminated mudstone

bioturbation affects the sediment, which is laminated and dark in color.

These three zones are recognized in enclosed seas with a restricted opening to the open ocean. The thickness of the aerobic zone is controlled by surface mixing (primarily due to wave effects) and so related to the size of the basin. The aerobic zone in the Black Sea is 50 meters deep but a smaller restricted basin (such as the Delaware Basin) would have a thinner aerobic zone, a larger basin a thicker zone. The thickness of the dysaerobic zone is due to two factors: vertical diffusion of oxygen and the sill depth. Vertical diffusion of oxygen down from the surface creates the low-oxygen dysaerobic layer beneath the aerobic zone. This diffusion process is relatively constant and independent of sill depth. Acting alone, it results in about a 100-meter thick dysaerobic zone. In the case of the Black Sea the dysaerobic zone caused by this diffusion of oxygen extends from 50 to 150 meters in depth. The remainder of the basin below 150 meters is anaerobic. However the thickness of the dysaerobic zone can be increased by lateral mixing of oxygenated ocean water with the basin water. This lateral mixing is limited to depths above sill level because the sill prevents mixing of oceanic water with deep basin water. If lateral mixing occurs below the depth of vertical diffusion of oxygen from the surface, the dysaerobic layer will be thickened down to the sill level. Anaerobic conditions are limited to the regions of the basin sill depth which are also below the zone of vertical diffusion of oxygen. The Black Sea example involves a high sill so the dysaerobic zone is only due to vertical diffusion processes. In the Gulf of California there is no sill protecting the entire basin. The dysaerobic zone extends completely to the bottom depths except in small basins where localized sills create anaerobic conditions.

In summary, the anoxic basin model predicts that the thickness of the aerobic and dysaerobic zones are related to two basin parameters: basin size (which affects the depth of surface mixing) and sill depth (which controls the depth of lateral mixing with ocean water).

The Cutoff Formation as an anoxic basin deposit

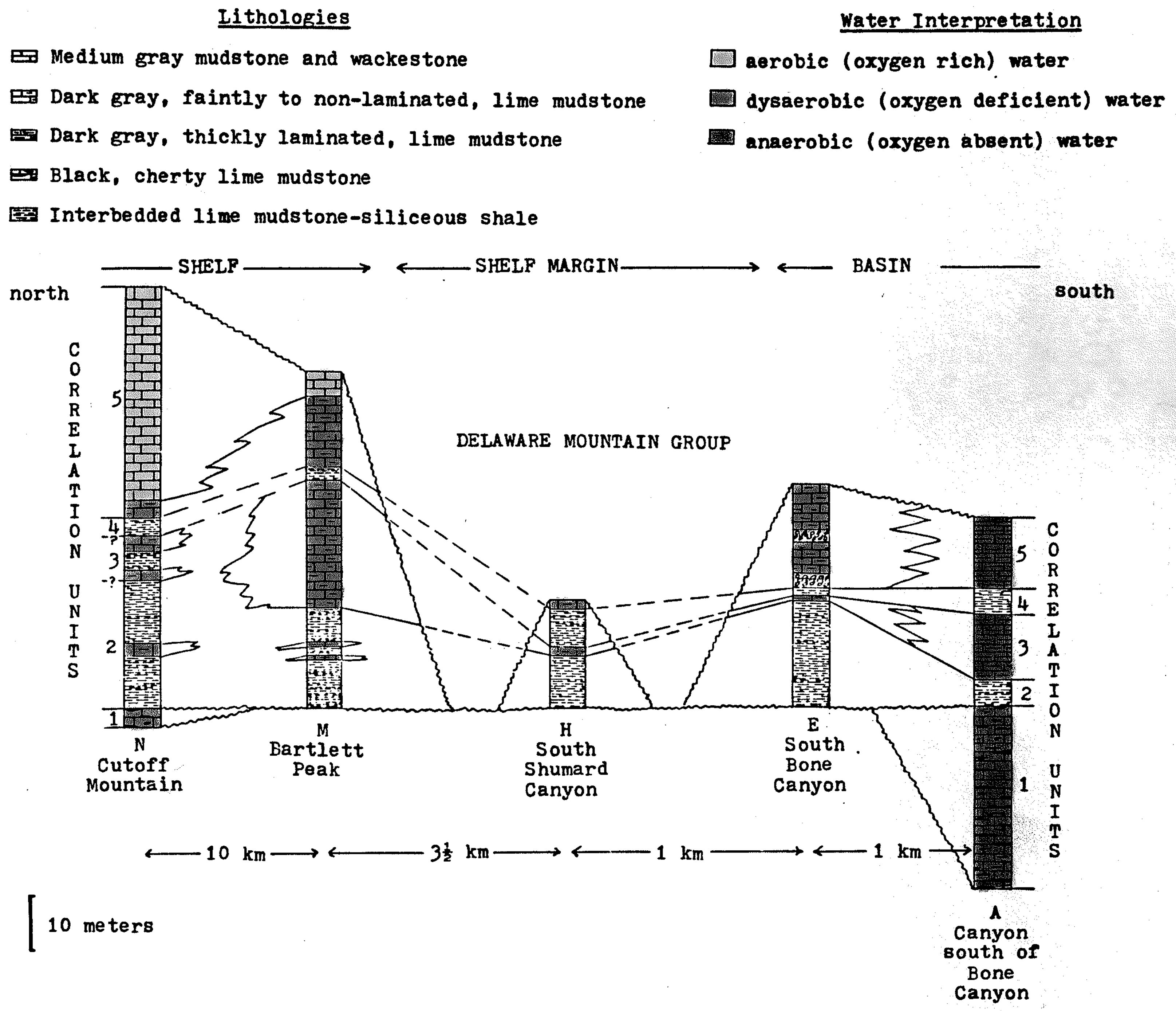
The depositional style and grain size of the lutites in the Cutoff Formation indicate deposition below the zone of active wave effects. Instead the nature of the sediment appears to be controlled by sediment delivery and by the biota or lack thereof. The anoxic basin model is applicable to biota-sediment patterns controlled by the level of oxygen concentration.

The anoxic model fits well with the pattern of Cutoff rock types (Fig. 33). The dark, well-laminated mudstones are interpreted by the model as anaerobic sediments. The dark gray, non-laminated mudstones which lack fauna are representative of dysaerobic conditions. This interpretation of non-laminated texture as due to sediment disturbance by bioturbation is not necessarily valid in all cases. The non-laminated mudstone may be an anaerobic deposit in which no laminations formed during deposition. However in the Cutoff Formation, the basinward strata correlative to the non-laminated mudstone (units 1, 3, and 5) is laminated. At the base of the shelf margin (section B to E) lamination quality gradually declines shelfward (shallower), apparently due to increased bioturbation. The laminations formed during deposition and were only preserved in the absence of later disruption. The medium gray mudstones and wackestones of the shelf represent an aerobic setting.

In an upslope direction from basin to shelf there is a progressive increase in inferred oxygen concentration in all three limestone correlation units (1, 3, and 5) (Fig. 34). There is a similar shift in the shelf area from the base to the top of the section. The uniformity of these changes in all cases (see plate 15 for all sections) is the best and most forceful argument that the changes are real and not a later, diagenetic affect.

The positions of the three water layers relative to

Figure 34: Selected sections showing distribution of interpreted water zones.



the Cutoff shelf profile can be inferred for units 1, 3, and 5 (Fig. 34, plate 15). The fissility of the interbedded lime mudstone-shale of units 2 and 4 is largely due to the large amount of clay material. Because the fissility obscures the lamination style, the anoxic model and interpretations will not be forced upon these strata.

The lower Cutoff (correlation unit 1) is black, cherty mudstone which is interpreted as an anaerobic and dysaerobic deposits. The well-laminated strata of the basin (section B) indicates anaerobic waters. The contemporaneous shelf margin and shelf were dysaerobic based on the occurrence of black, faintly laminated to non-laminated, cherty mudstone without benthonic fauna.

Correlation unit 3 is dark gray mudstone which is also interpretable as an anaerobic and dysaerobic deposit. The well-laminated mudstone of the basin (section B) grades northwards into faintly laminated to non-laminated mudstone at the edge of the basin (Bone Canyon sections D and E). This type of faintly laminated to non-laminated mudstone persists across the shelf margin and shelf.

Correlation unit 5 is the uppermost limestone unit. This contains a variety of rock types, including representatives of all three oxygen zones. The basin remained anaerobic throughout deposition of unit 5. This is represented by the well-laminated mudstones in section B.

From the edge of the basin (Bone Canyon) north across the shelf margin and shelf to the lower beds of unit 5 in the type section at Cutoff Mountain, the rocks of unit 5 are faintly laminated to non-laminated mudstones. These represent dysaerobic conditions. The upper portion of all shelf sections contain the medium gray mudstone and wackestone. These are inferred to be anaerobic sediments. The transition from dark gray to medium gray mudstone occurs near the base of unit 5 at Cutoff Mountain (40 meters down in the section) but at the shelf edge (Bartlett Peak) the transition occurs only in the upper 4 meters. Hence, the dysaerobic/aerobic interface appears to have shifted across the shelf during deposition of the unit. The gradational nature of the upward color change (reflecting oxygenation) from dark to medium gray (example: Bartlett Peak section M) may indicate that the Cutoff depositional surface built upwards through the dysaerobic/aerobic interface. Perhaps the shifting of the interface across the shelf, which presumably dipped slightly basinward, may reflect such a sediment accumulation on the shelf.

Once aerobic, dysaerobic, and anaerobic zones have been identified in the Cutoff strata, the thickness of the dysaerobic zone can be inferred from the excellent structural preservation of the Cutoff shelf profile, and by assuming a lack of later differential subsidence. In correlation unit 5 the vertical distance between the aerobic and anaerobic strata is about 400 meters, the inferred thickness of the dysaerobic zone. In correlation units 1 and 3 the aerobic environment is not represented but the minimum thickness of the dysaerobic zone required is about 400 meters.

Sill depth versus water depth

The pattern of sediment types can be combined with the anoxic basin model of water layers to give a reconstruction of water depth and sill depth.

Water depth: The shelf area should be the best area to try to estimate water depths because 1) the transition from dysaerobic to aerobic environments occurs here, and 2) the shallowest section should be the most sensitive to changes of water depth. The depth of the Cutoff deposits in the basin can be estimated from shelf depths because the relief of the shelf margin is directly observable.

The type section at Cutoff Mountain is 80 meters thick. The lower 40 meters is interpreted as dysaerobic, the upper 40 meters as aerobic. The entire section lacks evidence of much bottom turbulence (wave effects). Two approximations need to be made to interpret this pattern, the thickness of the aerobic zone and the depth of wave effects.

What is the probable thickness of the aerobic zone in the Delaware Basin? This is related to the size of the basin. The Black Sea is 4-5 times the size of the Delaware Basin and has a 50 meter thick aerobic zone. An examination of charts relating fetch and wave velocity to wave height (Komar, 1976, Fig. 4-5) suggests that the heights of storm waves in the Delaware Basin would be about 5 meters smaller than waves formed under similar conditions in the Black Sea. Therefore surface mixing in the Delaware Basin would affect a thinner layer than in the Black Sea. As an approximation the aerobic zone in the Delaware Basin may have been about 45 meters thick.

The second approximation to be made is the depth of wave agitation in the Delaware Basin. The fetch of the Delaware Basin (200 kilometers) would result in storm waves with a height of 5-9 meters (Komar, 1976, Fig. 4-5). These could move silt-sized particles to a depth of 12-20 meters (Komar, 1976, Fig. 8-9).

Now to apply these approximations to the Cutoff Mountain type section. The upper 40 meters is aerobic sediment apparently unaffected by wave activity. The depth range for this environment is between about 45 meters and 12-20 meters. To fit 40 meters of strata into this 25-33 meter thick depth zone requires at least 7-15 meters of subsidence. If the subsidence rate was constant once the Cutoff Mountain shelf area began to accumulate Cutoff strata, the entire 80 meter section of dysaerobic (lower and upper Cutoff) and aerobic (upper Cutoff) deposits could represent about 15-30 meters of subsidence and thus 65-50 meters of shallowing of the depositional surface. The initial shelf depth under these assumptions is: final depth (12-20 meters minimum) + thickness of strata (80 meters) - amount of subsidence (15-30 meters) = initial depth (about 75 meters). Because of the many approximations and assumptions, this figure is only a rough estimate but 65-85 meters is a reasonable approximation for initial shelf depth at Cutoff Mountain. This can be projected to indicate an initial depth during Cutoff deposition of 100-120 meters at the edge of the shelf at Bartlett Peak (section M), where the transition to aerobic sediment occurs 35 meters higher in the section. In the basin the 300 meters of relief indicate an initial depth of 400+ meters in Cutoff time.

Sill depth: The sill depth can be inferred from the position of the dysaerobic/anaerobic interface. Anaerobic conditions can only exist below the zone of lateral mixing with oceanic waters. The bottom of the zone of lateral mixing is the sill depth. Throughout Cutoff deposition only the most basinward portion (sections A and B) of the study area was accumulating anaerobic sediments. The thickness of the dysaerobic zone, extending from water depths of about 45 to 400 meters, indicates a sill depth of about 400 meters for the Delaware Basin.

Tectonism

There is evidence of tectonism related to depositional and erosional events during Cutoff time. There was a subsidence that brought a portion of the shelf to a depth of 65-85 meters. This subsidence occurred rapidly enough so that deep-water carbonates directly overlie shallow bank deposits (Victorio Peak Formation). This almost instant "transgression" resembles the Pliocene-Recent subsidence of the Tyrrehenian Sea at a rate of 1.1 mm./yr. (Fabbri and Selli, 1972). This report suggests that shelf subsidence was accomplished in an episodic manner. I suggest that a second pulse of subsidence may have occurred prior to deposition of the Cherry Canyon sandstone.

The pre-Cutoff subsidence occurred contemporaneously (or nearly so) with the erosion of the Shelf edge (although either subsidence or erosion may have preceded the other). The reason for this relation is not understood. Subsidence of the shelf may have led to erosion of the former shelf profile. Also related to the subsidence is the influx of terrigenous material which occurs as sandstone, siltstone and shale in the upper Cutoff strata. The cause is unclear but this may be due to: 1) an alteration of water circulation patterns on the shelf allowing clay to reach the basin, and/or 2) rejuvenation of a source area increasing the terrigenous influx into the basin. These suggestions are only speculations which only a study of the Upper Leonardian and Lower Guadalupian shelf strata could evaluate.

The area of the sill is also outside the study area. The most likely location for the sill is the Hovey Channel, just to the northwest of the Glass Mountains (Fig. 1). The Hovey Channel narrows to 40 kilometers between the Diablo Platform and the Southern Shelf Area. It is believed to be the outlet to the sea for both the Delaware and Midland Basins.

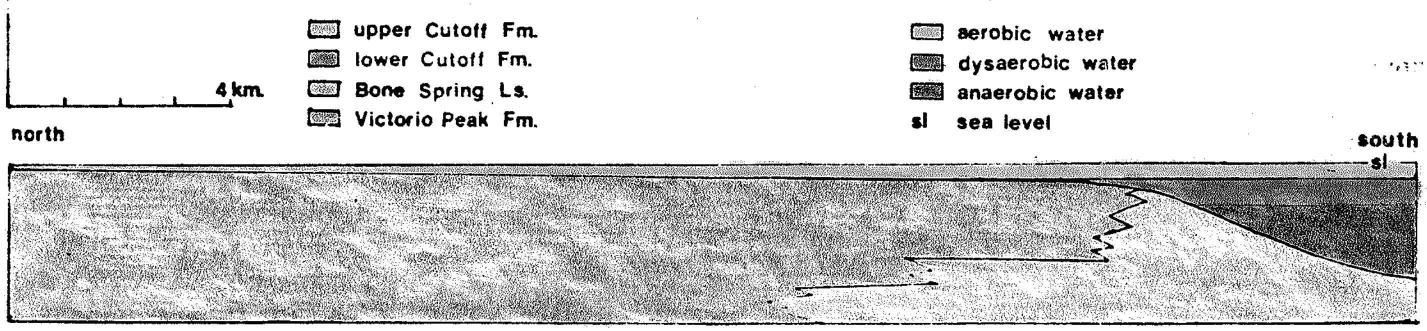
Cutoff depositional model - a summary

The major depositional, erosional, and tectonic events of Late Leonardian-Early Guadalupian time can be summarized (Fig. 35) as follows:

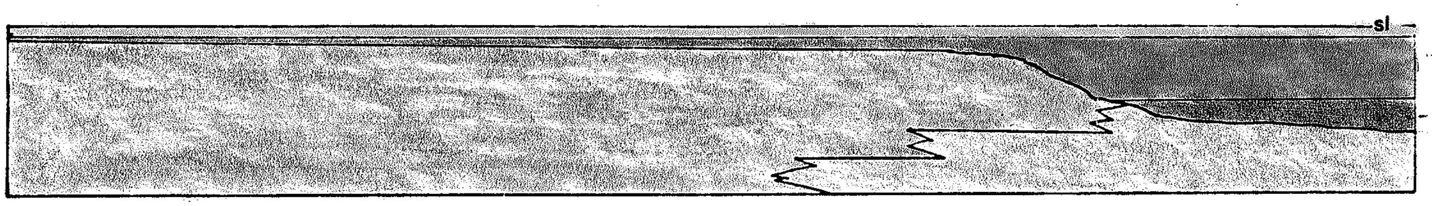
1) Late Leonardian carbonate bank deposition (Bone Spring Limestone-Victorio Peak Formation) occurred along the margins of the Delaware Basin, as shown in Figure 35 as stage 1.
2) Rapid subsidence of the northwest portion of the shelf to a depth of about 65-85 meters. Erosion creating a submarine unconformity (initiated by the subsidence?) removes up to 300 meters of the underlying bank sequence at the bank margin. This establishes a sharp shelf to basin profile with sharp profile breaks at

Figure 35

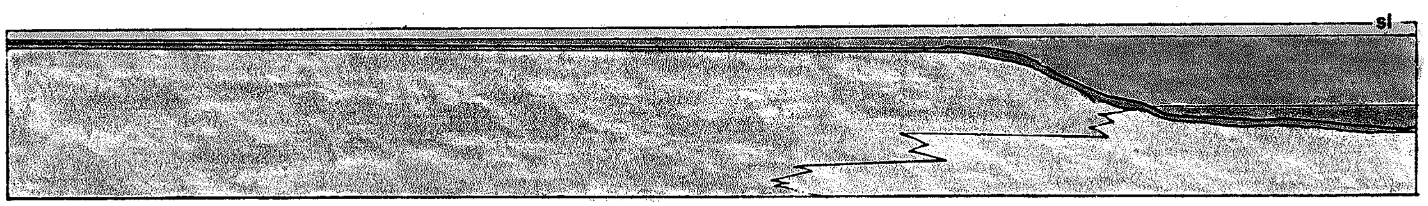
Conceptual model of depositional and erosional events during Cutoff time in a layered anoxic basin



1. Deposition of Victorio Peak-Bone Spring carbonate bank-to-basin sequence of pre-Cutoff age.

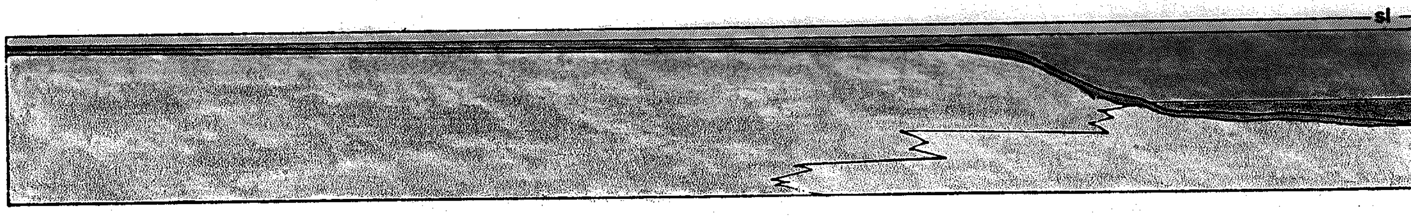


2. Submarine erosion of carbonate bank during shelf subsidence forms steep shelf margin profile.

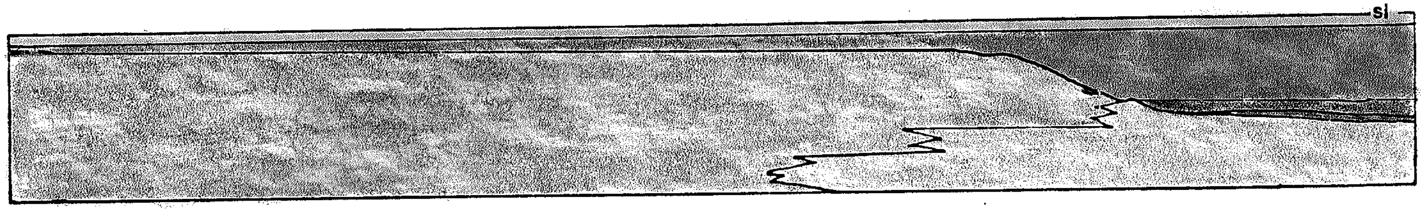


3. Deposition of lower Cutoff.

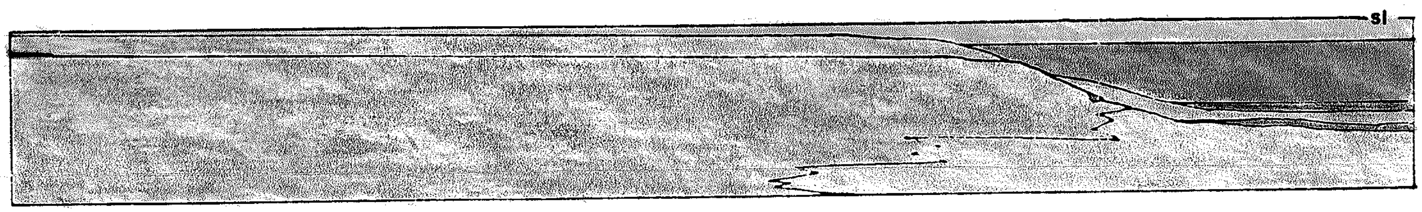
2. Submarine erosion of carbonate bank during shelf subsidence forms steep shelf margin profile.



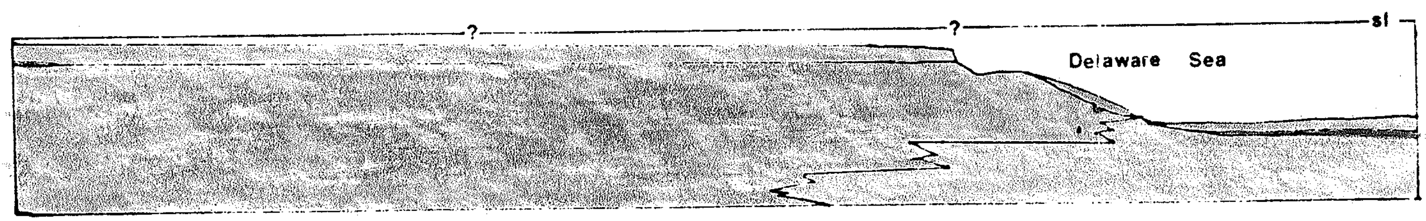
3. Deposition of lower Cutoff.



4. Erosion of lower Cutoff. (Preserved thickness on shelf is slightly exaggerated.)



5. Deposition of upper Cutoff with contemporaneous erosion of upper shelf margin.



6. Post-Cutoff submarine erosion. Positions of interfaces between water layers, and sea level are uncertain.

top and bottom of the shelf margin. (Stage 2)

3) Deposition of the lower Cutoff Formation in dysaerobic waters in the shelf and shelf margin areas and in anaerobic waters in the basin area. (Stage 3) The transgression of oxygen-deficient (dysaerobic) waters brought basin lithologies across 20 kilometers of the shelf.

4) A second major erosional episode establishes a second major unconformity surface which strips away most of the lower Cutoff strata of the shelf and shelf margin areas. (Stage 4)

5) Deposition of the upper Cutoff Formation. Anaerobic waters are restricted to the basin. The dysaerobic waters initially cover both shelf margin and shelf areas but retreat off the shelf as the Cutoff strata build upward into the aerobic zone above a depth of 45 meters but below the region of wave effects (12-20 meters). Minor shelf subsidence takes place and erosion of the uppermost shelf margin continues. (Stage 5)

6) Post-Cutoff erosion establishes a third unconformity surface. Maximum removal occurs on the shelf margin and locally removes the Cutoff strata entirely. Shelf and basin areas are less affected. (Stage 6)

7) Deposition of the Brushy Canyon Formation. Possibly another major shelf subsidence between the end of

Cutoff time and the start of Cherry Canyon Formation deposition.

