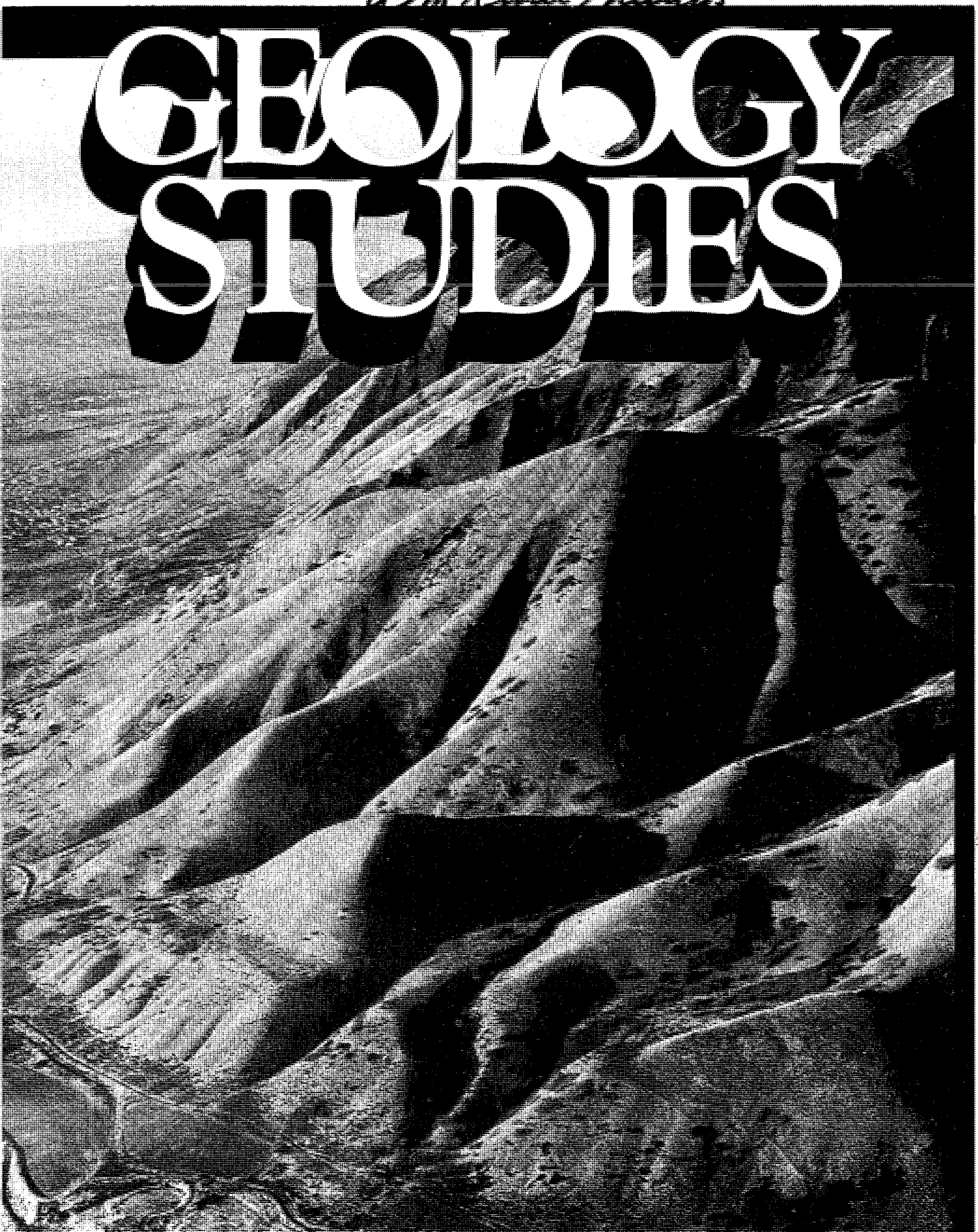
BRIGHAM YOUNG UNIVERSITY

GEOLOGY STUDIES



VOL. 25, PART 3 [illegible]

Brigham Young University Geology Studies

Volume 25, Part 3

CONTENTS

THE GLORY OF GOD IS INTELLIGENCE

Cover: Compound faceted spurs along the Wasatch Mountains indicate alternating periods of fault displacement and tectonic stability.