CONCLUSIONS

"What matters it how far we go?
His scaly friend replied,
There is another shore you know,
Upon the other side."
Carrol

The Cutoff Formation, as exposed along the west escarpment of the Guadalupe Mountains, overlies a 3 kilometer wide shelf to basin profile with a relief of 300 meters. It is a splendidly exposed example of a deep marine drape of basin facies, of nearly 100 meters thickness. It represents the transgression of basin-style sedimentation 20 kilometers into a shelf setting in the time between deposition of the Bone Spring - Victorio Peak and the Delaware Mountain Group. The Cutoff strata are divisible into shelf, shelf margin, and basin areas on the basis of the pre-Cutoff surface created by submarine erosion phenomena.

The major findings of this study are as follows.

1) A vertical succession of five correlation units can be recognized in the Cutoff strata across the 3 kilometer wide shelf margin. These consist of alternating units of interbedded lime mudstone-shale and medium bedded lime mudstone.

   A. The rock types are lutites. Most are comprised of lime mud with lesser amounts of clay. Silt also occurs. The lutites were deposited from suspension, including basinal interflows.

B. The correlation units can be traced from the shelf to the basin. The Cutoff strata in the basin can be clearly and unambiguously recognized for the first time. The strata can be traced from Bone Canyon south, and include most of the low hills of black limestone south and west of El Capitan.

2) An anoxic basin model can be applied to the pattern of lithologies within the Cutoff Formation.

A. The basin area remained anaerobic throughout Cutoff deposition. The entire shelf margin section and the initial shelf deposits are dysaerobic. As the later shelf deposits accumulated, the depositional surface built up into the aerobic zone.

B. Initial water depths are estimated to have been 65-85 meters at the Cutoff Mountain shelf area, 100-120 meters at the shelf edge (Bartlett Peak), 400+ meters in the basin.

3) Erosional surfaces associated with the Cutoff Formation are concentrated in the shelf margin and basin areas.

A. The lower contact of the Cutoff, the surface between the lower and upper Cutoff strata, and the upper contact of the Cutoff are all wide-spread erosion surfaces which occur throughout the study area, and are interpreted as unconformities. These unconformity surfaces appear to be caused by submarine erosion. The initial truncation of 300 meters of underlying Victorio Peak strata at the shelf margin occurred during or subsequent to shelf subsidence.

B. Two large "half-channel" features characterize part of the upper and lower unconformities. These features truncate at least 100 meters of underlying Cutoff and Victorio Peak strata at the shelf edge. These spoon-shaped surfaces strike nearly parallel to the shelf edge and dip basinwards. The origin of these surfaces is problematical.

C. The Cutoff shelf strata are interrupted by a 100 meter deep channel near Bartlett Peak which was formed after Cutoff deposition. This channel truncates both Cutoff and Victorio Peak strata and is filled by Delaware Mountain Group sandstones, probably all Cherry Canyon sandstone. It is oriented at an oblique angle to the shelf edge and may have served as a feeder channel of sand into the Delaware Basin.

D. Channels are widespread in the shelf margin and basin areas, and occur throughout the Cutoff strata. The channel fills are predominantly intraclastic rudstone, megabreccia, and lulites, but skeletal rudstone and sandstone also occur. The channel orientations are compatible with a general transport direction down the shelf margin into the basin.

E. The geometry of the channel fillings is similar to that described by Harms' (1974) model of basin sedimentation, except for a greater importance of drape and suspension deposition. A combination of density-driven bottom-flows and interflows are believed to have transported sediment and cut channels. These currents may have been driven by contrasts in salinity, temperature, or suspended clay current.

4) The fauna in the Cutoff Formation is sparsely distributed. It is largely allochthonous and dominated by brachiopods. Much of King's (1948) and Newell *et al.*'s (1953) "Bone Spring Limestone fauna" appears to have been collected from Cutoff strata.

5) The age of the upper Cutoff Formation is Guadalupian, based on previously reported fusulinid data (Wilde and Todd, 1968). The age of the lower Cutoff is unknown. I propose that the series boundary be drawn at the

unconformity between the upper and lower Cutoff Formation.

Bibliography

Adams, J. E., Cheney, M. G., DeFord, R. K., Dickey, R. I., Dunbar, C. O., Hills, J. M., King, R. E., Lloyd, E. R., Miller, A. K., Needham, C. E., 1939, Standard Permian section of North America: Am. Assoc. of Petroleum Geologists Bull., v. 23, p. 1673-1681.

Babcock, L. C., 1974, Statistical approaches to the conodont paleoecology of the Lamar Limestone, Permian Reef Complex, West Texas: Ph.D. dissertation, Univ. Wisconsin, Madison, 175 p.

Bagnold, R. A., 1954, Experiments on a gravity-free dispersion of large solid spheres in a Newtonian fluid under shear: Royal Soc. London Proc., Ser. A., v. 225, p. 49-63.

Blanchard, W. G., and Davis, M. J., 1929, Permian stratigraphy and structure of parts of southeastern New Mexico and southwestern Texas: Am. Assoc. Petroleum Geologists Bull., v. 13, p. 957-995.

Boyd, D. W., 1958, Permian sedimentary facies, central Guadalupe Mountains, New Mexico: New Mexico Bureau of Mines and Mineral Resources Bull. 49, 100 p.

Bozanich, R. G., 1979, The Bell Canyon and Cherry Canyon Formations, Eastern Delaware Basin, Texas: Lithology, Environments and Mechanisms of Deposition: in Sullivan, N. M. (ed.), Guadalupian Delaware Mountain Group of West Texas and Southeast New Mexico, Permian Basin Section S. E. P. M. Symposium Publ. 79-18, p. 121-141.

Bricker, O. P. (ed.), 1970, Carbonate cements: The John's Hopkins Press, Baltimore, Maryland, 376 p.

Byers, C. W., 1977, Biofacies Patterns in Euxinic Basins: A General Model: in Cook, H. E. and Enos, P. (eds.), Deep-Water Carbonate Environments, Soc. Econ. Paleo. Min. Spec. Publ. 25, p. 5-18.

Cook, H. E., McDaniel, P. N., Mountjoy, E. W., and Pray, L. C., 1972, Allochthonous carbonate debris flows at Devonian bank ('reef') margins, Alberta, Canada: Canadian Petroleum Geol. Bull., v. 20, p. 439-497.

Cooper, G. A., and Grant, R. E., 1972-1977, Permian Brachiopods of West Texas, I-VI: Smithsonian

Contributions to Paleobiology, no. 14, 15, 19, 21, 24, 32, 3370 p.

Crawford, G. A., in progress, Sedimentology of the Goat Seep Dolomite (Guadalupian, Permian), Guadalupe Mountains, West Texas and New Mexico: Ph.D. dissertation, Univ. Wisconsin, Madison.

Davies, G. R., 1977, Turbidites, Debris Sheets and Truncation Structures in Upper Paleozoic Deep-Water Carbonates of the Sverdrup Basin, Arctic Archipelago: in Cook, H. E. and Enos, P. (eds.), Deep-Water Carbonate Environments, Soc. Econ. Paleo. Min. Spec. Publ. 25, p. 221-248.

Dott, R. H., 1963, Dynamics of subaqueous gravity depositional processes: Am. Assoc. Petroleum Geologists Bull., v. 47, p. 104-128.

Dunham, R. J., 1962, Classification of carbonate rocks according to depositional texture: in Ham, W. E. (ed.), Classifiction of Carbonate Rocks, Am. Assoc. Petroleum Geologists Memoir 1, p. 104-121.

Elam, J. G., and Chuber, S. (eds.), 1969, Cyclic Sedimentation in the Permian Basin, West Texas Geol. Symposium Publ. 69-56, 203 p.

Embry, A. V., and Klovan, J. E., 1971, A Late Devonian Reef Tract on Northeast Banks Island, Northwest Territories: Canadian Petroleum Geol. Bull., v. 19, p. 730-781.

Fabbri, A., and Selli, R., 1972, The Structure and Stratigraphy of the Tyrrhenian Sea: in Stanley, D. J. (ed.), The Mediterranean Sea: A Natural Sedimentation Laboratory, Dowen, Hutchinson & Ross, Stroudsburg, Penn., p. 75-81.

Harms, J. C., 1974, Brushy Canyon Formation, Texas: A Deep-Water Density Current Deposit: Geol. Soc. America Bull., v. 85, p. 1763-1784.

Harms, J. C., and Pray, L. C., 1974, Erosion and Deposition along the Mid-Permian intercratonic basin margin, Guadalupe Mountains, Texas (abs.): in Dott, R. H., and Shaver, R. H. (eds.), Modern and ancient geosynclinal sedimentation, Soc. Econ. Paleo. Min. Spec. Publ. 19, p. 37.

Hayes, P. T., 1959, San Andres Limestone and related Permian rocks in Last Chance Canyon and vicinity, southeastern New Mexico: Am. Assoc. Petroleum Geologists Bull., v. 43, p. 2197-2213.

Hayes, P. T., 1964, Geology of the Guadalupe Mountains, New Mexico: U. S. Geol. Survey Prof. Paper 446, 69 p.

Hay-Roe, H., 1957, Geology of Wylie Mountains and vicinity, Culberson and Jeff Davis Counties, Texas: Bureau of Econ. Geology, Univ. Texas, Austin, Geologic Quadrangle Map No. 21.

Hileman, M. E., and Mazzulo, S. J. (eds.), 1977, Upper Guadalupian Facies, Permian Reef Complex, Guadalupe Mountains, New Mexico and West Texas, 1977 Field Conf. Guidebook, v. 1: Permian Basin Section S. E. P. M. Publ. 77-16, 508 p.

Hills, J. M., 1972, Late Paleozoic Sedimentation in West Texas Permian Basin: Am. Assoc. Petroleum Geologists Bull., v. 56, p. 2303-2322.

Ingram, R. L., 1954, Terminology for the thickness of stratification and parting units in sedimentary rocks: Geol. Soc. America Bull., v. 65, p. 937-938.

Jacka, A. D., Beck, R. H., St. Germain, L. C., and Harrison, S. C., 1968, Permian Deep-Sea Fans of the Delaware Mountain Group (Guadalupian), Delaware Basin: in Silver, B. A. (ed.), Guadalupian Facies, Apache Mountains area, west Texas, Permian Basin Section S. E. P. M. Guidebook 68-11, p. 49-90.

Jacka, A. D., Thomas, C. M., Beck, R. H., Williams, K. W., and Harrison, S. C., 1969, Guadalupian Depositional Cycles, Delaware Basin and Northwest Shelf: in Elam, J. G., and Chuber, S. (eds.), Cyclic Sedimentation in the Permian Basin, West Texas Geol. Soc. Symposium Publ. 69-56, p. 152-196.

King, P. B., 1934, Permian stratigraphy of trans-Pecos, Texas: Geol. Soc. America Bull., v. 45, p. 697-798.

King, P. B., 1942, Permian of west Texas and southeastern New Mexico: Am. Assoc. Petroleum Geologists Bull., v. 26, p. 535-763.

King, P. B., 1948, Geology of the southern Guadalupe

Mountains, Texas, U. S. Geol. Survey Prof. Paper 215, 183 p.

King, P. B., 1965, Geology of the Sierra Diablo region, Texas: U. S. Geol. Survey Prof. Paper 480, 185 p.

Komar, P. D., 1976, Beach Processes and Sedimentation: Prentice-Hall, Englewood Cliffs, N. J., 429 p.

Lang, W. B., 1937, The Permian formations of the Pecos valley of New Mexico and Texas: Am. Assoc. Petroleum Geologists Bull., v. 21, p. 833-898.

Lowe, D. R., 1976, Grain flows and grain flow deposits: Jour. Sed. Petrology, v. 46, p. 188-199.

Lowry, W. D. and Cooper, B. N., 1970, Penecontemporaneous Downdip Slump Structures in Middle Ordovician Limestone, Harrisonburg, Virginia: Am. Assoc. Petroleum Geologists Bull., v. 54, p. 1938-1945.

Matter, A., 1974, Burial diagenesis of pelitic and carbonate deep-sea sediments from the Arabian Sea: in Whitmarsh, R. B., Wiser, O. E., Ross, D. A. et al., Initial Reports of the Deep Sea Drilling Project, v. 23, U. S. Gov. Printing Office.

McDaniel, P. N., and Pray, L. C., 1967, Bank to basin transition in Permian (Leonardian) carbonates, Guadalupe Mountains, Texas (abs.): Amer. Assoc. Petroleum Geologists Bull., v. 51, p. 474.

Middleton, G. V., and Hampton, M. A., 1976, Subaqueous Sediment Transport and Deposition by Sediment Gravity Flows: in Stanley, D. J., and Swift, D. J. P. (eds.), Marine Sediment Transport and Environmental Management, Wiley & Sons, New York, p. 197-218.

Mountjoy, E. W., Cook, H. E., Pray, L. C., and McDaniel, P. N., 1972, Allochthonous carbonate debris flows-worldwide indicators of reef complexes, banks, or shelf margins: 24th Internat. Geol. Congress, Sect. 6, p. 172-189.

Newell, N. D., Rigby, J. K., Fisher, A. G., Whiteman, A. J., Hickox, J. R., Bradley, J. S., 1953, The Permian reef complex of the Guadalupe Mountains region, Texas and New Mexico: Freeman & Co., San Francisco, 236 p.

Olsen, C. R., 1978, Sedimentation rates: in Fairbridge, R. W., and Bourgeois, J. (eds.), The Encyclopedia of Sedimentology, Dowden, Hutchinson & Ross, Stroudsburg, Penn, p. 687-692.

Oriel, S. S., Myers, D. A., and Crosby, E. J., 1967, West Texas Permian basin region: in McKee, E. D., Oriel, S. S., and others, Paleotectonic Investigations of the Permian System in the United States, U. S. Geol. Survey Prof. Paper 515, p. 21-60.

Pray, L. C., 1960, Compaction in calcilutites (abst.): Geol. Soc. America Bull., v. 71, p. 1946.

Pray, L. C., 1971, Submarine slope erosion along the Permian bank, west Texas (abs.): Amer. Assoc. Petroleum Geologists Bull., v. 55, p. 358.

Pray, L. C., 1977, The All Wet Constant Sea Level Hypothesis of Upper Guadalupian Shelf and Shelf Edge Strata, Guadalupe Mountains, New Mexico and Texas: in Hileman, M. E., and Mazzullo, S. J. (eds.), Upper Guadalupian Facies, Permian Reef comlex, Guadalupe Mountains, New Mexico and West Texas, 1977 Field Conf. Guidebook, v. 1, Permian Basin Section S. E. P. M., Publ. 77-16, p. 433.

Pray, L. C., Crawford, G. A., Harris, M. T., and Kirkby, K. C., 1980, Early Guadalupian (Permian) bank margin erosion surfaces, Guadalupe Mountains, Texas: Amer. Assoc. Petroleum Geologists Bull., v. 64, p. 768.

Pray, L. C., and Esteban, M. (eds.), 1977, Road logs and locality guides, Upper Guadalupian Facies, Permian Reef complex, Guadalupe Mountains, New Mexico and West Texas, 1977 Field Conf. Guidebook, v. 2: Permian Basin Section S. E. P. M., Publ. 77-16, 194 p.

Pray, L. C., and Stehli, F. G., 1963, Allochthonous origin, Bone Spring "patch reefs", west Texas (abs.): Geol. Soc. of America Special Paper No. 73, p. 218-219.

Rhodes, D. C., and Morse, J. W., 1971, Evolutionary and ecologic significance of oxygen-deficient marine basins: Lethaia, v. 4, p. 413-428.

Richardson, G. R., 1904, Report of a reconnaissance in Trans-Pecos Texas north of the Texas and Pacific Railway: Univ. Texas Bull., no. 9, 119 p.

Silver, B. A., and Todd, R. G., 1969, Permian cyclic strata, northern Midland and Delaware basins, West Texas and southeastern New Mexico: Amer. Assoc. Petroleum Geologists Bull., v. 30, p. 2223-2251.

Warren, W. C., 1955, Introduction to field trip: in Permian Field Conference to the Guadalupe Mountains, Permian Basin Section S. E. P. M., Guidebook 55-1, p. 11-14.

Wilde, G. L., and Todd, R. G., 1968, Guadalupian Biostratigraphic Relationships and Sedimentation in the Apache Mountain Region, West Texas: in Silver, B. A. (ed.), Guadalupian Facies, Apache Mountains area, West Texas, Permian Basin Section S. E. P. M., Guidebook 68-11, p. 10-31.

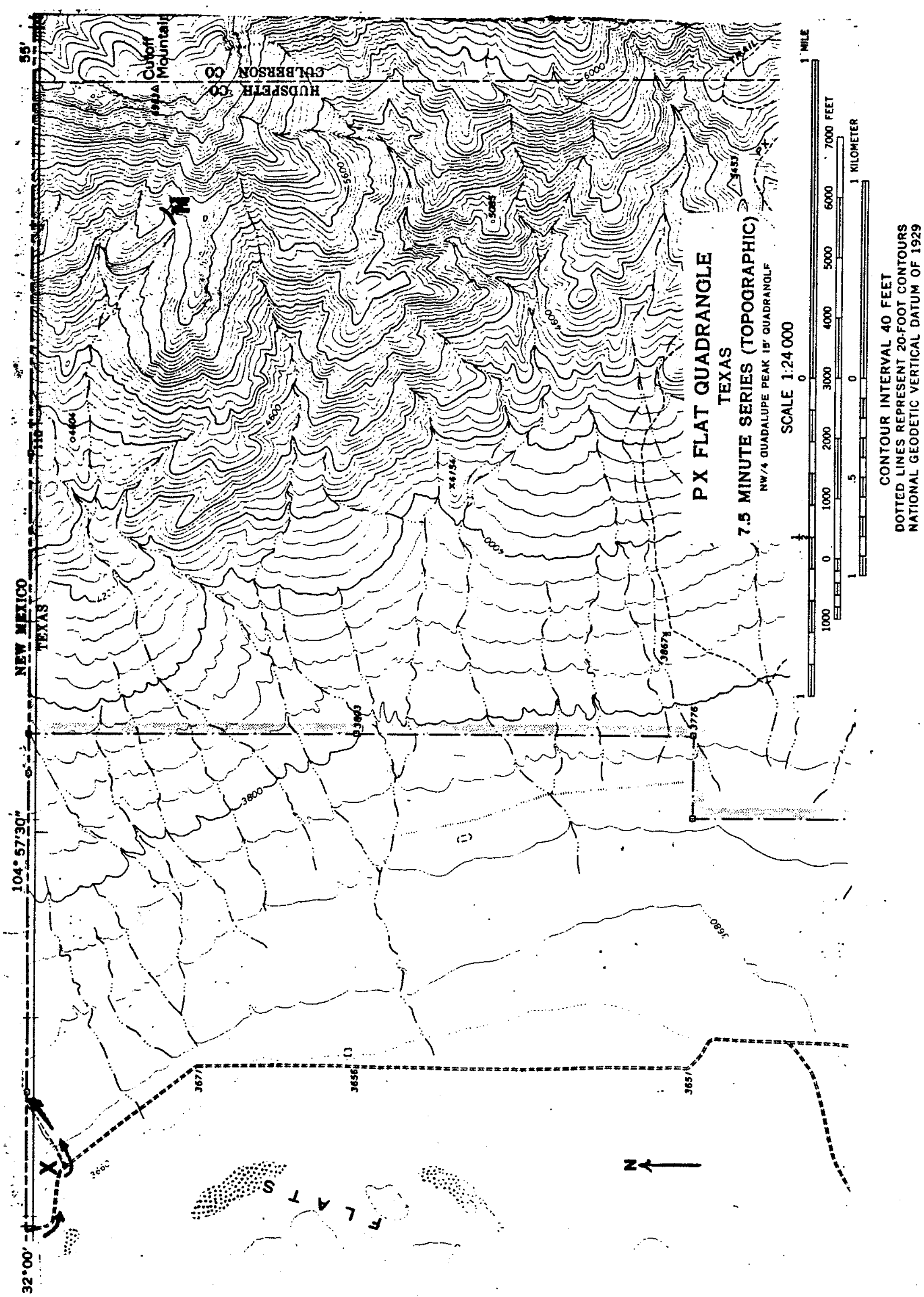
Williamson, C. R., 1979, Deep-Sea Sedimentation and Stratigraphic Traps, Bell Canyon Formation (Permian), Delaware Basin: in Sullivan, N. M. (ed.), Guadalupian Delaware Mountain Group of West Texas and Southeast New Mexico, Permian Basin Section S. E. P. M., Symposium Publ. 79-18, p. 39-74.

Wilson, J. L., 1967, Cyclic and reciprocal sedimentation in Virginia strata of southern New Mexico: Geol. Soc. America Bull., v. 78, p. 805-818.

Wilson, J. L., 1975, Carbonate Facies in Geologic History: Springer-Verlag, New York.

Winn, R. D. Jr., and Dott, R. H., 1979, Deep-water fan-channel conglomerates of Late Cretaceous age, southern Chile: Sedimentology, v. 26, p. 203-228.

Wood, J. W., 1968, Geology of the Apache Mountains, Trans-Pecos Texas: Bureau of Economic Geology, Univ. Texas, Austin, Geologic Quadrangle Map No. 35, 32 p.


P X FLAT QUADRANGLE
TEXAS
7.5 MINUTE SERIES (TOPOGRAPHIC)
NW/4 GUADALUPE PEAK 15' QUADRANGLE
SCALE 1:24 000
CONTOUR INTERVAL 40 FEET
DOTTED LINES REPRESENT 20-FOOT CONTOURS
NATIONAL GEODETIC VERTICAL DATUM OF 1929
1 MILE
7000 FEET
1 KILOMETER
NEW MEXICO
TEXAS
HUDSPETH CO
CULBERSON CO
Cutoff Mountain
104° 57'30"
55'
32°00'
FLATS
N
X

Appendix 1:

Road log to Cutoff Mountain

Mileage Cumulative	Mileage Interval	
0.0	0.0	Intersection of U.S. 62/180 with Texas 1576, east of Salt Plats Cafe. Proceed north of Texas 1576.
17.0	17.0	Continue straight at the crossroad, staying on Texas 1576. Dell City is 3 miles to the west.
19.9	3.9	Road turns sharply to the right 90°.
20.9	1.0	Crossroad. Take Texas 1576 to the left.
21.9	1.0	Crossroad. Take Texas 1576 to the right.
23.2	1.3	Go straight on the dirt road. This is a private road on the Guitar Ranch which follows the Texas/New Mexico state line.
25.0	1.8	Sixteen-mile marker of the Clark Survey (1859) of the border is on the right.
25.8	0.8	Crossroad. Continue straight ahead.
26.4	0.6	Dirt road enters at an oblique angle on the right. Continue straight.
29.0	2.6	Road veers away from the fence line.
30.5	1.5	Road forks. Turn right.
30.8	0.3	Ranchhouse on the right.
30.9	0.1	Go through the gate and turn left.
31.1	0.2	Turn left onto track. This is point X on the map opposite.
31.6	0.5	Camp on New Mexico side of state line,

Mileage

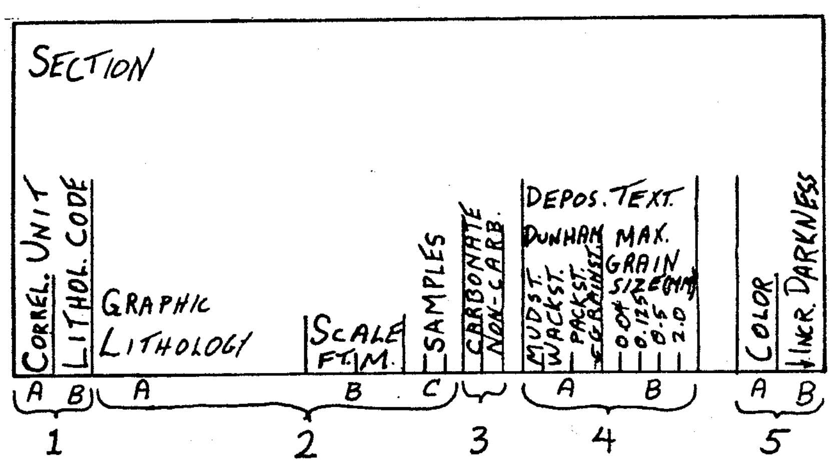
Cumulative	Interval	
31.6 (cont.)	0.5	just before ditch. Section N is located on the west face of Cutoff Mountain, as shown on map. King's type section is located just slightly to the north.

Appendix 2:

Stratigraphic sections A to N and explanation of their format

Diagrams of stratigraphic sections A to N are located in the pocket at the back of this thesis. The field locations of the sections are indicated on figure 3, except for sections A and N. Section A is located at the approximate location of King's (1948) section 17. The location of section N (Cutoff Mountain) is shown in appendix 1, with a road log to the area.

The stratigraphic sections appear as constructed in the field, and lithologies have been checked by laboratory study of available samples. Sections have a standard format. Headings used for the sections and explanatory notes are given below.



1. Columns with coded summary of lithology and correlation unit. These two columns are shown on the graphic logs

in the correlation diagram of the stratigraphic sections (plate 15).

A. Correlation unit: Position of correlation units each section. Unit 1= lower Cutoff Formation, units 2-5= upper Cutoff Formation.

B. Lithology Code: Two basic types of symbols, one for lutites, one for rudites.

Lutite lithology codes are all prefixed by an "L" which is followed with a number to indicate which lutite lithology.

L1= black, cherty lime mudstone

L2= thinly laminated, fissile lime mudstone

L3= siliceous shale

L4= siltstone

L5= thinly laminated, medium bedded, lime mudstone

L6= faintly laminated to non-laminated, medium bedded, lime mudstone

L7= medium gray lime mudstone

L8= medium gray lime wackestone

Rudite codes indicate texture and location. The same coding is used in the section and in table 3. The code has three parts: 1) two initial letters which indicate the rudite type, 2) a third letter in parentheses which indicates special textural features in some of the rudites, and 3) a number to tie the rudite body in the section to the description in table 3. Each rudite texture is numbered seperately. The letter code is: MB= megabreccia

IR= intraclastic rudstone

SR= skeletal rudstone

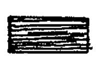
(V)= deposited with void spaces between the clasts

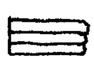
(S)= sheet-shaped body

For example, MB 1 is the megabreccia south of Bone Canyon at the base of section D; IR(V) 3 is the intraclastic rudstone with primary void space, located at the base of section B.

2. Graphic log of lithologic column

A. Graphic log illustrates bedding style and thickness, weathering profile, and types of grains. Subdivisions of the columns are indicated immediately to the right of the column. The symbols in the column are:

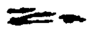
 = thinly laminated strata with no larger scale bedding, that is fissile strata

 = medium bedded limestone

 = intraclastic rudstone or megabreccia

 = sandstone

 = carbonate clasts

 = chert seams and nodules

 = concretion in lutite

 = crinoids

 = brachiopods

y = bryozoans

 = rugose corals

 = fusulinids

 = conularids

B. Vertical scale in feet and meters.

C. Horizons at which samples were taken.

3. Rock type: The predominant lithology, either limestone or non-carbonate (terrigenous silicates).

4. Texture

A. Depositional texture follows Dunham (1962). The curve reflects the amount of mud, decreasing to the right. The boundary (dashed) between wackestone and packstone depends on grain support and not a fixed mud percentage. The extreme right edge indicates a grainstone and the complete absence of mud.

In this report, Dunham's textural classification has been applied to all clastic rocks, whether carbonates or terrigneous silicates. For example, a shale without silt is texturally equivalent to a mudstone; a clean sandstone to a grainstone; a megabreccia with mud-filled intraclastic spaces to a packstone.

B. Maximum grain size: This is a practical "maximum", and is the upper size limit of abundant grains, not the rare fossil. For example, a lone brachiopod in several beds of mudstone is ignored, but not the silt scattered throughout.

5. Color

A. The code of the rock color from the GSA rock color chart (reprinted 1970).

B. Darkness of the rock, increasing to the right. Derived from the lightness values of the rock color, values range from 9 (lightest) to 1 (darkest).

Appendix 3:

Terminology of rock types and stratification.

A. Rock Types

1. Rock names used in this study for limestones are after Embry and Klovan's (1971) modification of Dunham's (1962) classification of carbonates according to depositional texture:

<table>
<tr><td colspan="6">Allochthonous limestones
original components not organically bound during deposition</td><td colspan="3">Autochthonous limestones
original components organically bound during deposition</td></tr>
<tr><td colspan="4">Less than 10% > 2 mm components</td><td colspan="2">Greater than 10% > 2 mm components</td><td rowspan="4">By organisms which act as baffles</td><td rowspan="4">By organisms which encrust and bind</td><td rowspan="4">By organisms which build a rigid framework</td></tr>
<tr><td colspan="3">Contains lime mud (< .03 mm)</td><td>No lime mud</td><td rowspan="3">Matrix supported</td><td rowspan="3">> 2 mm component supported</td></tr>
<tr><td colspan="2">Mud supported</td><td colspan="2" rowspan="2">Grain supported</td></tr>
<tr><td>Less than 10% grains (> .03 mm < 2 mm)</td><td>Greater than 10% grains</td></tr>
<tr><td>Mudstone</td><td>Wackestone</td><td>Packstone</td><td>Grainstone</td><td>Floatstone</td><td>Rudstone</td><td>Bafflestone</td><td>Bindstone</td><td>Framestone</td></tr>
</table>

2. Additional rock names used in this study are defined below.

<u>megabreccia</u>- a deposit in which angular clasts larger than 1 meter are conspicuous components and which may contain some clasts many meters across. (Cook *et al.*, 1972)

<u>lutite</u>- a rock in which the dominant grain size

is smaller than 1/16 millimeter. No compositional implication.

<u>shale</u>- a lutite composed of terrigenous silicates with a fissile character. Usually ≥2/3 clay-sized particles.

<u>siltstone</u>- a rock which is composed of terrigenous silicates of which ≥2/3 of the particles are between 1/16 and 1/256 millimeter in size (silt-size range).

<u>rudite</u>- a rock in which the dominant grain size is larger than 2 millimeters. No compositional implication.

B. Terms for stratification follow Ingram's (1954) classification:

Thickness of stratification	Term
no strat. planes	massive
>100 cm.	very thick beds
100-30 cm.	thick beds
30-10 cm.	medium beds
10-3 cm.	thin beds
3-1 cm.	very thin beds
1-0.3 cm.	thick laminations
<0.3 cm.	thin laminations

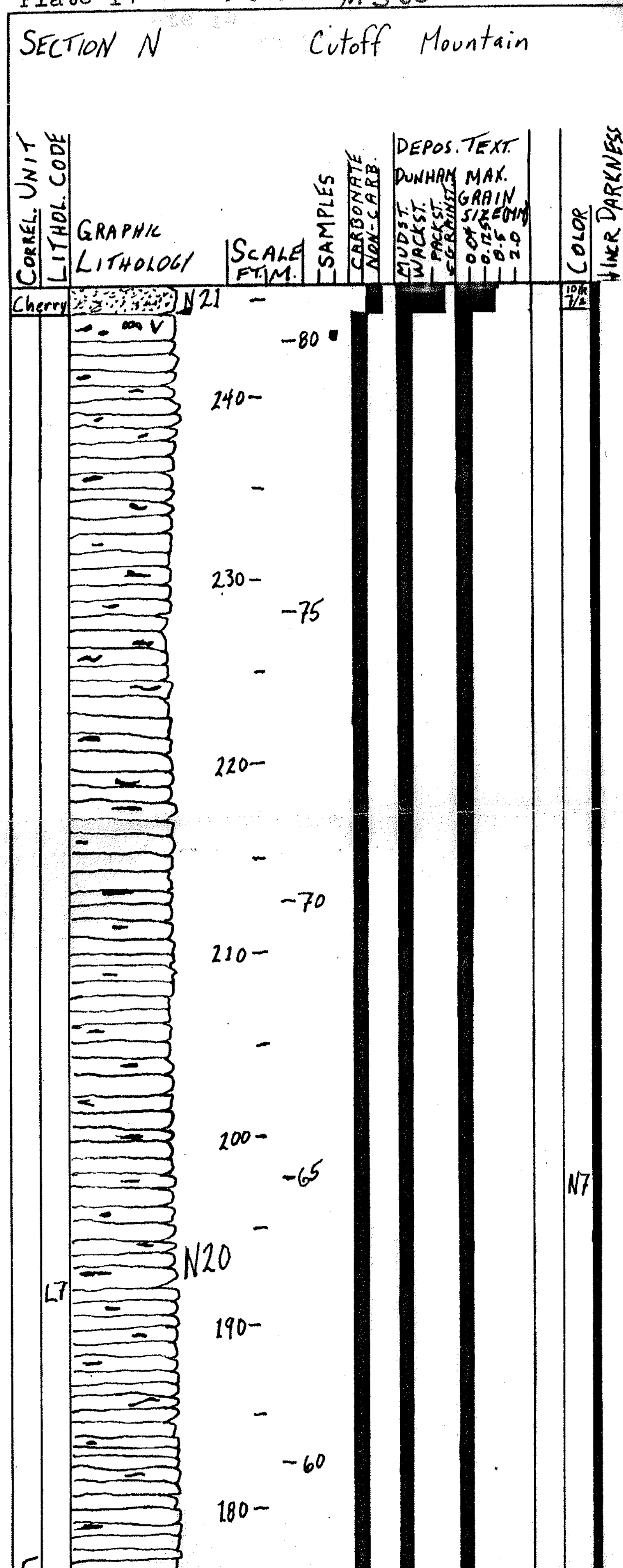
Approved:

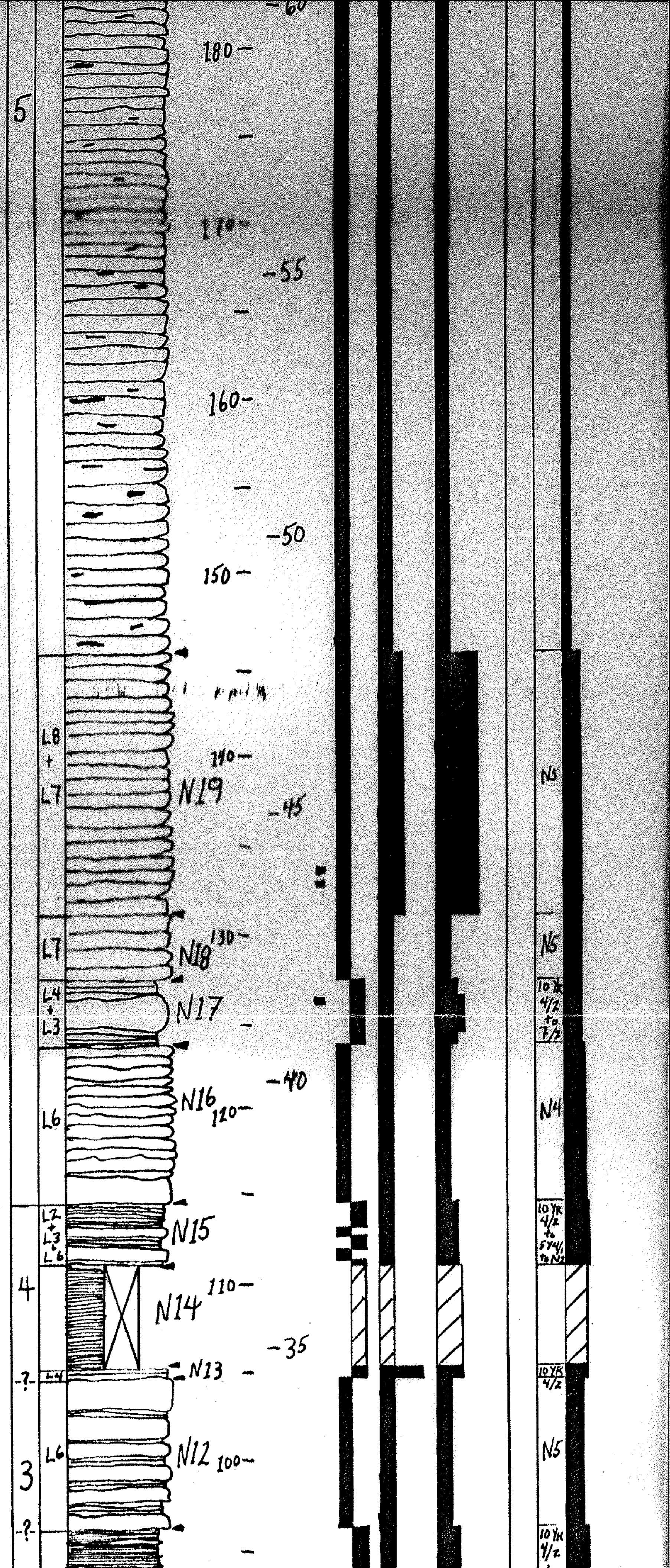
Lloyd C. Pray

Lloyd C. Pray, Professor of Geology

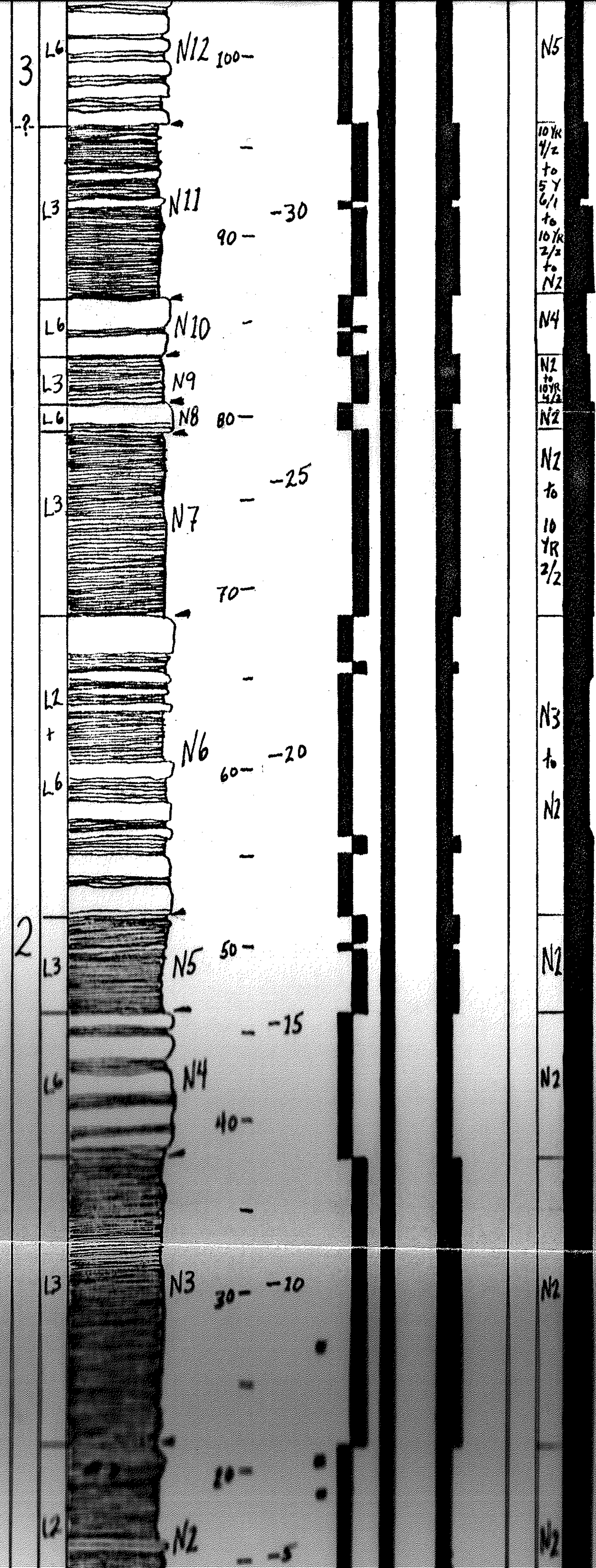
April 26, 1982

Plate 14 597690 AWO 4315 M365

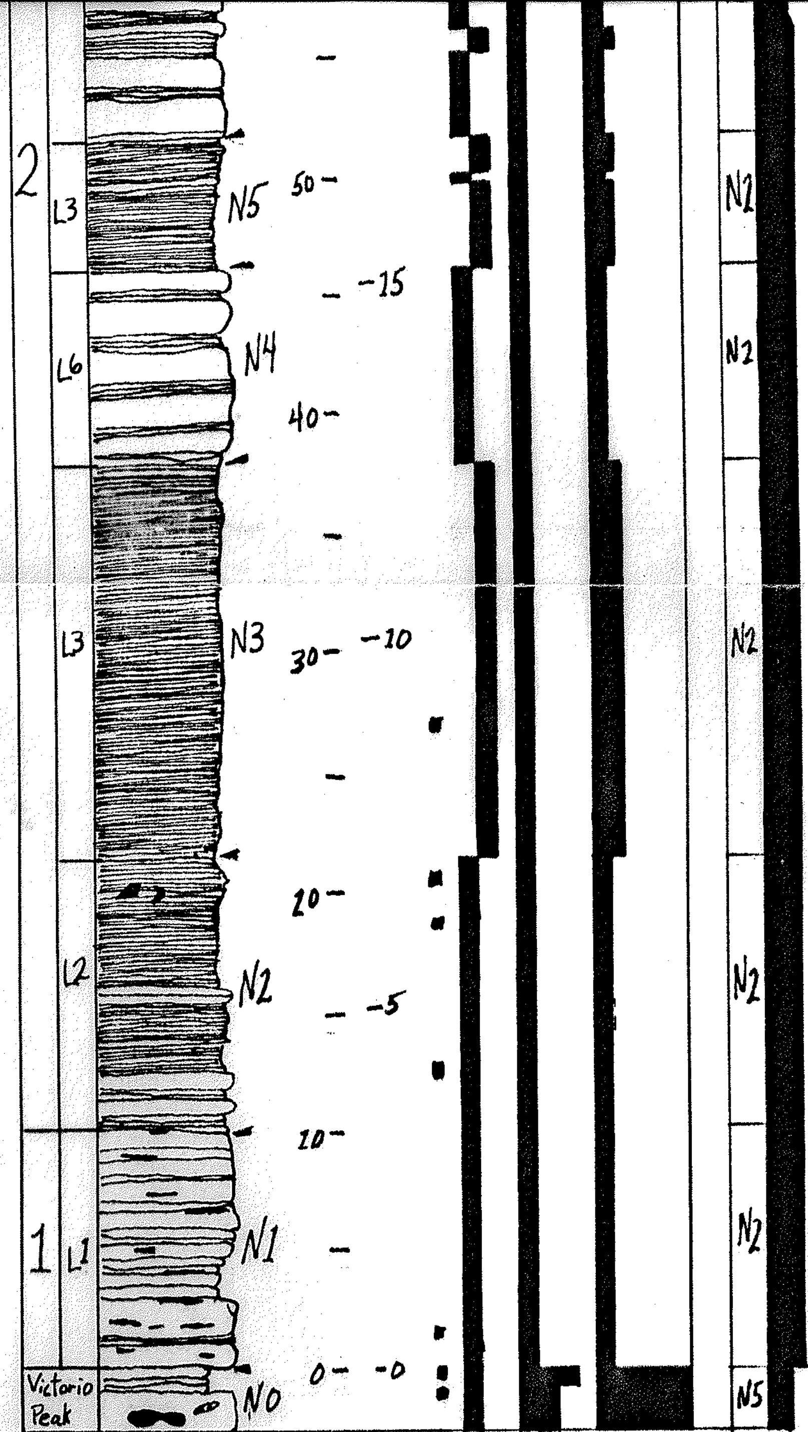




5
180
170
-55
160
-50
150
L8 + L7
140
N19
-45
N5
L7
N18
130
N5
L4 + L3
N17
10 YR 4/2 to 7/2
-40
L6
N16
120
N4
L2 + L3 + L6
N15
4
N14
110
-35
N13
10 YR 4/2
-?-
L4
L6
N12
100
3
N5
-?-
10 YR 4/2

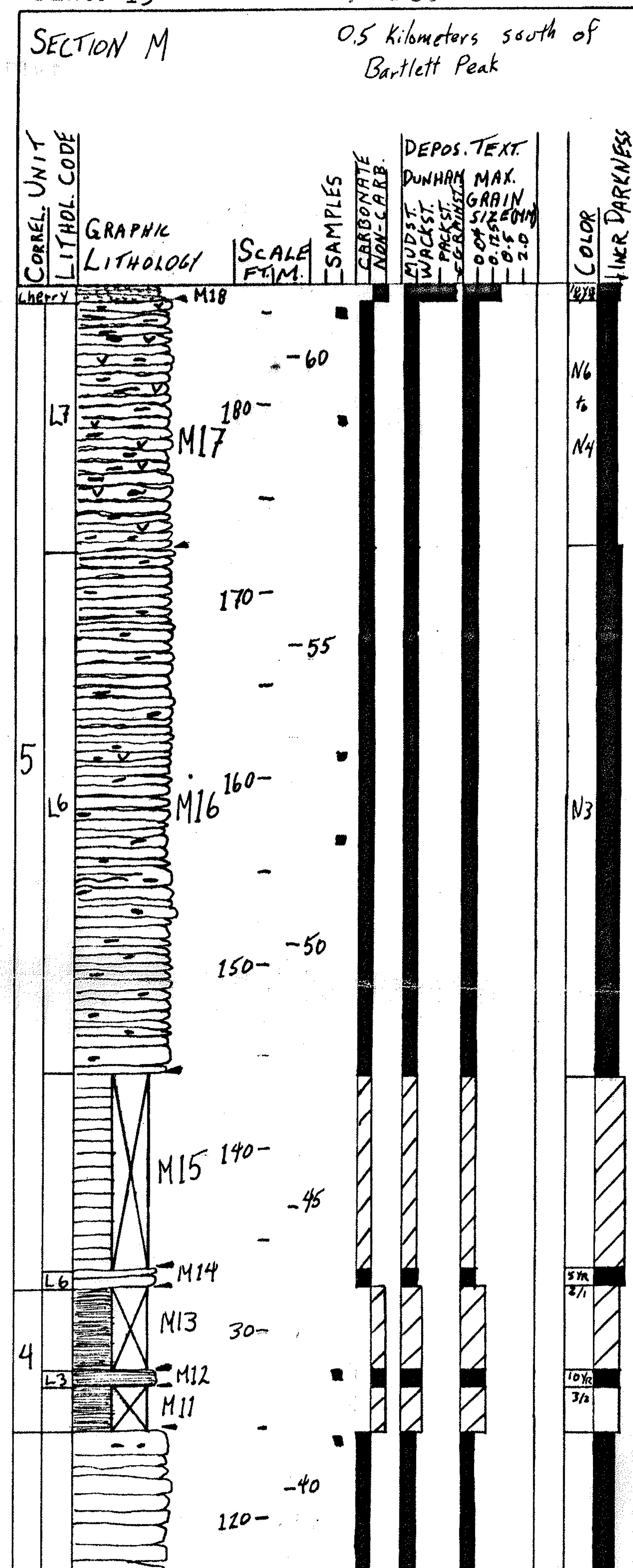


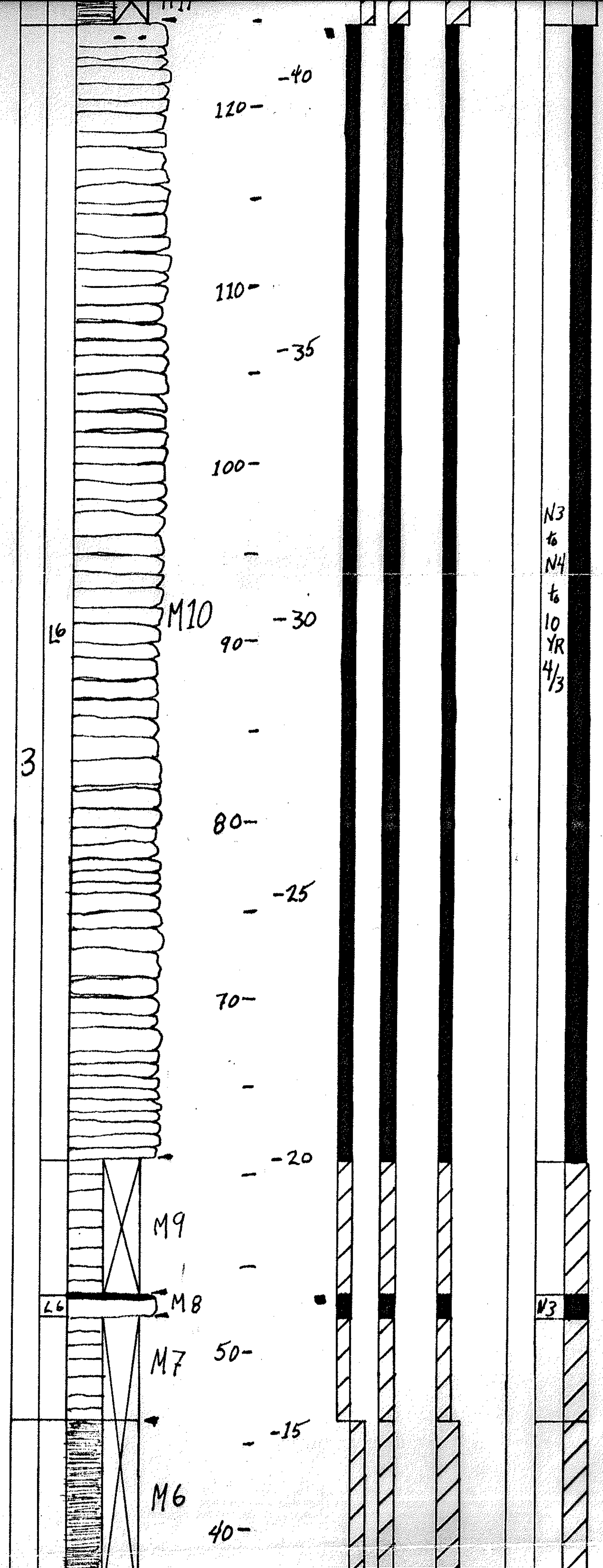
3
L6
N12
100
-?-
L3
N11
-30
90
L6
N10
L3
N9
L6
N8
80
L3
-25
N7
70
L2 + L6
N6
-20
60
2
L3
N5
50
-15
L6
N4
40
L3
N3
30
-10
20
L2
N2
-5
N5
10 YR 4/2 to 5 Y 6/1 to 10 YR 2/2 to N2
N4
N2 to 10YR 4/2
N2
N2 to 10 YR 2/2
N3 to N2
N2
N2
N2
N2