A publication of the

Department of Geology

Brigham Young University

Provo, Utah 84602

Brigham Young University Geology Studies is published semiannually by the department. *Geology Studies* consists of graduate-student and staff research in the department and occasional papers from other contributors. *Studies for Students* supplements the regular issues and is intended as a series of short papers of general interest which may serve as guides to the geology of Utah for beginning students and laymen.

ISSN 0068-1016

Distributed December 1978

12-78 525 34943

CONTENTS

Figures

Petrology and Petrography of the Bridal Veil Limestone Member of the Oquirrh Formation at Cascade Mountain, Utah*

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ABSTRACT.—A petrographic study of thin sections made from 130 rock samples led to the identification of eight major rock types in the Rock Canyon section of the Lower Pennsylvanian Bridal Veil Limestone Member of the Oquirrh Formation at Cascade Mountain. Four sedimentary facies typify the section and include: (1) calcareous sandstone–sandy limestone facies; (2) mudstone–fine-grained wackestone facies; (3) skeletal wackestone–packstone facies; and (4) pelletal to oolitic limestone facies. Each facies exhibits microshifts producing several subfacies with carbonate grains of skeletal fragments, intraclasts, pellets, coated grains, and ooids together with fine to very fine quartz sand. Facies are interpreted as reflecting deposition on a broad platform in an unstable carbonate realm of the Oquirrh basin in the eastern portion of the Cordilleran miogeosyncline and are herein interpreted to have accumulated in an environment which can be divided into five depositional zones: (1) an area of terrigenous clastics deposited closest to shore by inflowing streams off the craton; (2) a broad, quiet lagoonal zone marked by deposition of fine carbonate sediment; (3) an area of skeletal detritus scattered behind a bioherm shoal of organism development, debris being transported cratonward by tidal action, storms, and local currents; (4) a fringing belt of bioherms comprised mostly of crinoids, bryozoans, and algae with abundant intrabiohermal skeletal detritus; and (5) interfingering oolite, coated-grain, and algal pellet-producing marine waters seaward of the bioherms. These five subdivisions are all within the shallow marine zones Z (one through four) and Y (five) proposed by Irwin (1965). Shifts or oscillations of the environment within these zones may have produced the sharp contacts between individual units seen as abrupt changes in rock type. Chert, authigenic feldspar, and iron oxide pseudomorphs within sediments deposited in the quiet lagoon indicate high amounts of silica entering the depocenter and possible high salinities and reducing conditions.

INTRODUCTION

The study area for the Lower Pennsylvanian Bridal Veil Limestone Member of the Oquirrh Formation is a well-exposed section on the southwest side of Cascade Mountain in the second left fork of Rock Canyon in the NE¼, section 27, and the SE¼, section 22, T. 6 S, R. 3 E, in the south central Wasatch Range of central Utah (fig. 1). Here, this lowermost member has a thickness of 320.8 m. Elevation of the area above mean sea level is 2134 m at the canyon floor rising to 3325 m at the crest of Cascade Mountain. Rocks in the study area range from Upper Mississippian through Middle Pennsylvanian age and dip in a general northeasterly direction from 20–30 degrees. The southwest face of Cascade Mountain offers a well-exposed, but steep, section for field investigation. Gullies on the mountain front are steep and narrow, and there are no permanent trails on the mountain side.

Accessibility to the study area is from Utah highway 189 in Provo Canyon via Squaw Peak Trail Road, through Pole Canyon, to within 1 km of Rock Canyon Campground. The study area is within 250 m of the road and is characterized by rugged terrain, with steep slopes and cliff-forming sequences (fig. 2).