2
L3
N5
50
-15
L6
N4
40
L3
N3
30
-10
20
L2
N2
-5
10
1
L1
N1
0
-0
Victorio Peak
N0
N2
N2
N2
N2
N2
N5

Plate 13 597690 AWO H315 M365





-40
120
110
-35
100
N3 to N4 to 10 YR 4/3
M10
-30
L6
90
3
80
-25
70
-20
M9
L6
M8
N3
50
M7
-15
M6
40

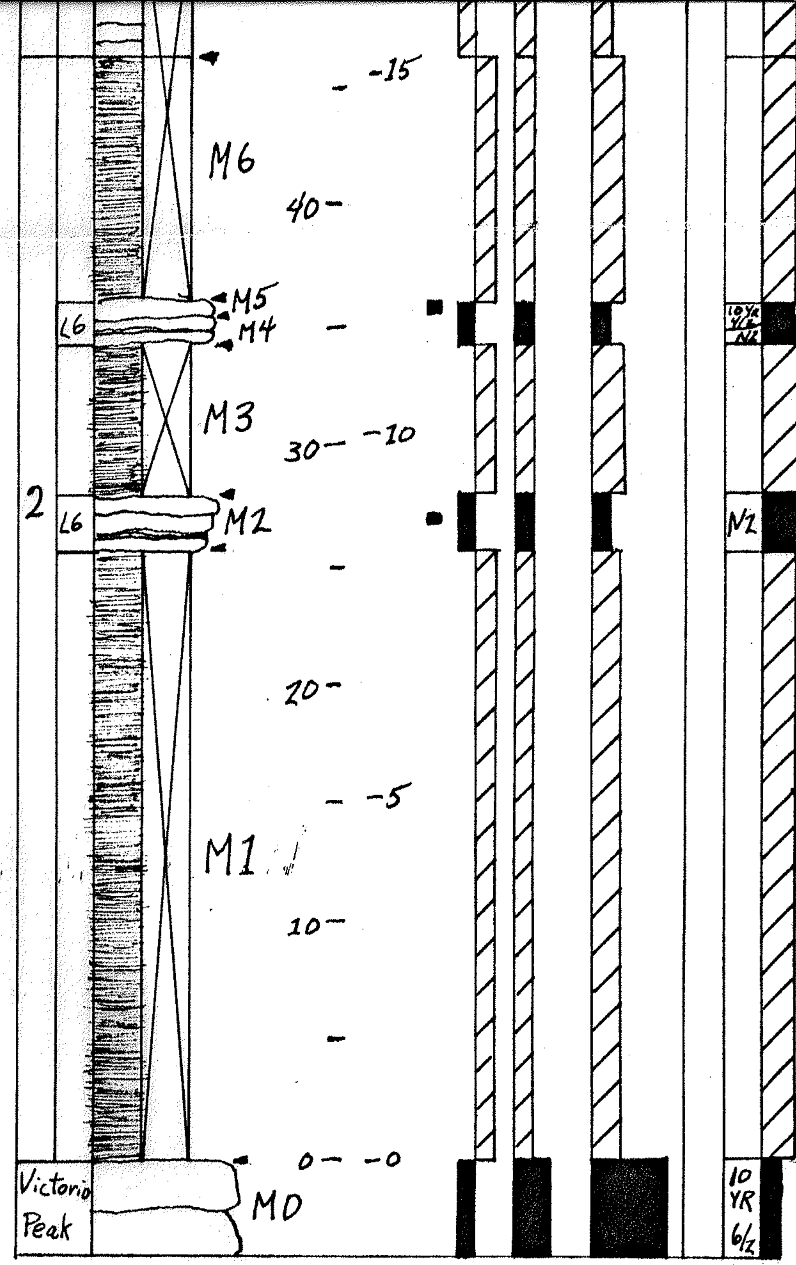
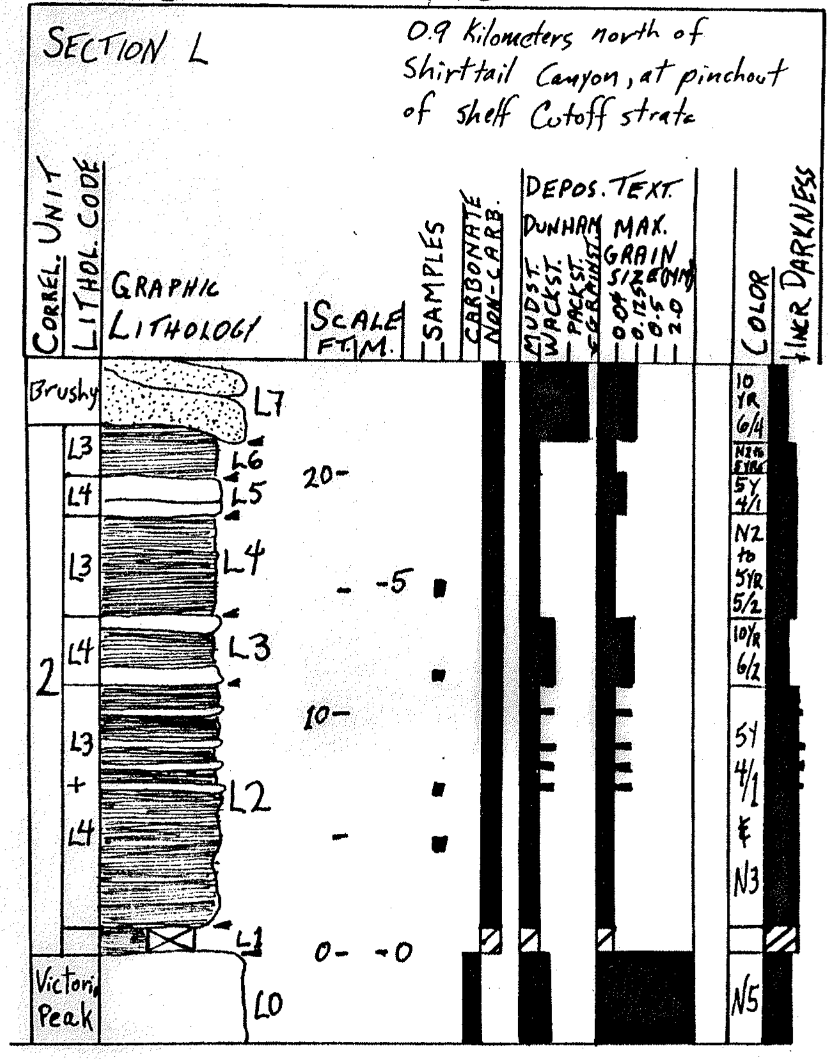

-15
M6
40
M5
M4
L6
M3
30
-10
2
L6
M2
20
-5
M1
10
0
-0
Victorio Peak
M0
N2
10 YR 6/2

Plate 12 597690

AWO 4315 M365



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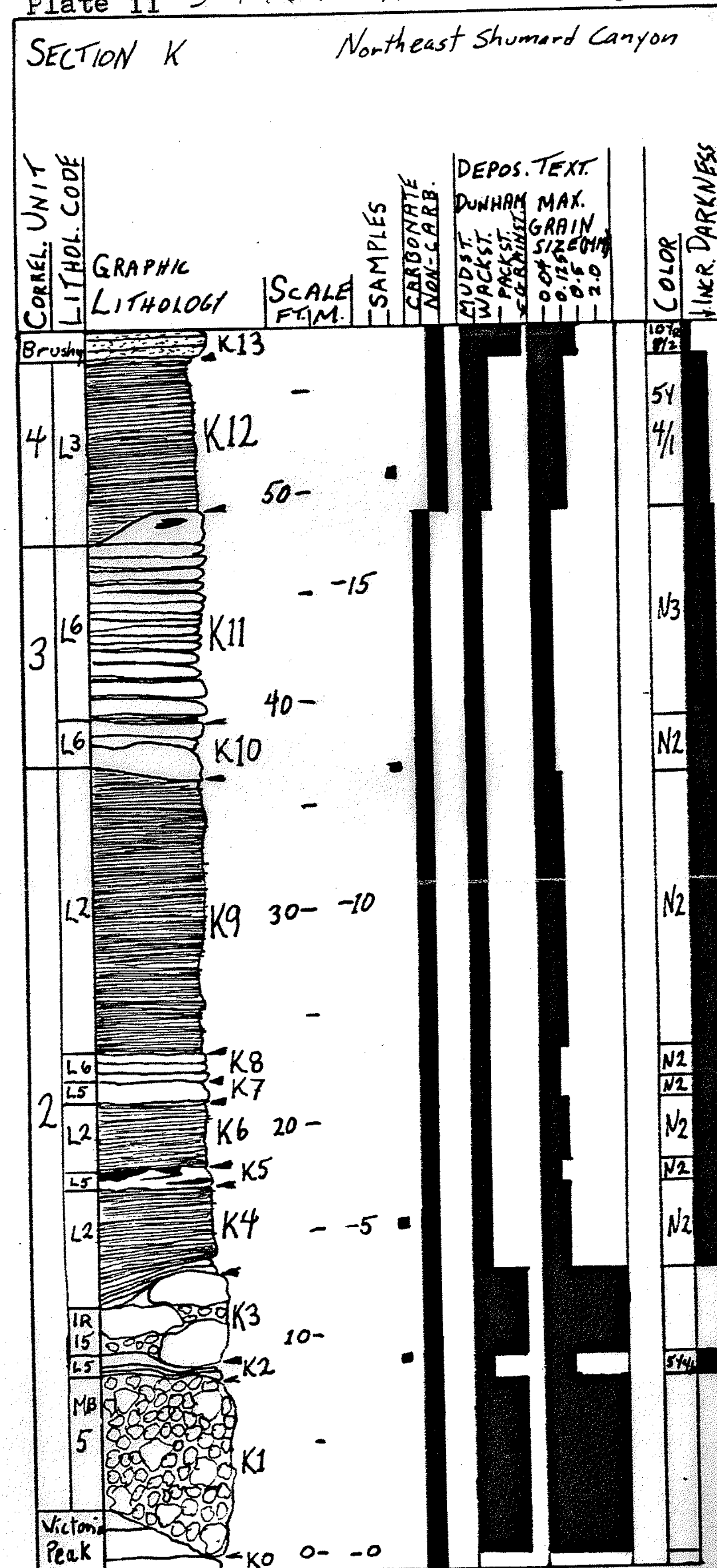

Plate 10 597690

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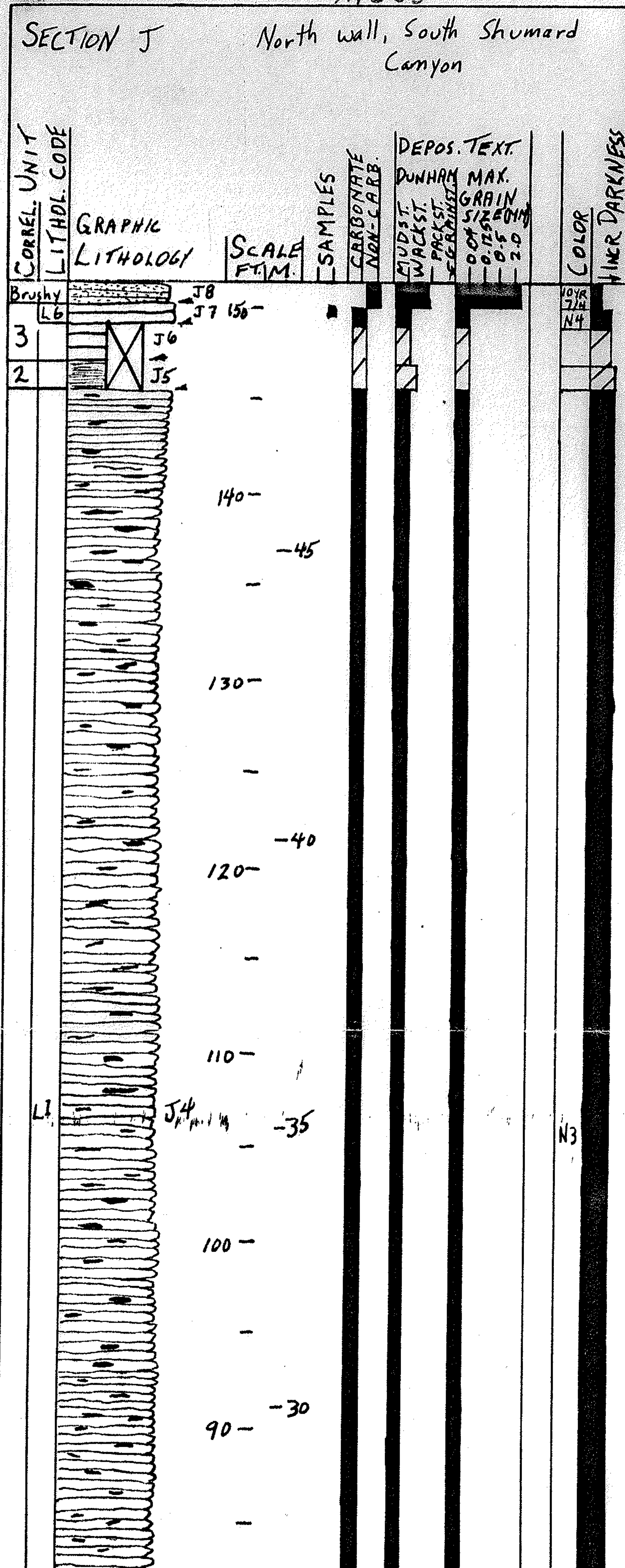


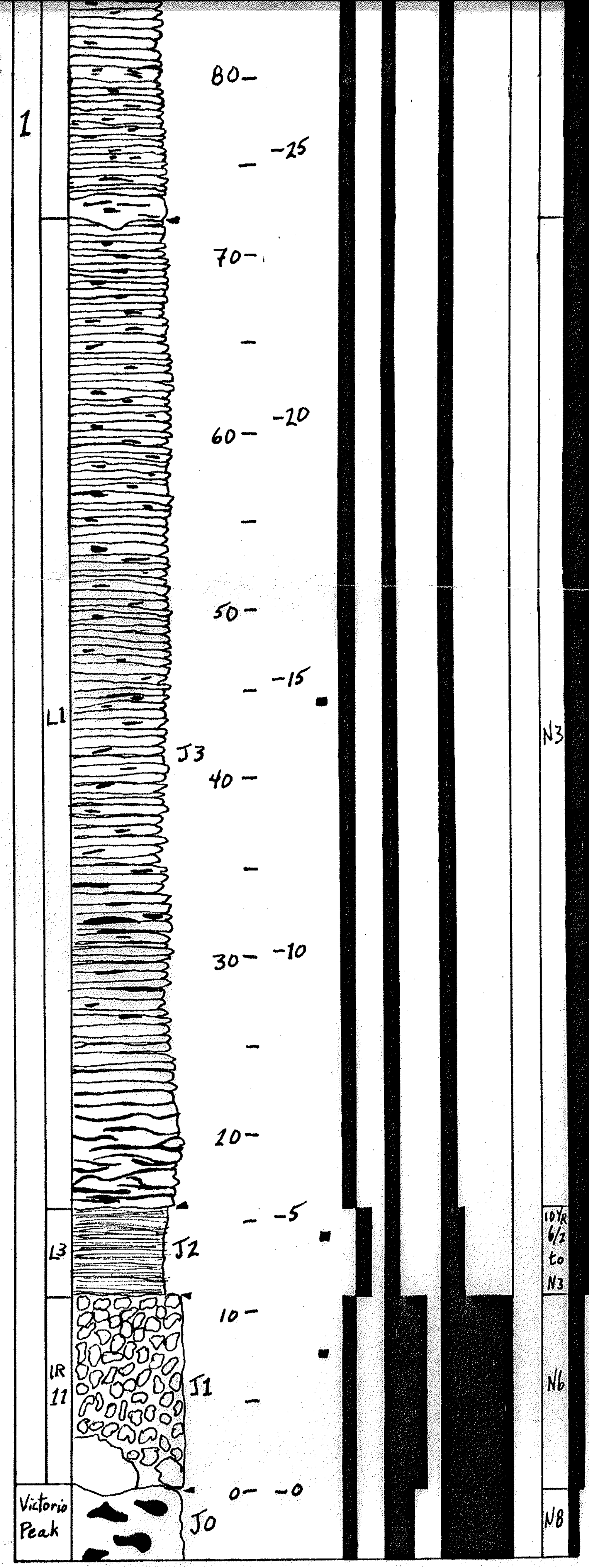

1
80
-25
70
-20
60
50
-15
L1
J3
N3
40
30
-10
20
-5
10YR 6/2 to N3
L3
J2
10
LR 11
J1
N6
0
-0
Victorio Peak
J0
N8

Plate 9 597690 AWO H315 M365

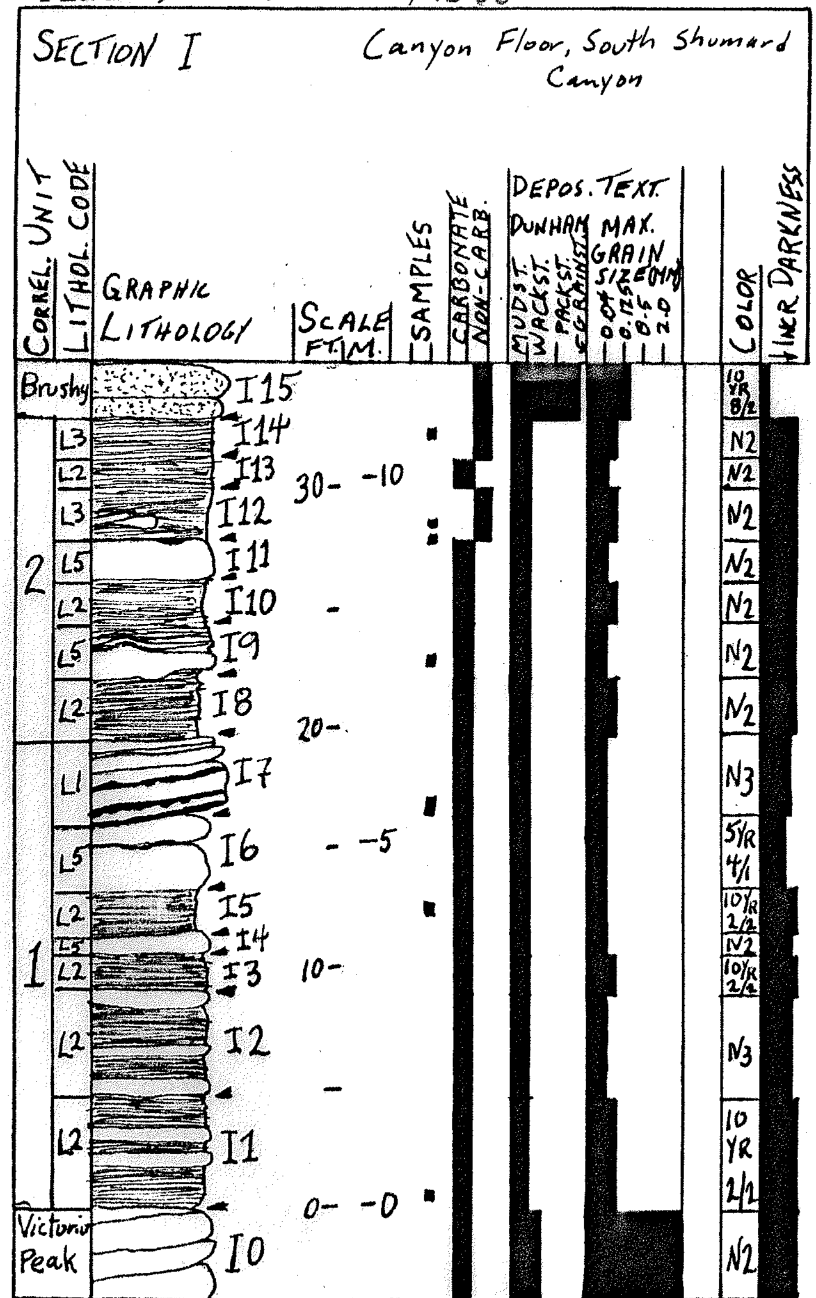


Plate 8 597690 AWO H315 M365

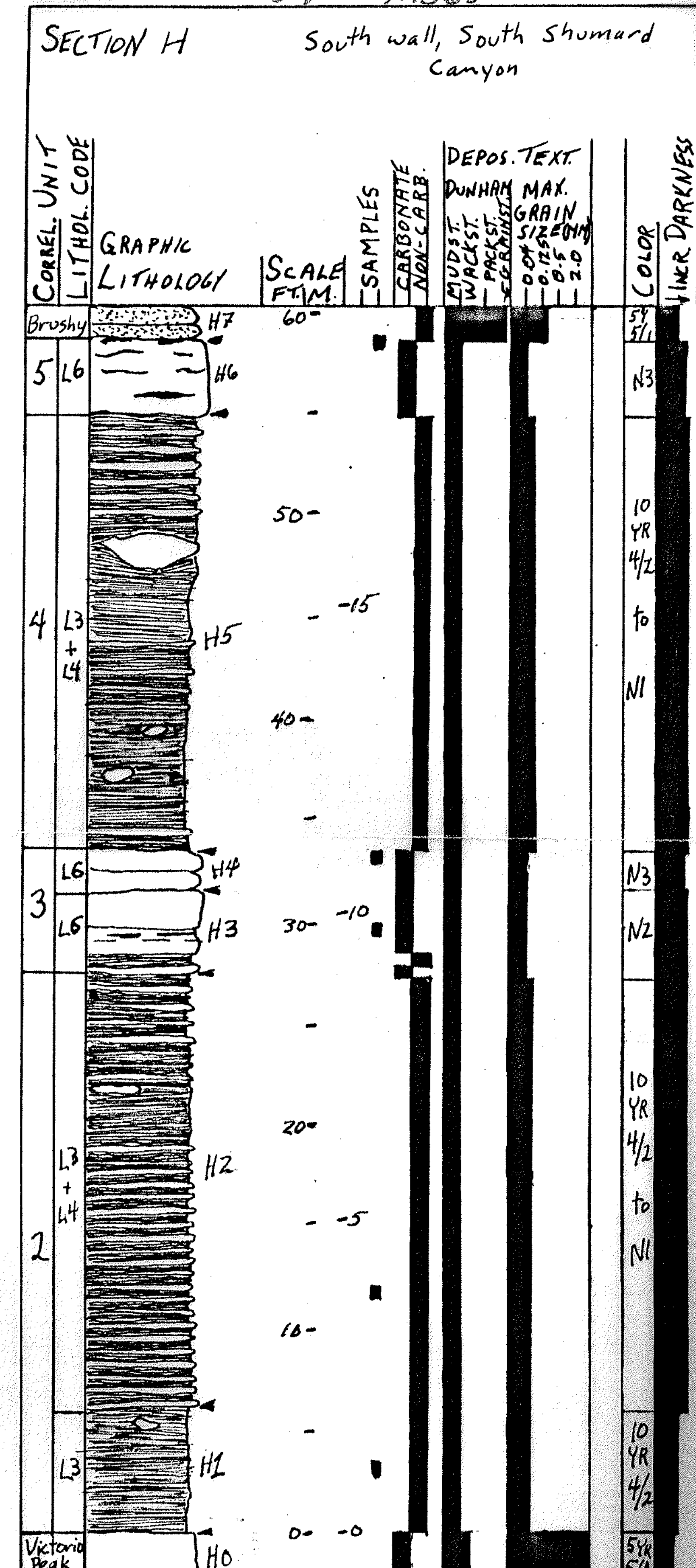


Plate 7 597690 AWO H315 M365

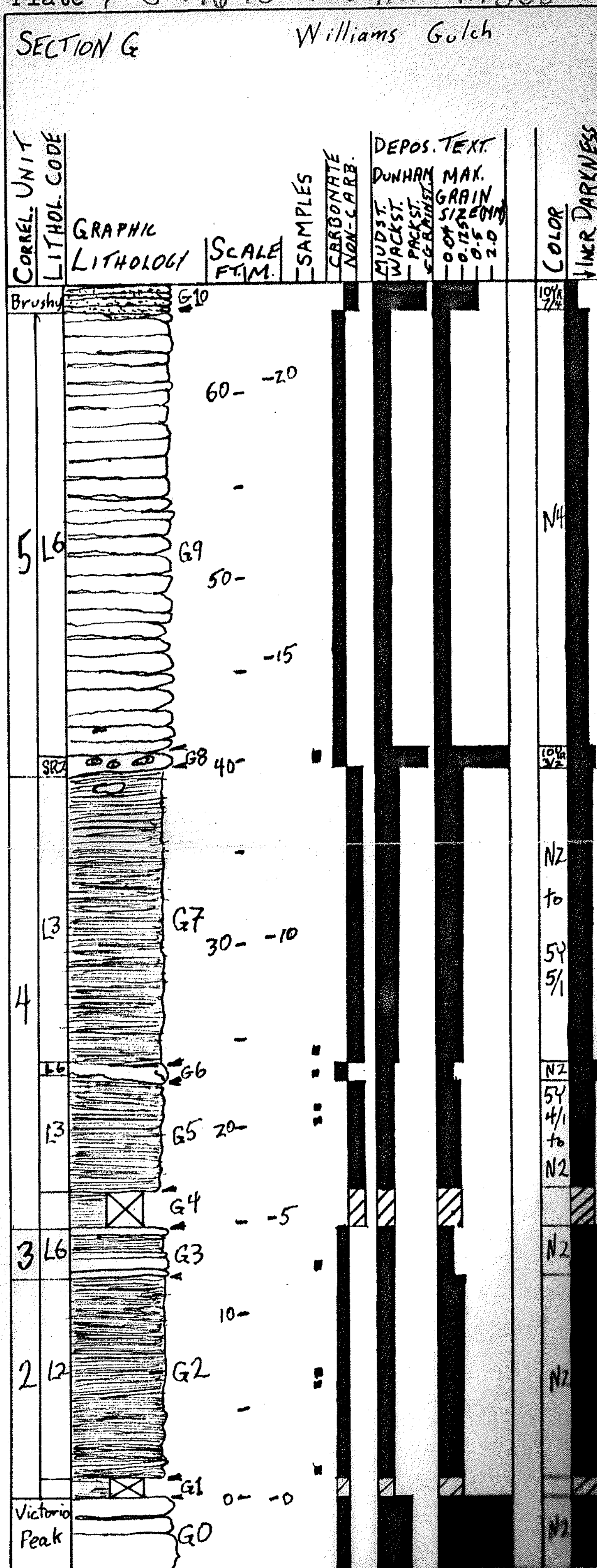
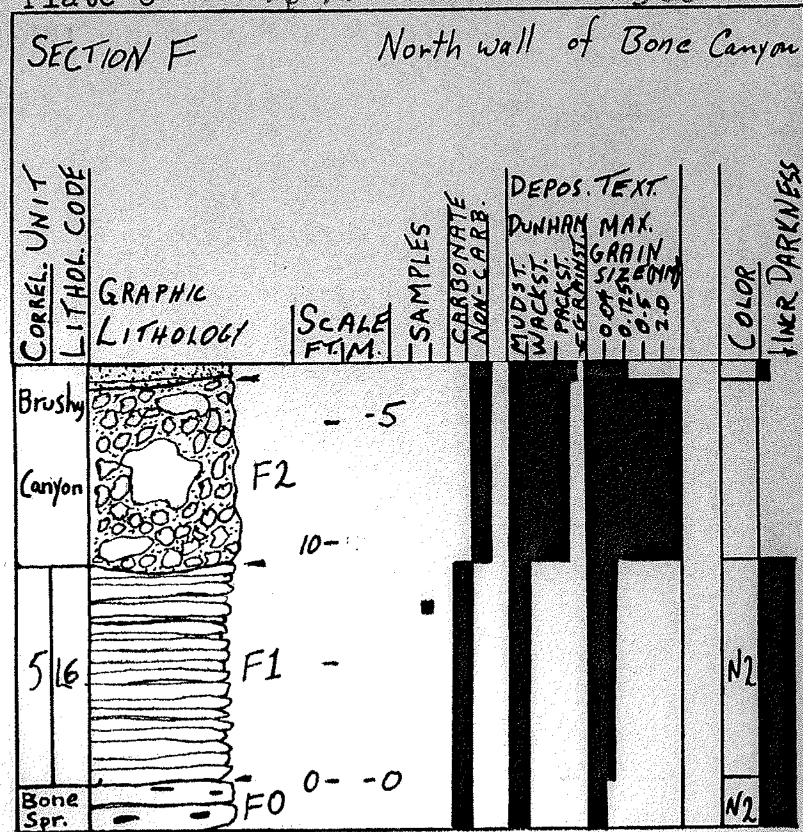


Plate 6 S97690 AWO H315 M 365



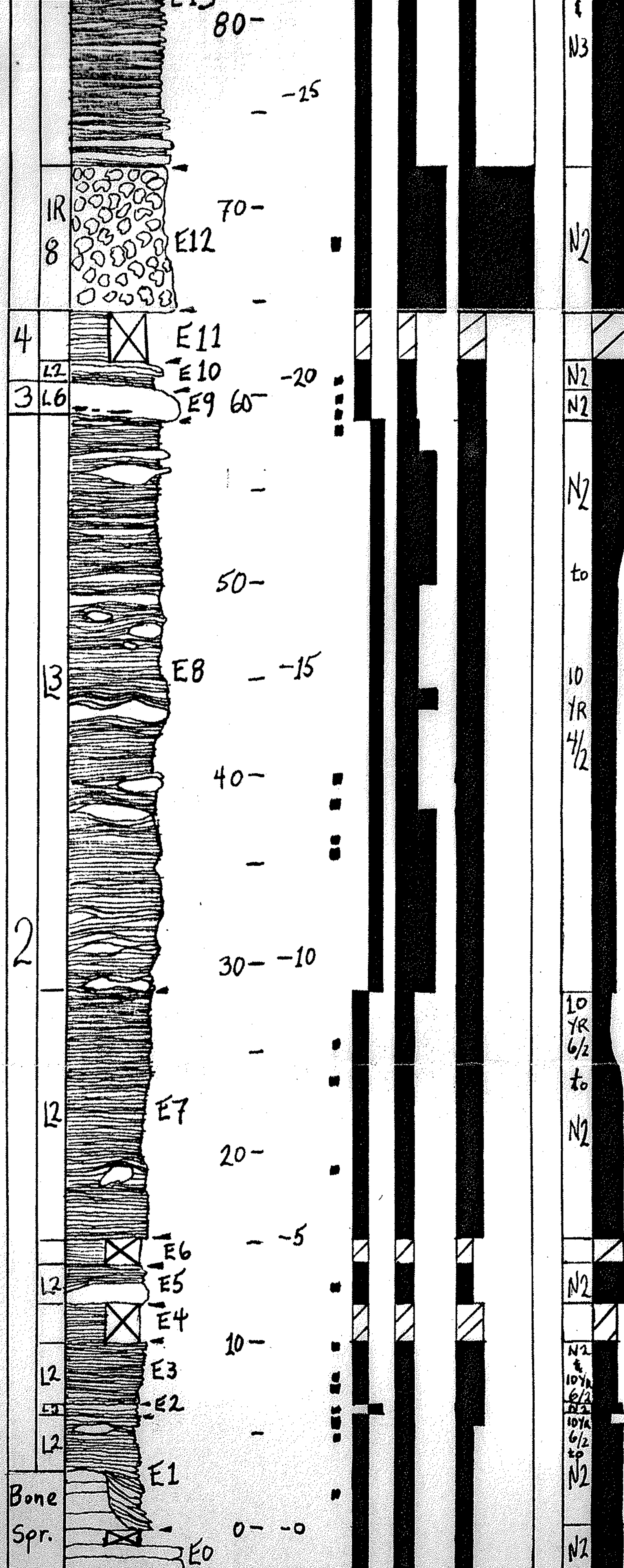

80-
N3
-25
70-
IR
8
E12
N2
4
E11
L2
E10
-20
3
L6
E9 60-
N2
N2
N2
50-
to
E8
-15
L3
10
YR
4/2
40-
2
30- -10
10
YR
6/2
to
N2
L2
E7
20-
E6
-5
E5
L2
N2
E4
10-
N2
&
10YR
6/2
L2
E3
E2
10YR
6/2
to
N2
L2
E1
Bone
Spr.
0- -0
E0
N2

Plate 5

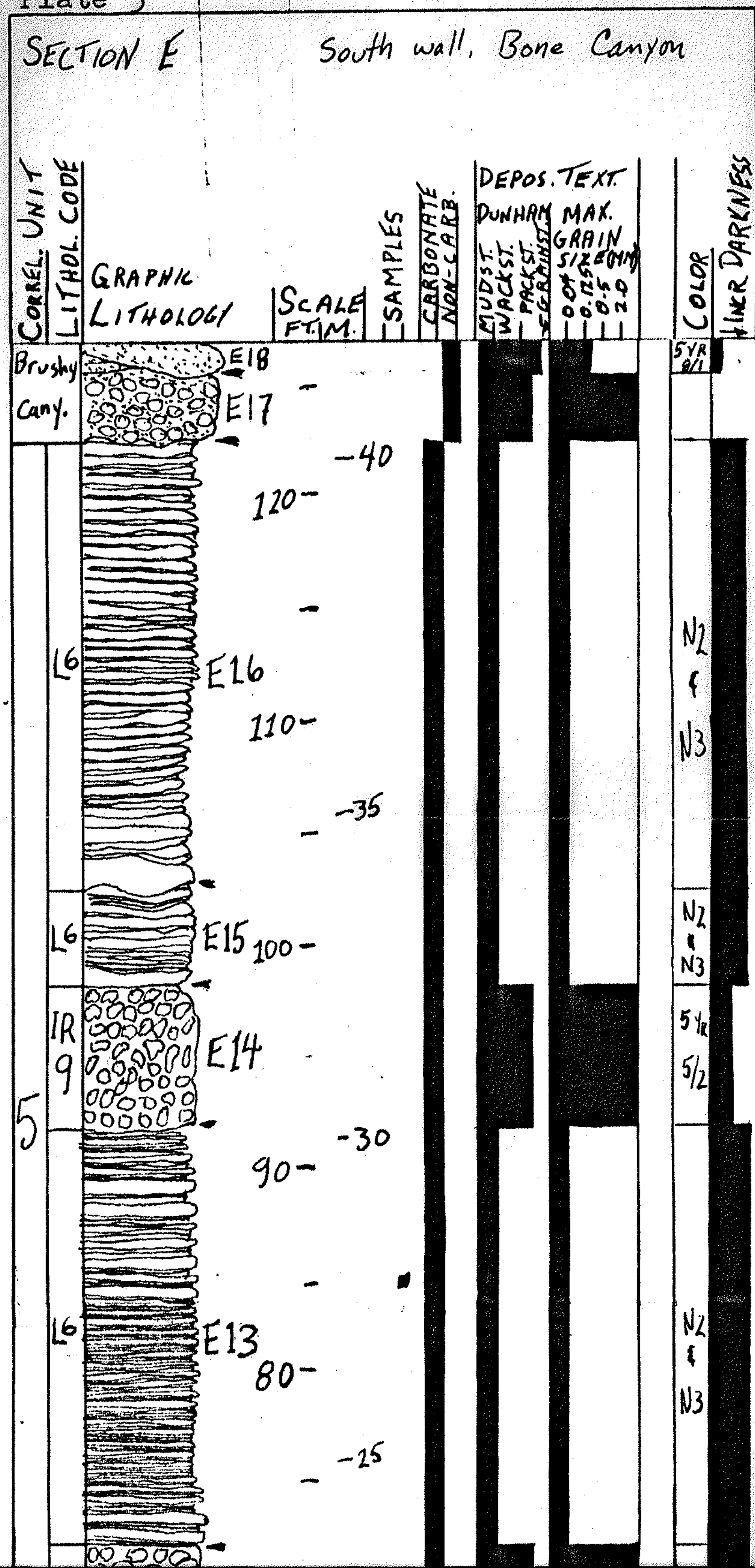
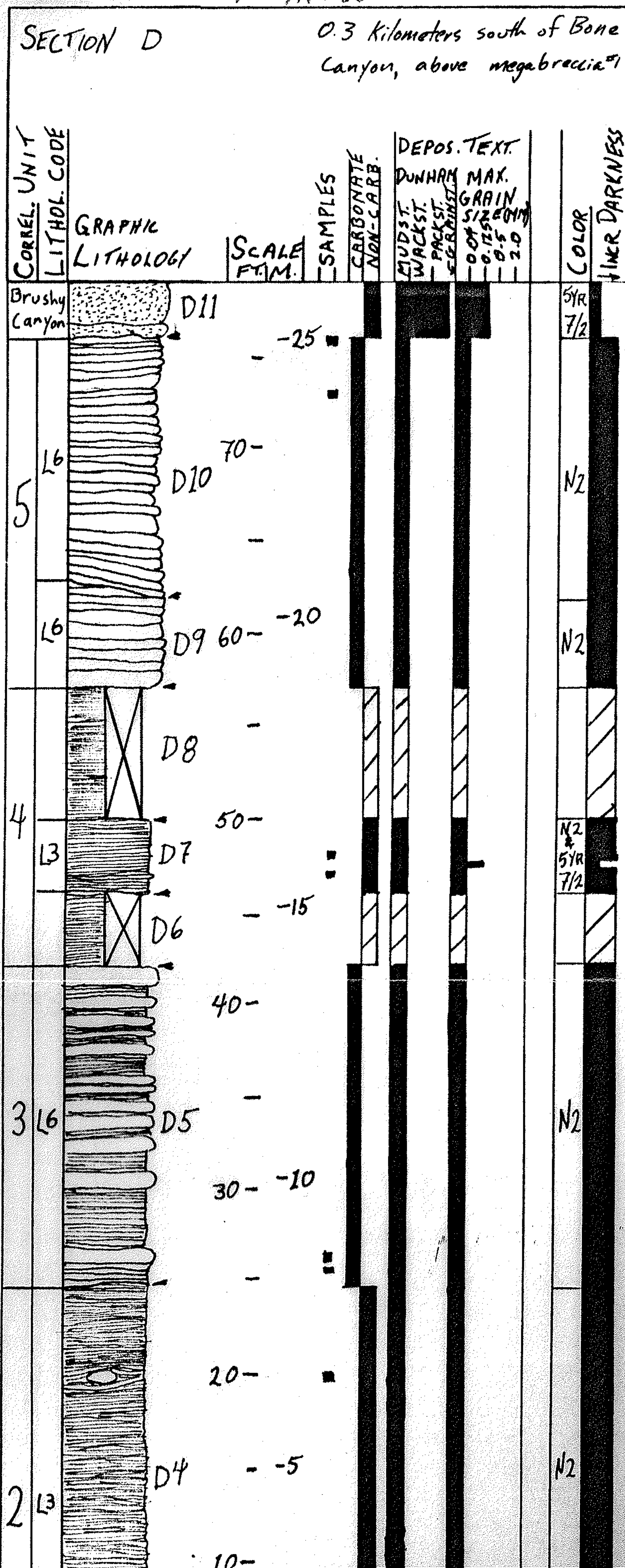
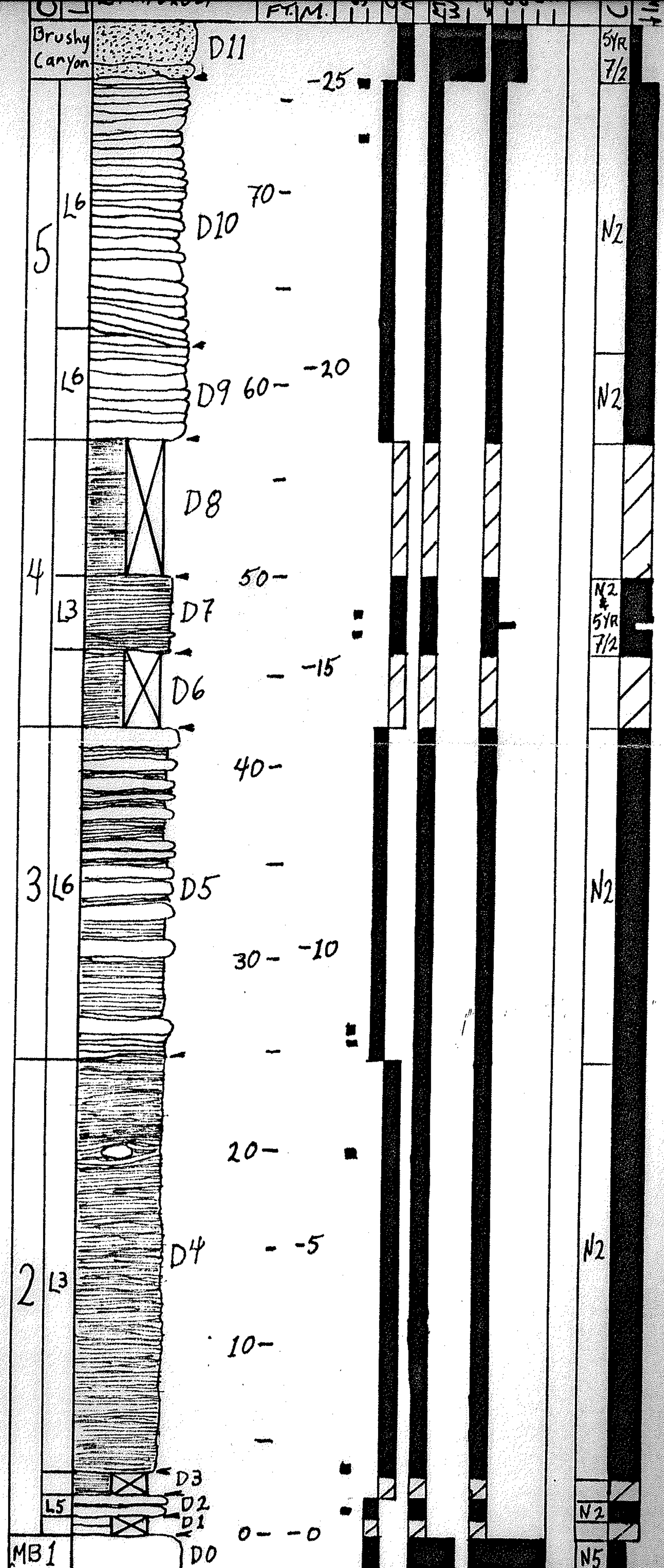

SECTION E
South wall, Bone Canyon
CORREL. UNIT
LITHOL. CODE
GRAPHIC LITHOLOGY
SCALE FT. M.
SAMPLES
CARBONATE NON-CARB.
DEPOS. TEXT.
DUNHAM
MUDST. WACKST. PACKST. GRAINST.
MAX. GRAIN SIZE (MM)
0.04 0.125 0.5 2.0
COLOR
LIMER DARKNESS
Brushy Cany.
E18
E17
-40
120
L6
E16
110
N2 & N3
-35
L6
E15
100
N2 & N3
IR 9
E14
5 YR 5/2
5
-30
90
L6
E13
80
N2 & N3
-25
5YR 8/1

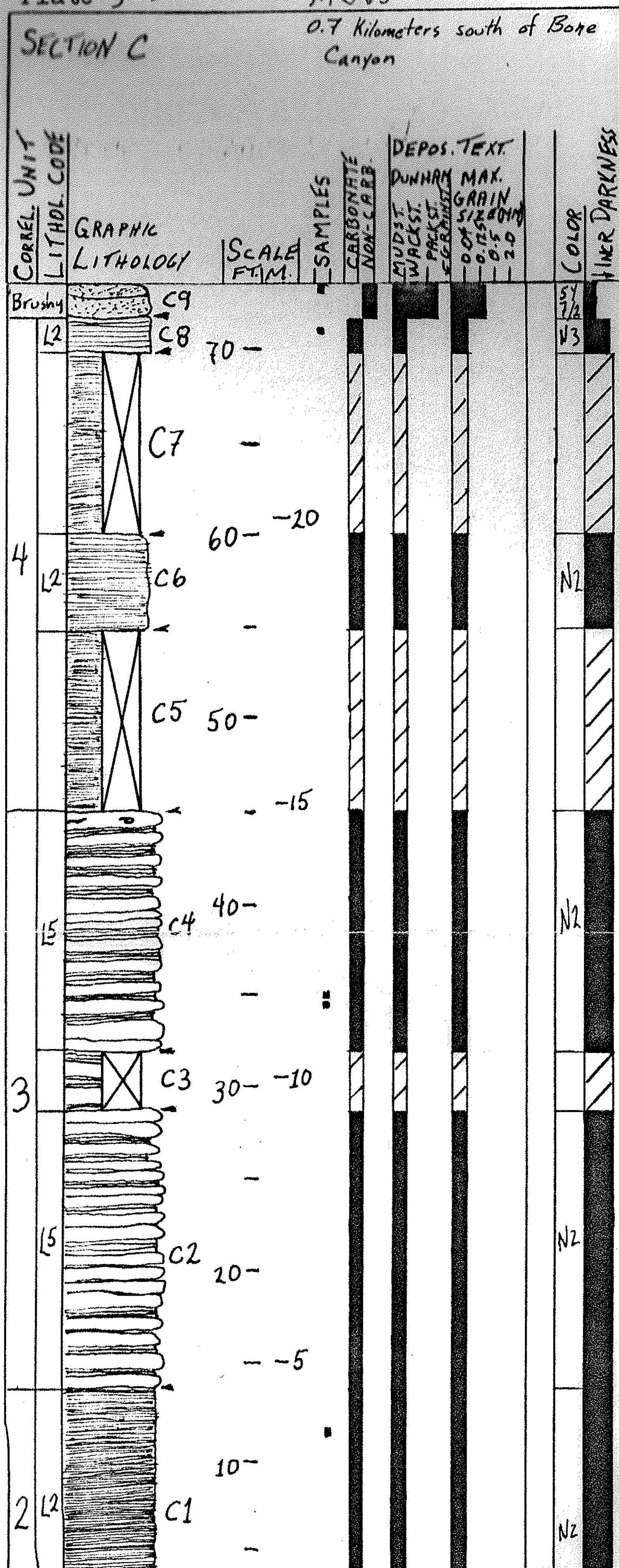
Plate 4 597690 AWO H315 M365

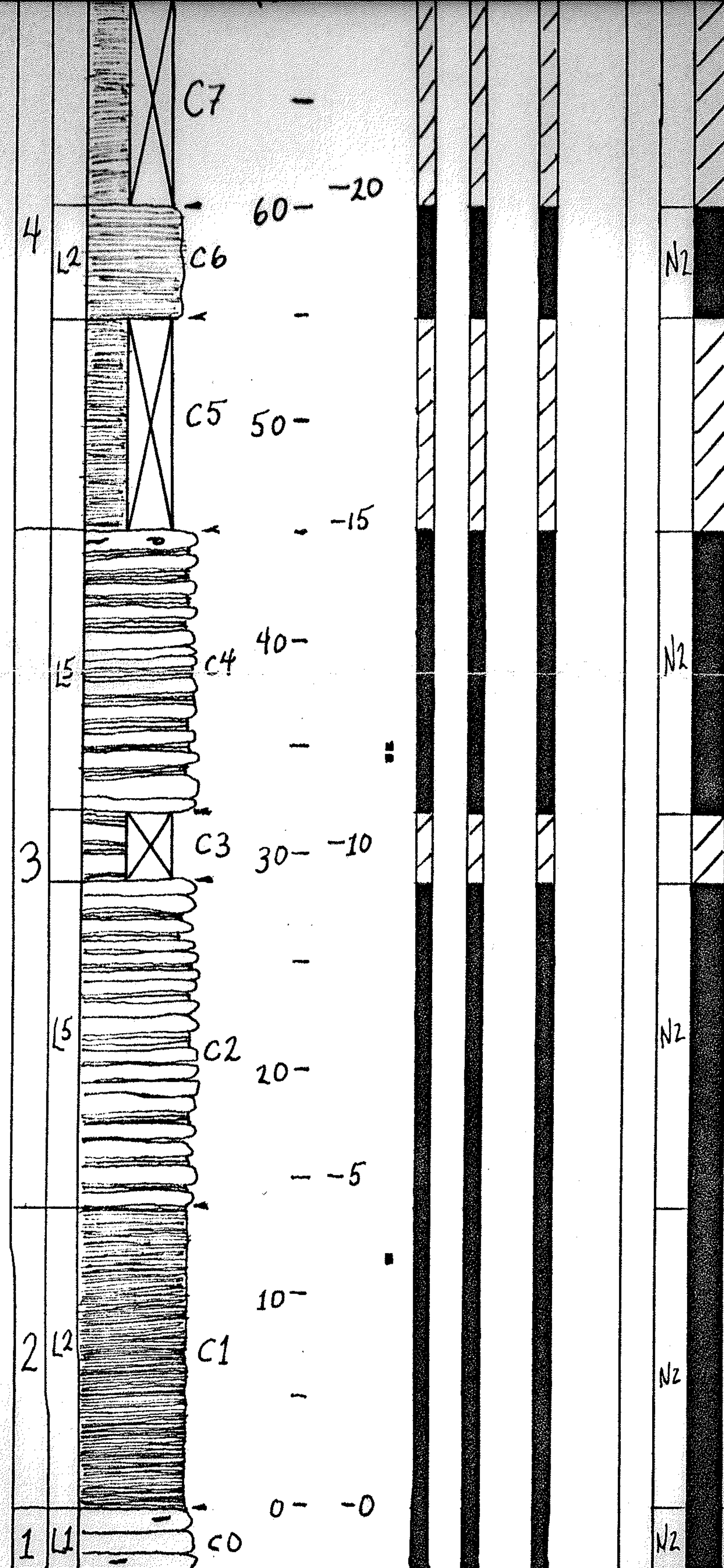




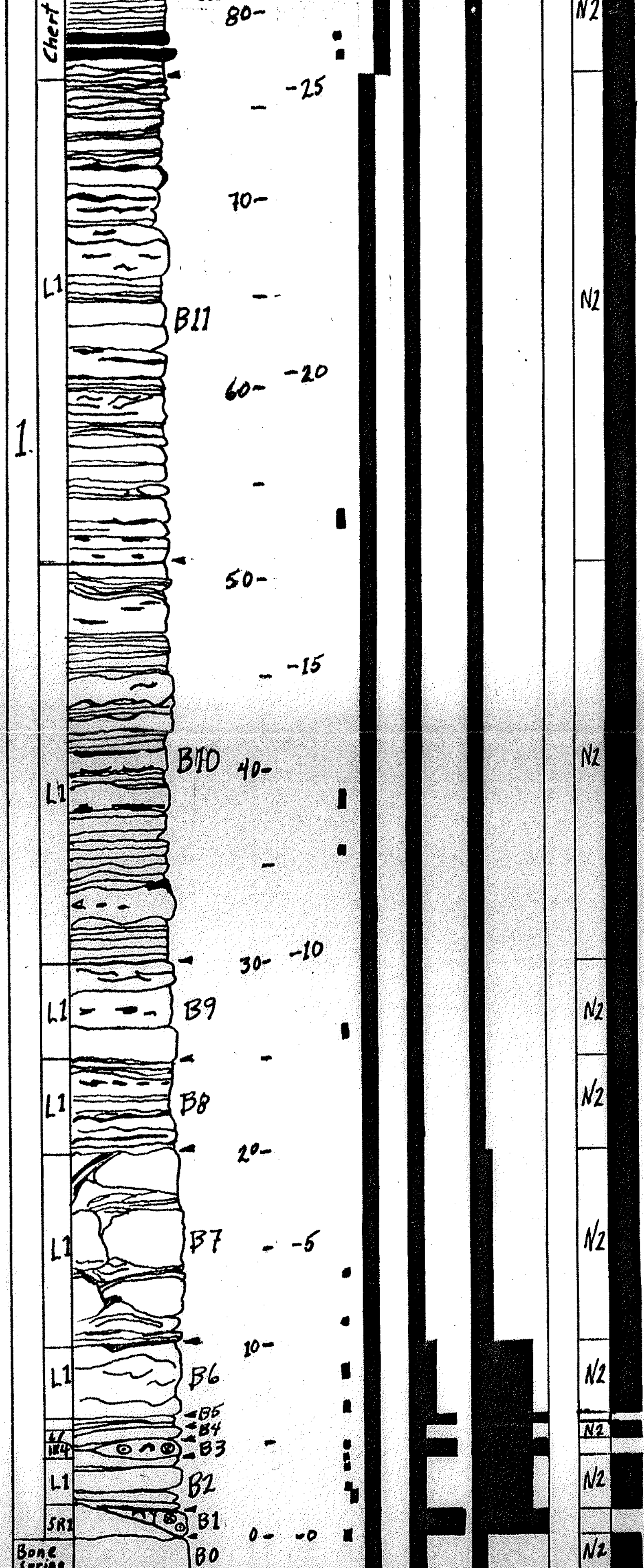
FT.
M.
Brushy Canyon
D11
5YR 7/2
-25
70
L6
5
D10
N2
-20
L6
D9
60
N2
D8
4
50
L3
D7
N2 & 5YR 7/2
-15
D6
40
3
L6
D5
N2
30
-10
20
-5
D4
2
L3
N2
10
D3
L5
D2
D1
N2
0
-0
MB1
D0
N5

Plate 3 597690 AWO H315 M365





C7
60– –20
4
L2
C6
N2
C5
50–
–15
40–
L5
C4
N2
C3
3
30– –10
L5
C2
N2
20–
– –5
10–
2
L2
C1
N2
0– –0
1
L1
C0
N2


1.
Chert
L1
L1
L1
L1
L1
L1
L/ IB4
L1
SR1
Bone Spring
B11
B10
B9
B8
B7
B6
B5
B4
B3
B2
B1
B0
80-
70-
60-
50-
40-
30-
20-
10-
0-
-25
-20
-15
-10
-5
-0
N2

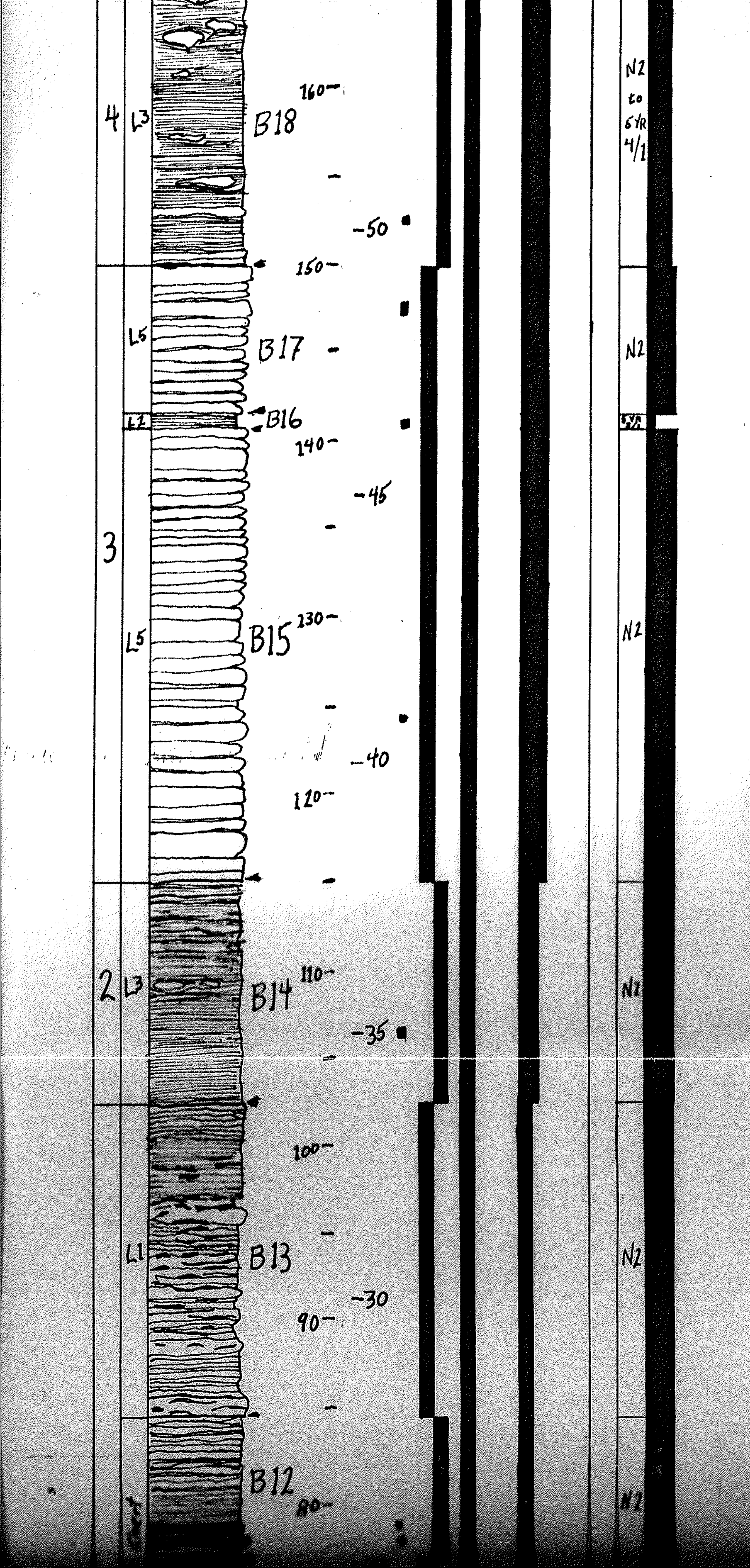
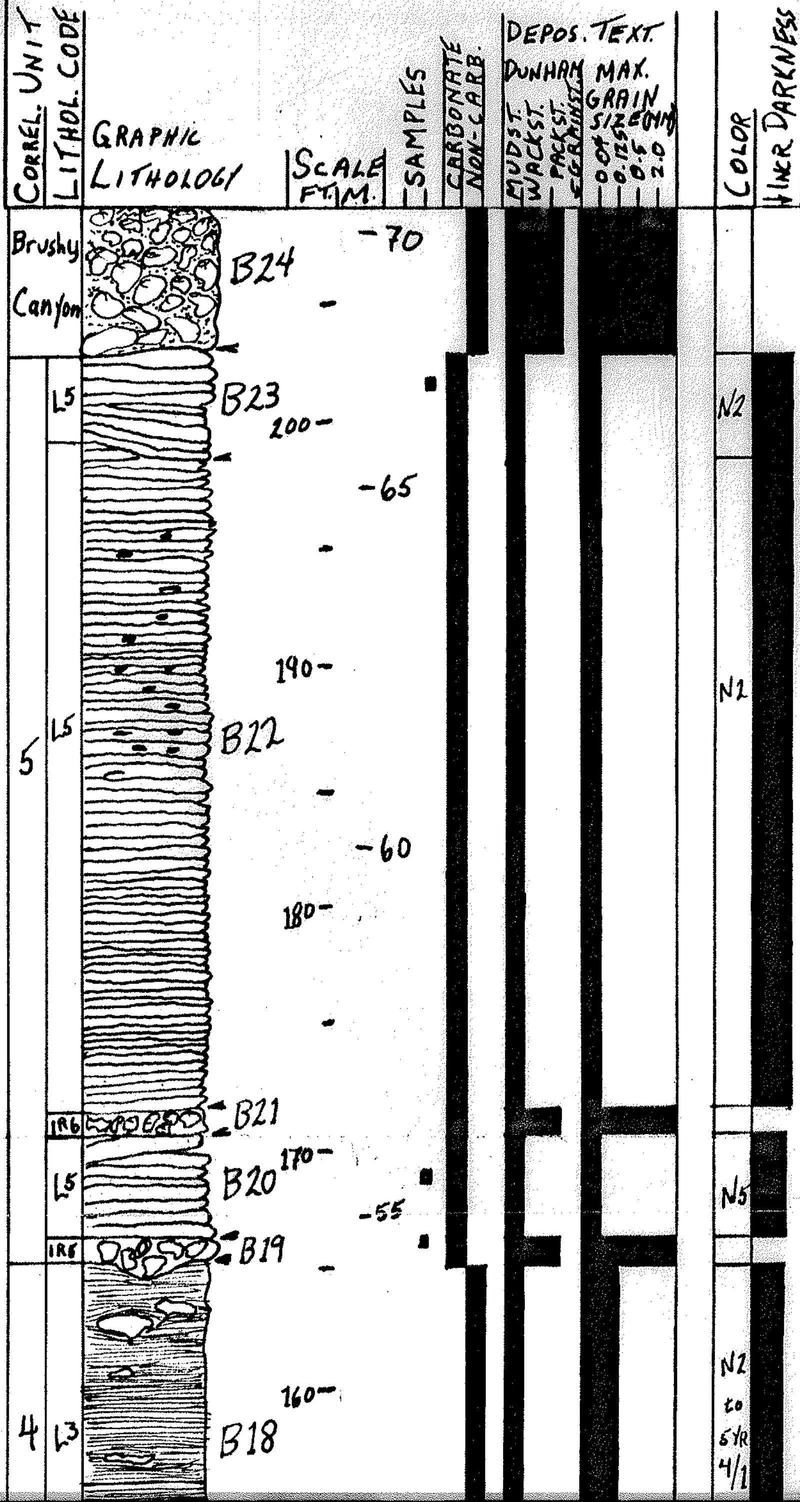

4
L3
B18
160
N2 to 5YR 4/1
-50
150
L5
B17
N2
B16
L2
5YR
140
-45
3
L5
B15
230
N2
-40
120
2
L3
B14
110
N2
-35
100
L1
B13
N2
-30
90
B12
80
Cont
N2

Plate 2

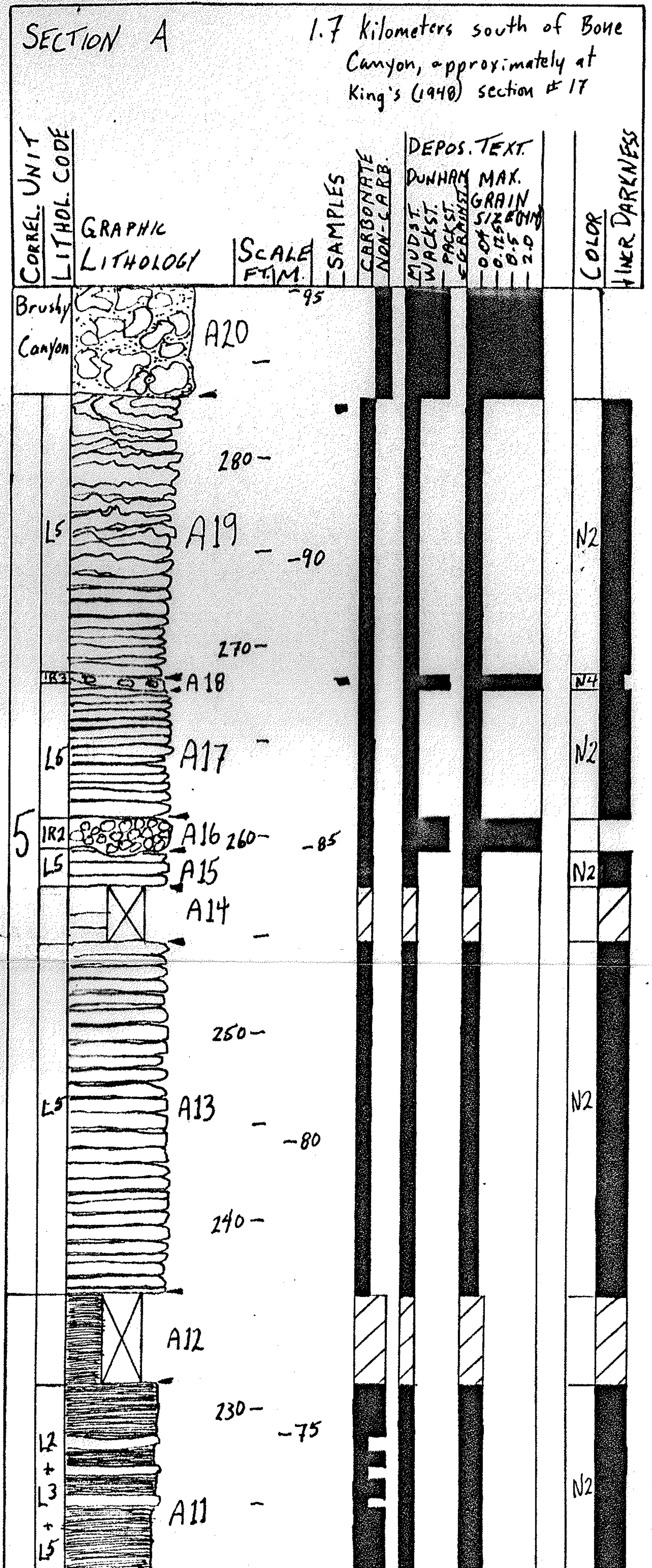
SECTION B

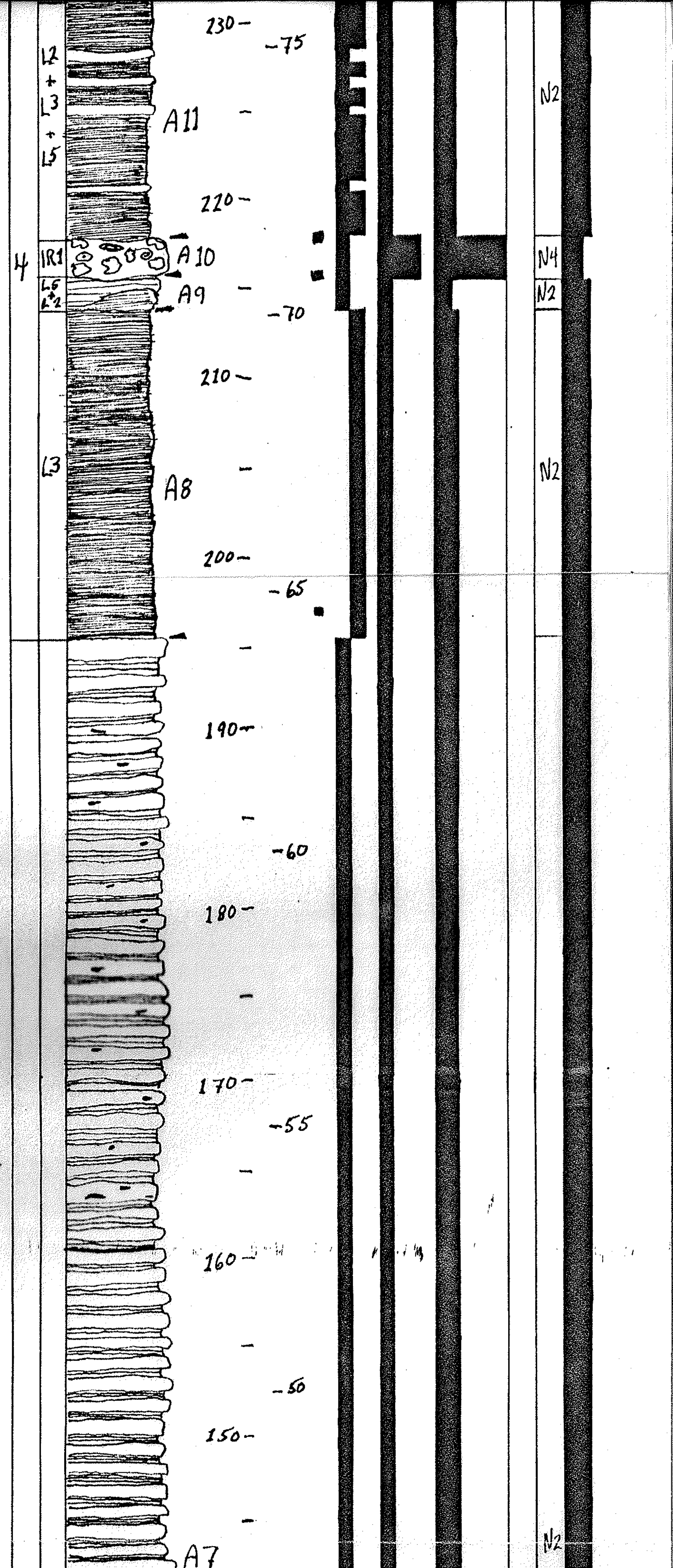
Canyon 0.85 Kilometers south of Bone Canyon



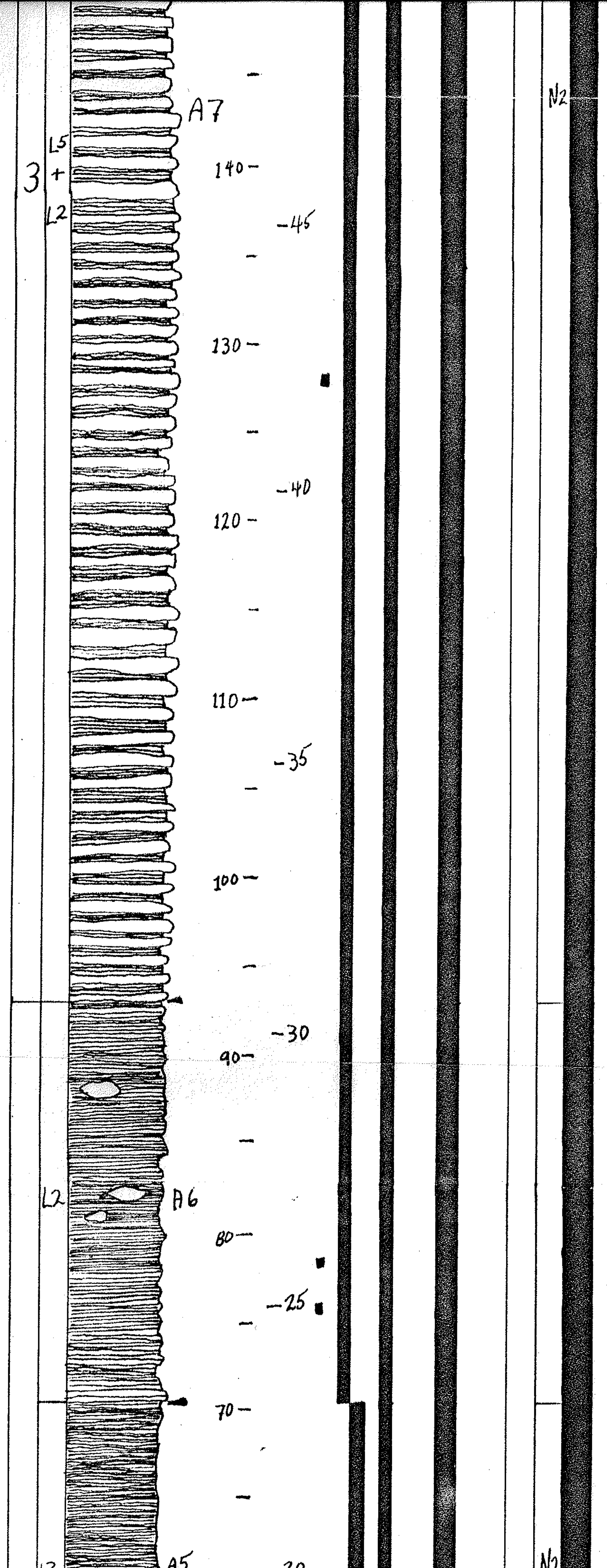
597690 AWO H315 M365

Plate 1

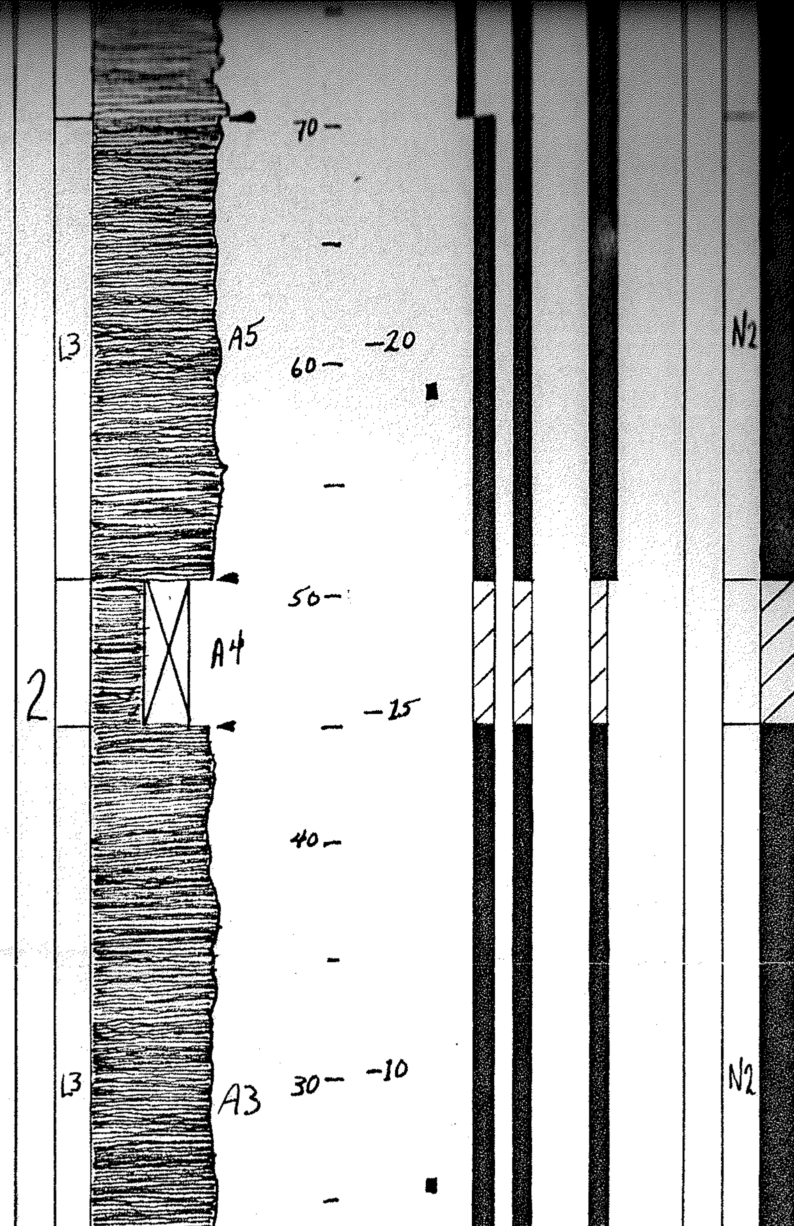




230
220
210
200
190
180
170
160
150
75
70
65
60
55
50
L2 + L3 + L5
IR1
L6 + L2
L3
4
A11
A10
A9
A8
A7
N2
N4
N2
N2
N2



N2
A7
L5
3
+
140
L2
45
130
40
120
110
35
100
30
90
L2
A6
80
25
70
A5
N2

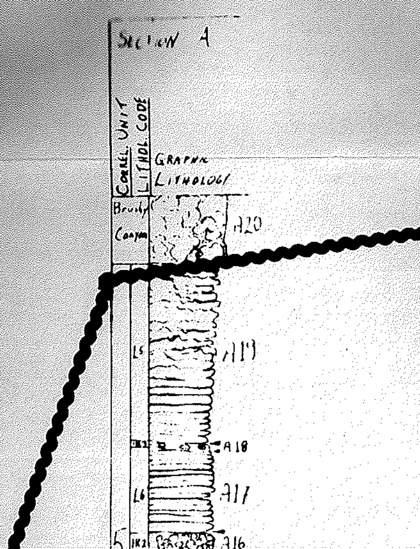


2
1
L3
L3
L2 + L3
L1
A5
A4
A3
A2
A1
A0
70
60
50
40
30
20
10
0
-20
-15
-10
-5
-0
N2
N2
N2
N3

F FORMATION

SOUTH

SIN



CTIONS, CUTOFF

ATION UNITS 1-5.

RGIN BAS

ATIGRAPHIC SEC

ONTINUITY OF CORRELAT

SHELF MAR

LATION OF STRAT

SHOWING LATERAL CON

LATE 15: CORREL

S

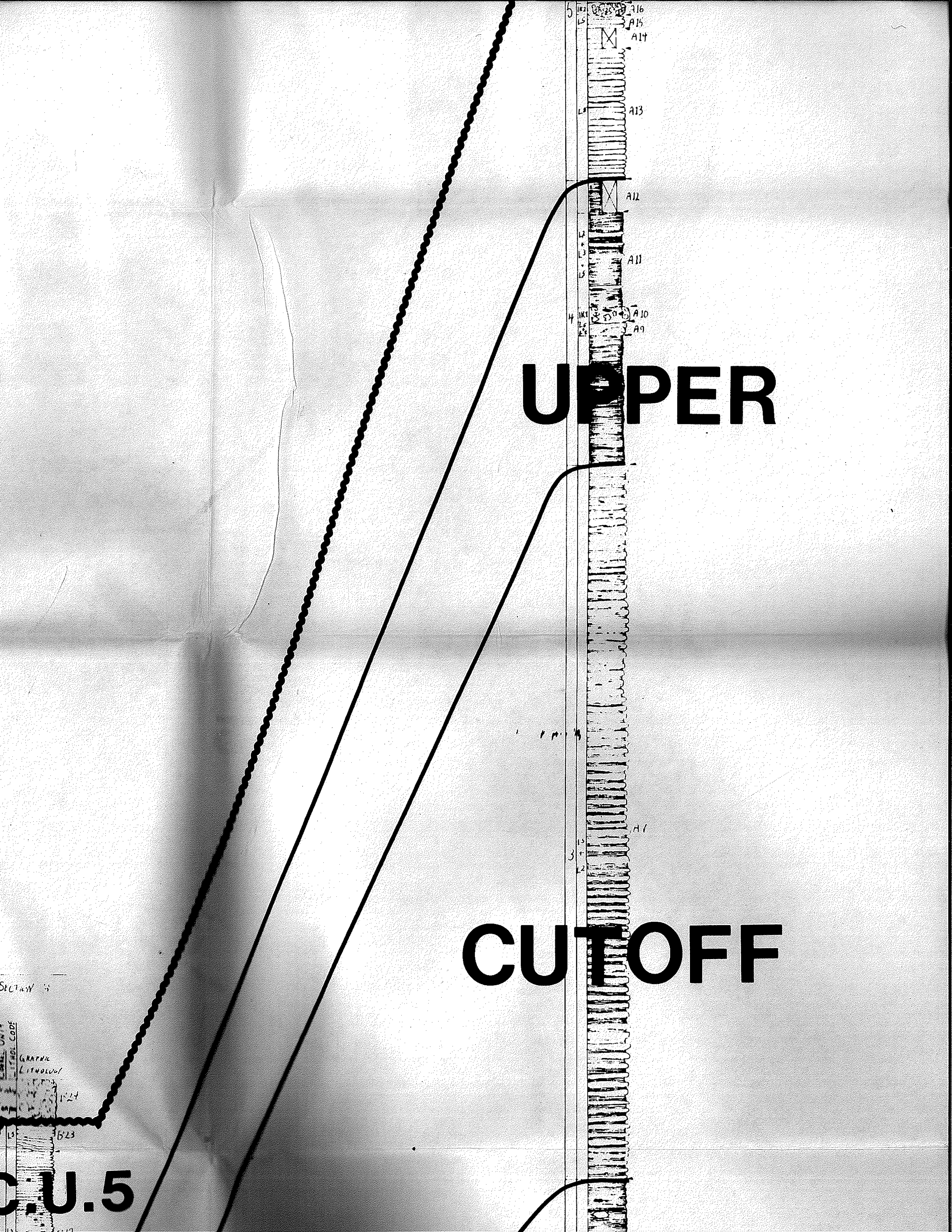
NORTH

SHELF

PLATE 15: CO

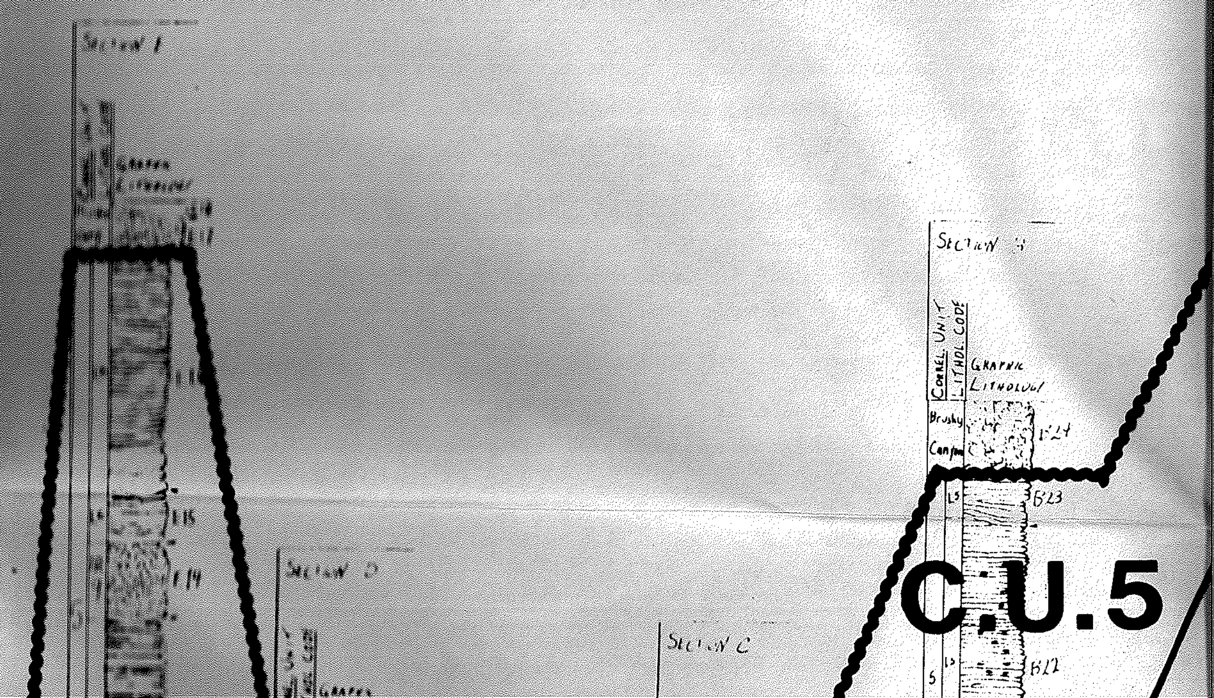
NORTH

SHELF



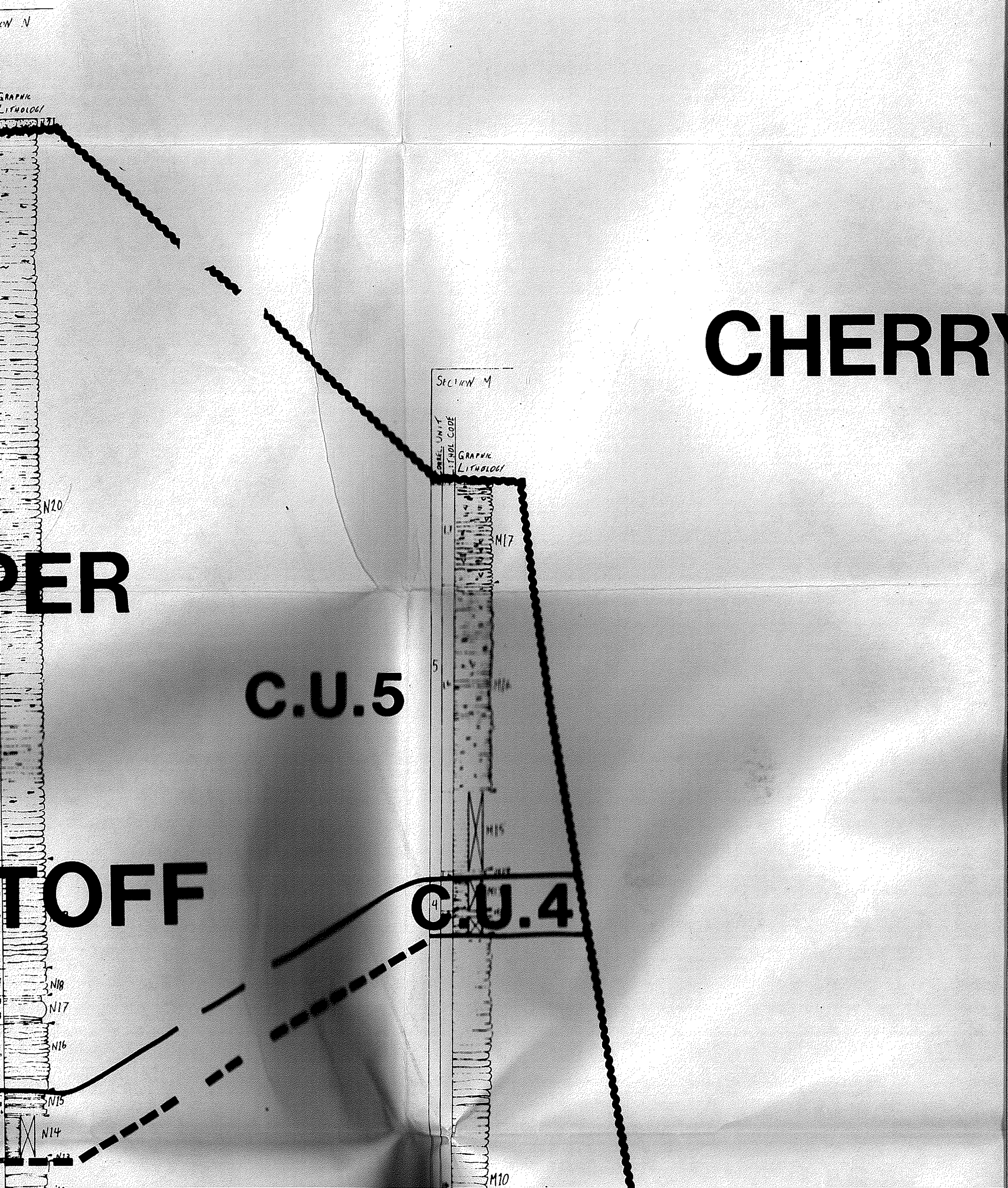
UPPER
CUTOFF
C.U.5
A16
A15
A14
A13
A12
A11
A10
A9
5
4
3
GRAPHIC
LITHOLOGY
B24
B23

FORMATION

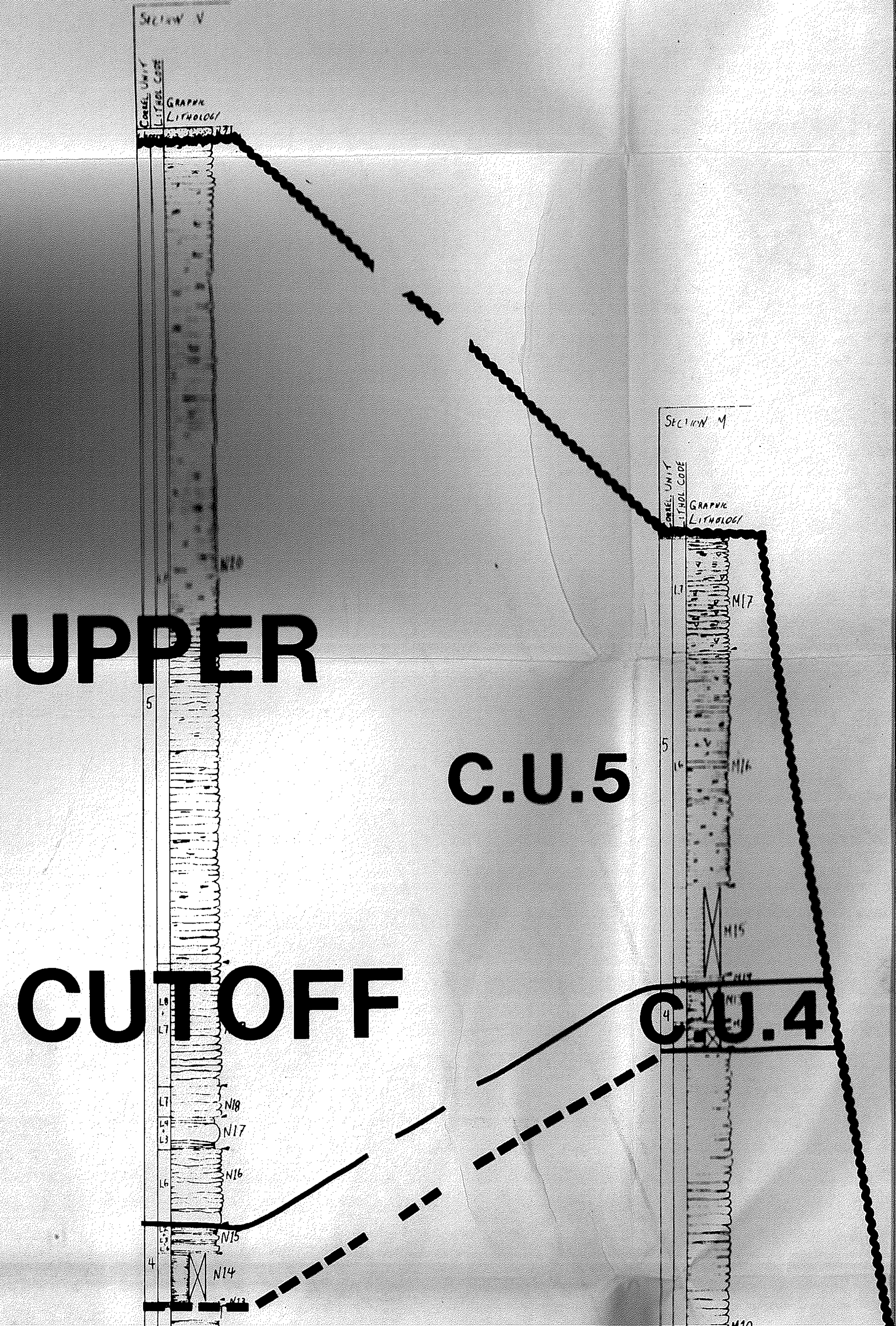


BRUSHY CANYON F

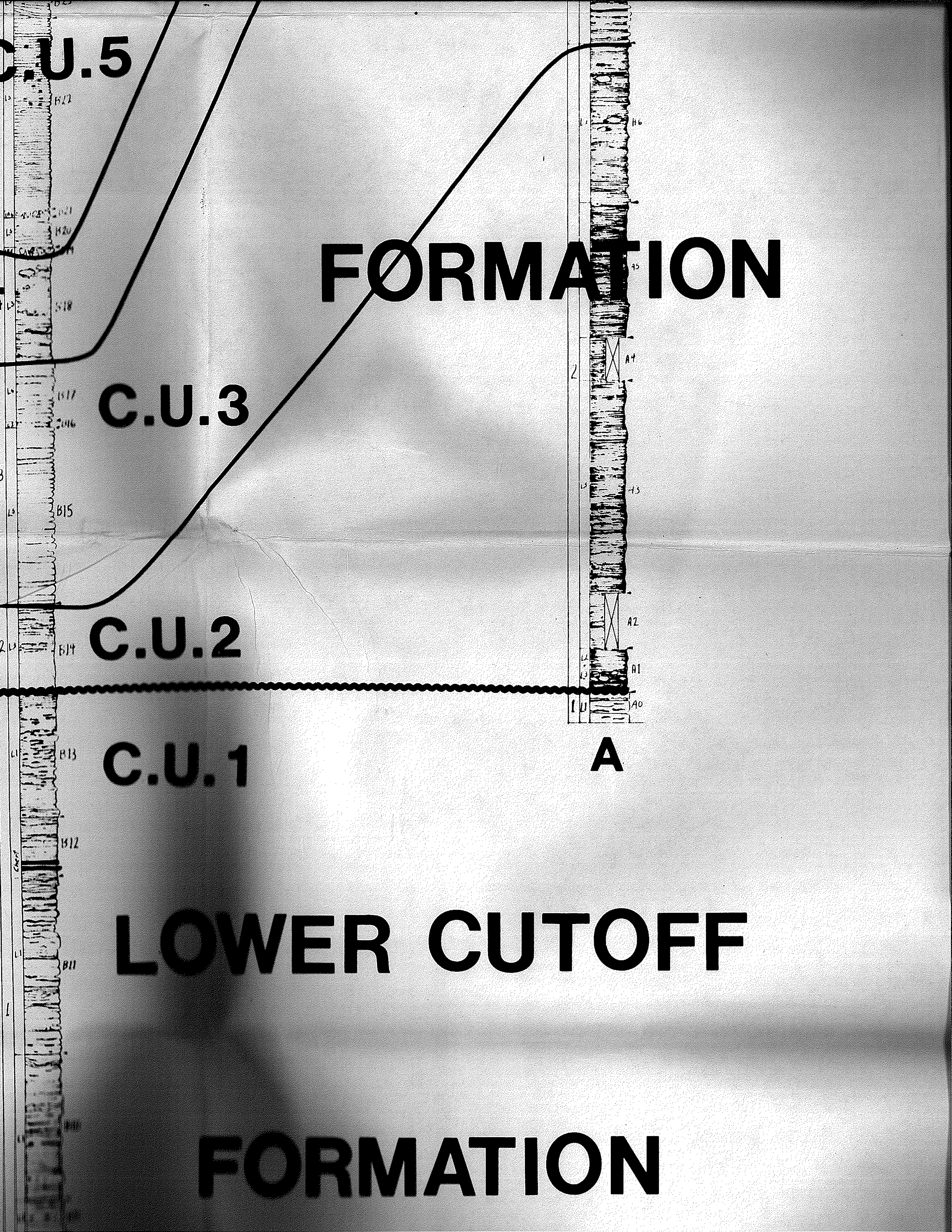
RY CANYON FORMATION

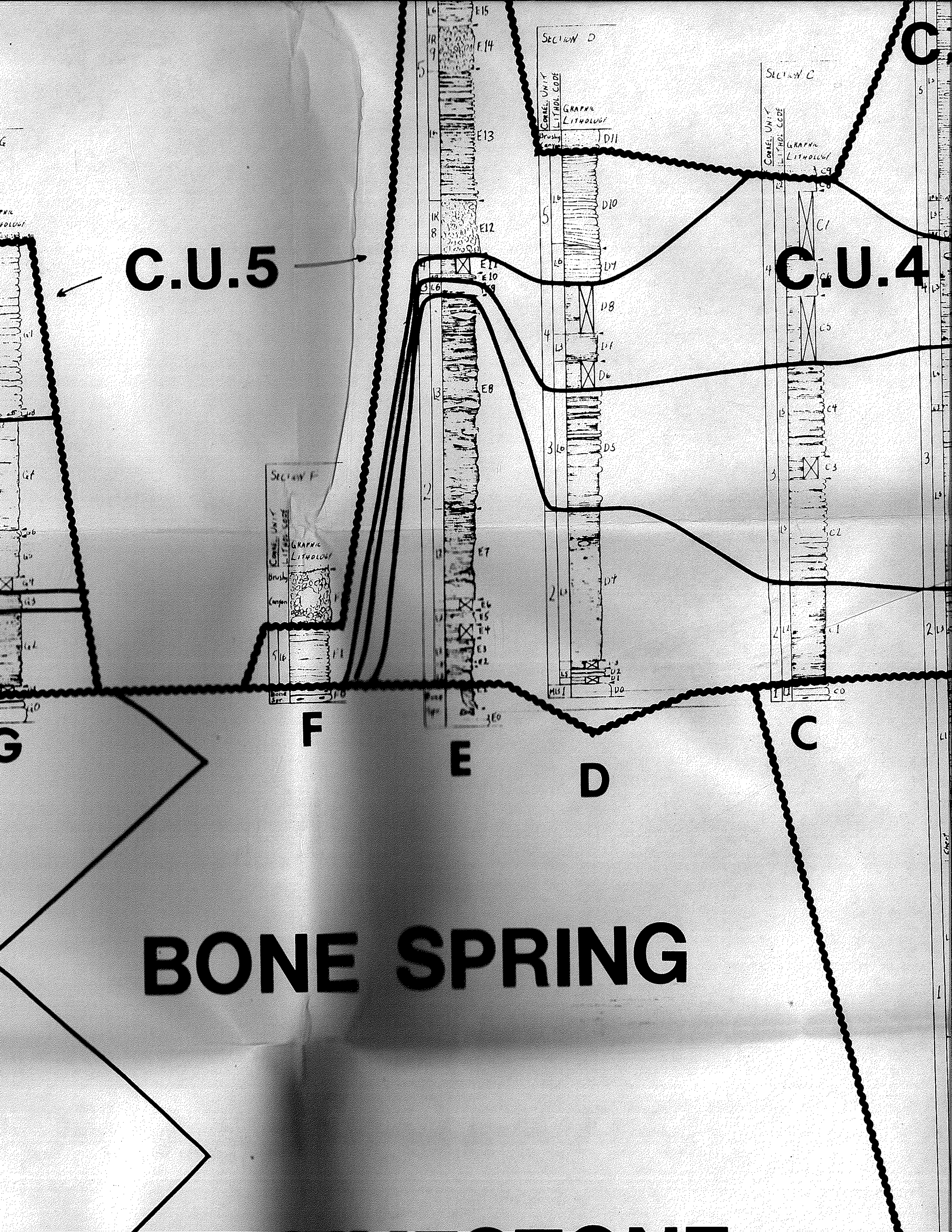


Graphic Lithology
N20
PER
C.U.5
TOFF
N18
N17
N16
N15
N14
Section M
Graphic Lithology
M17
M15
C.U.4
M10
CHERRY

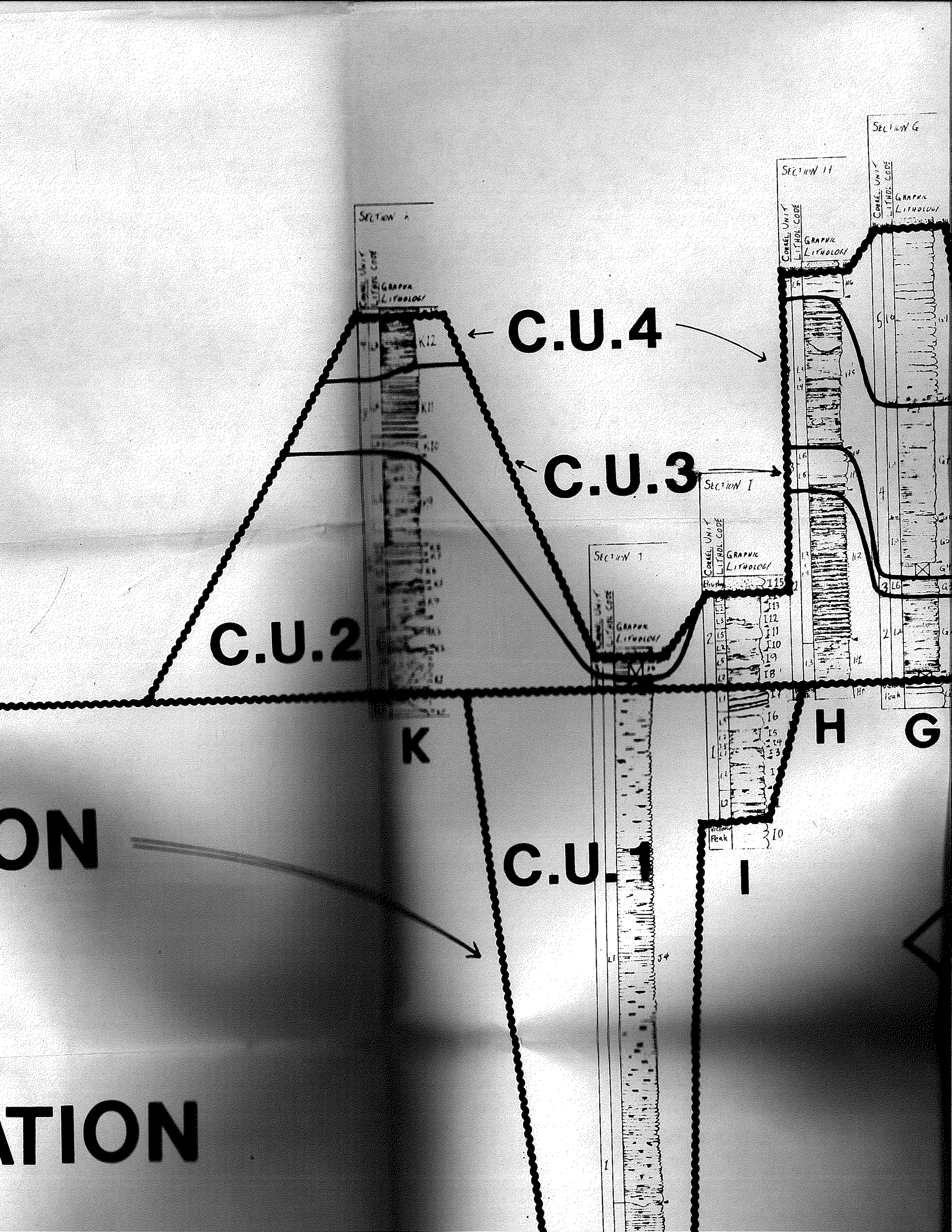


SECTION V
CORREL. UNIT
LITHOL CODE
GRAPHIC LITHOLOGY
N18
N17
N16
N15
N14
SECTION M
M17
M16
M15
UPPER
CUTOFF
C.U.5
C.U.4

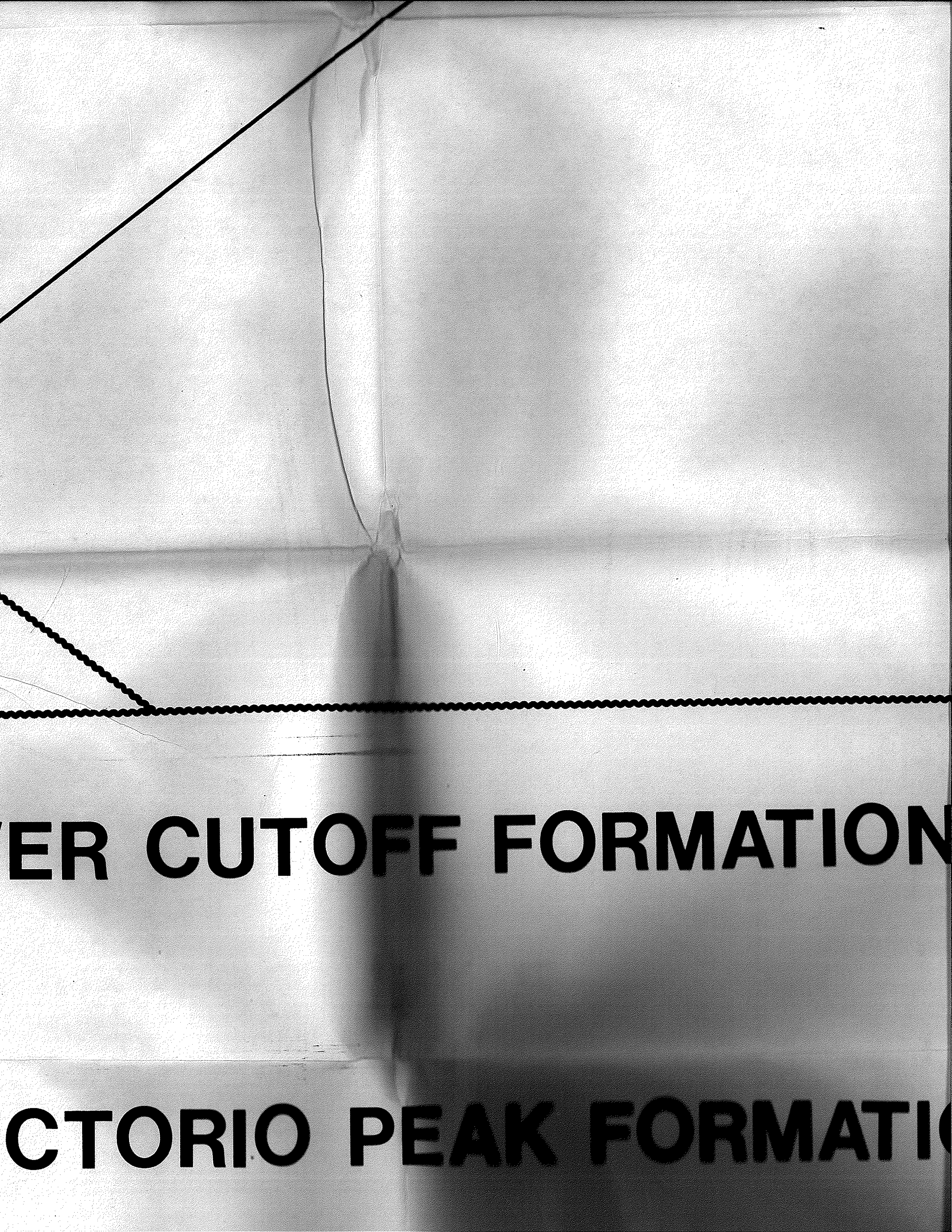

C.U.5
FORMATION
C.U.3
C.U.2
C.U.1
A
LOWER CUTOFF
FORMATION
B22
B20
B18
B17
B15
B14
B13
B12
B11
A6
A4
A3
A2
A1
A0



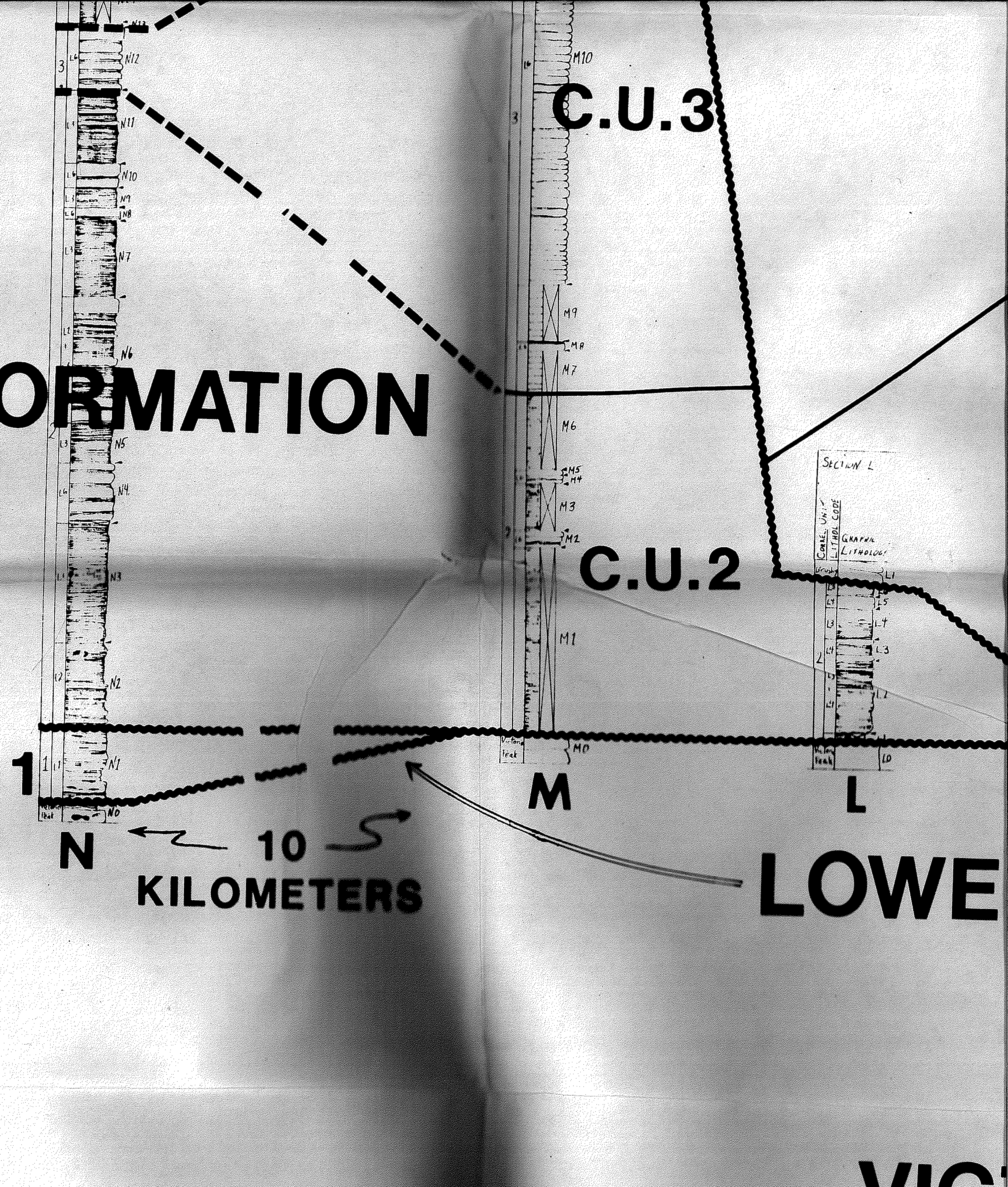
C.U.5
C.U.4
SECTION D
SECTION C
SECTION F
CORREL. UNIT
LITHOL. CODE
GRAPHIC LITHOLOGY
Brushy Canyon
Bone Spr.
D11
D10
D9
D8
D6
D5
D4
D0
E15
E14
E13
E12
E11
E10
E9
E8
E7
E6
E5
E4
E3
E2
E1
E0
C9
C8
C7
C6
C5
C4
C3
C2
C1
C0
G
F
E
D
C
BONE SPRING



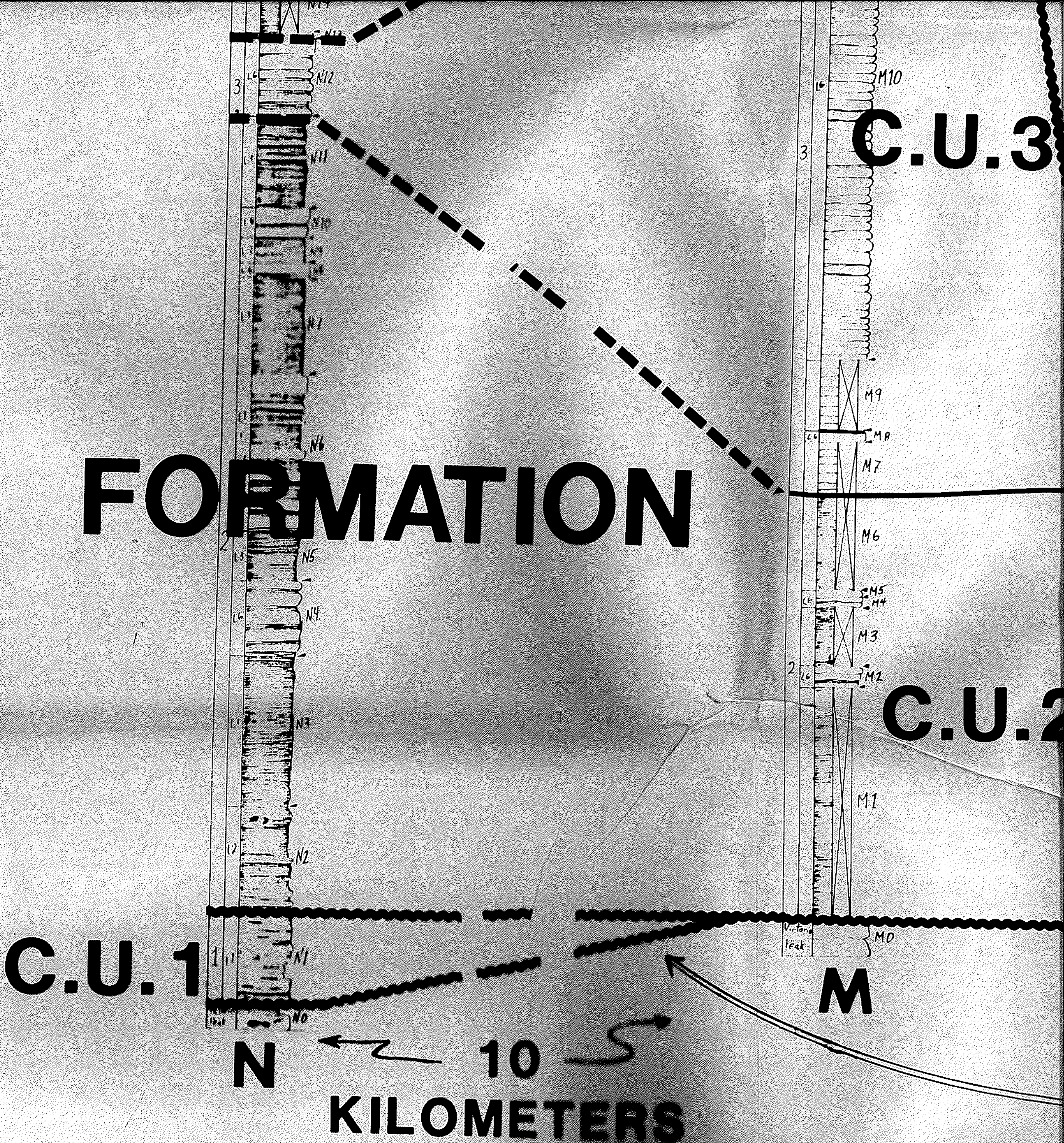
C.U.4
C.U.3
C.U.2
C.U.1
K
H
G
I
ON
ATION



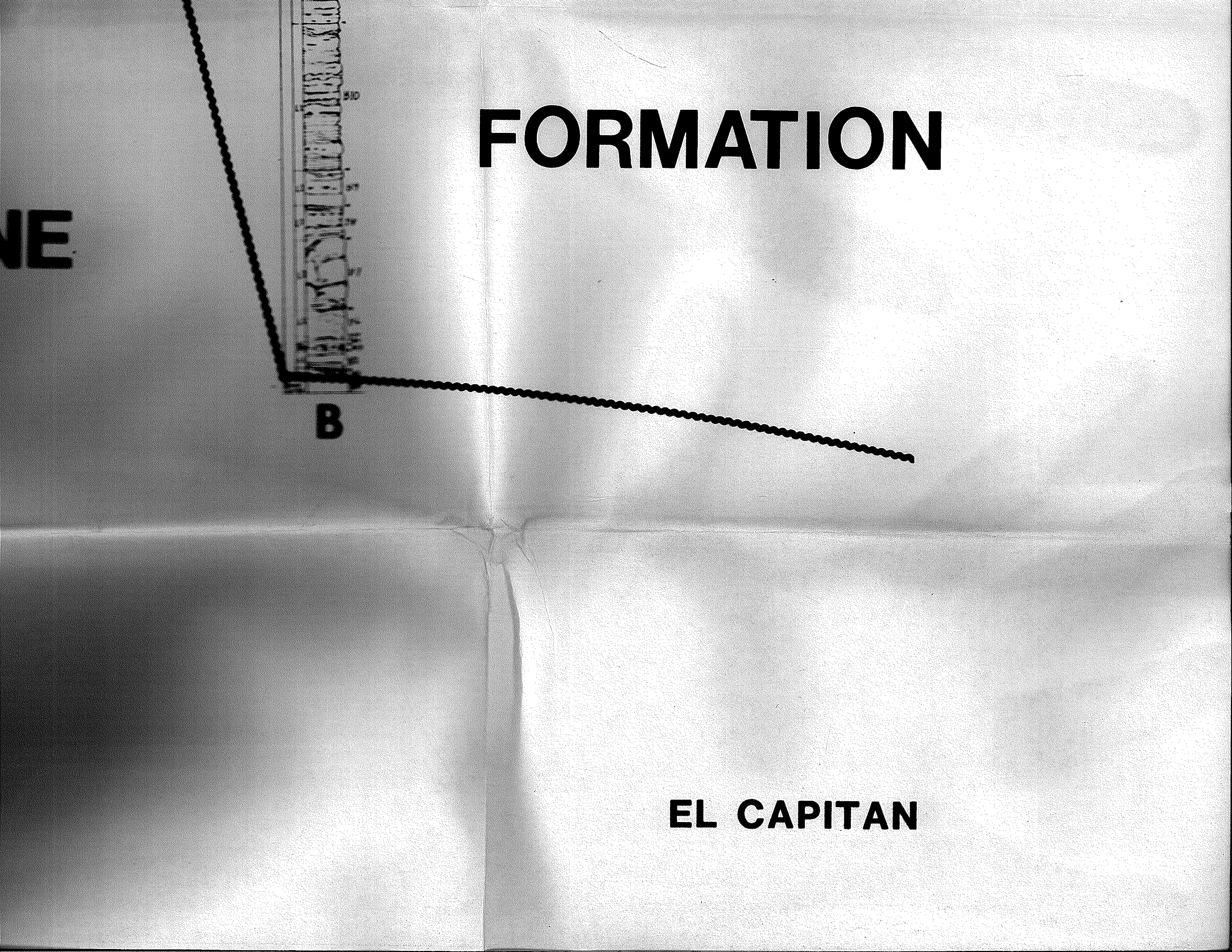
ER CUTOFF FORMATION
CTORIO PEAK FORMATI

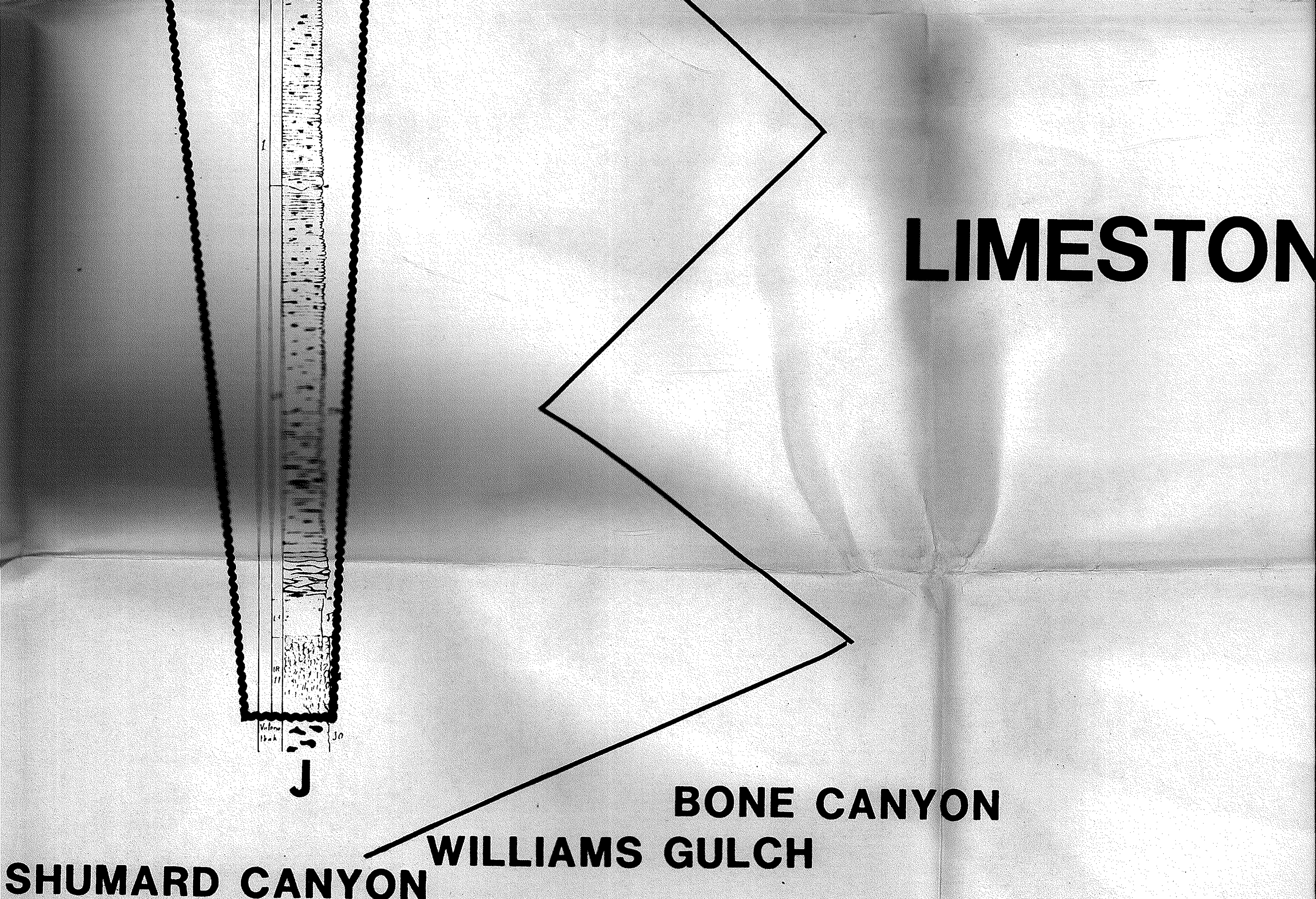


C.U.3
ORMATION
C.U.2
SECTION L
CORREL. UNIT
LITHOL CODE
GRAPHIC LITHOLOGY
1
N
M
L
10
KILOMETERS
LOWE
VIC



FORMATION
C.U.3
C.U.2
C.U.1
N12
N11
N10
N7
N6
N5
N4
N3
N2
N1
N0
M10
M9
M8
M7
M6
M5
M4
M3
M2
M1
M0
N
M
10
KILOMETERS


NE
FORMATION
B
EL CAPITAN


LIMESTON
J
BONE CANYON
WILLIAMS GULCH
SHUMARD CANYON

TORIO PEAK FORMATION

E

ETER

TION UNIT

TTAIL CANYON

SHU

VICT

1.0 MILE

1.0 KILOME

10 30

5 15

0 0

METERS FEET

C.U. = CORRELAT

BARTLETT PEAK

CUTOFF MOUNTAIN

SHIRT