Previous Work

The first stratigraphic work done near Cascade Mountain was in Provo Canyon in the south central Wasatch Range by King and Emmons (1877). They applied the name Weber Quartzite for Carboniferous rocks of this area, which is now known as the upper part of the Oquirrh Formation. The lower unit (now known as the Bridal Veil Limestone Member of the Oquirrh Formation), as well as the Mississippian limestone and shale, were placed in what they designated the Wahsatch Limestone. In 1895, the upper part of the Wahsatch, which later became known as the lower member of the Oquirrh, was placed in the lower part of the Upper Intercalated Series by Spurr for rocks in the Mercur mining district of the Oquirrh Mountains.

Oquirrh as a stratigraphic name was first used by Keyes (1924, p. 37) to apply to quartzitic Carboniferous rocks. Nolan (1930) used the name Oquirrh for what he later (1935) designated as Pennsylvanian-Permian rocks in the Gold Hill district. Gilluly (1932, p. 34–38) formally named the Oquirrh Forma-

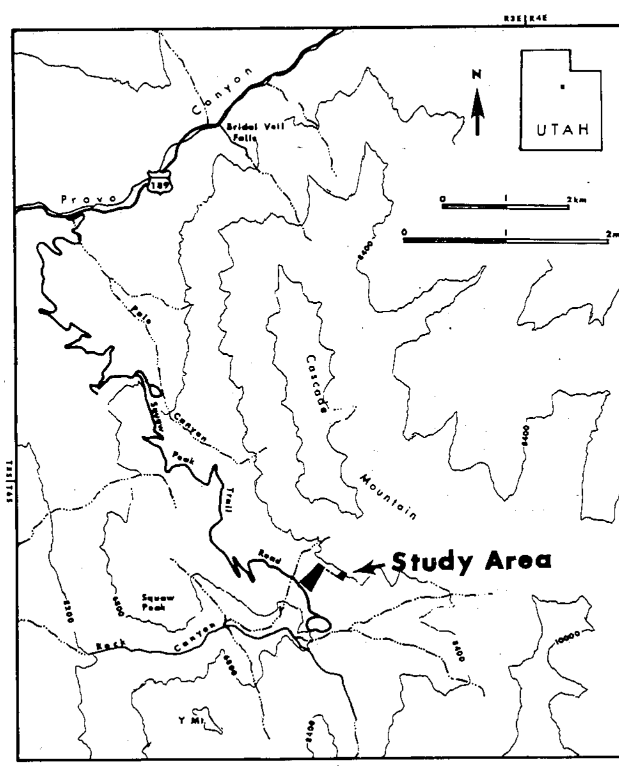


FIGURE 1.—Index map of study area.

*A thesis presented to the Department of Geology, Brigham Young University, in partial fulfillment of the requirements for the degree Master of Science, December 1978. Thesis committee chairman, Harold J. Bissell.

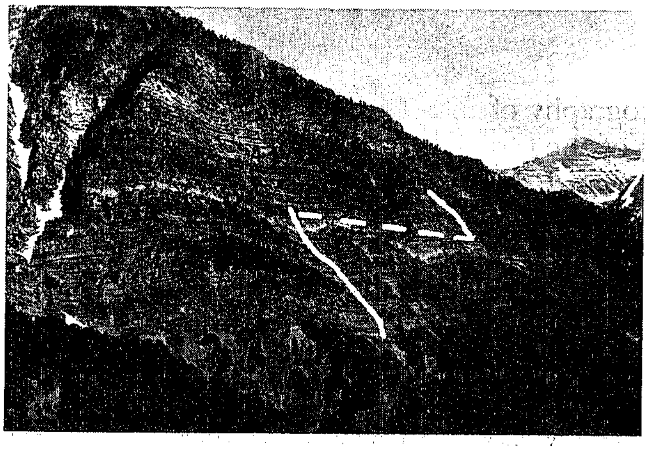


FIGURE 2.–Southwest face of Cascade Mountain in the second left fork of Rock Canyon with measured section route outlined.

tion from more than 518 m of outcrop in the Oquirrh Mountains 32 km northwest of Provo. Bissell (1936a) was the first to use the name Oquirrh Formation for Pennsylvanian sequences found in the south central Wasatch Mountains of central Utah. Other studies of various units in the Oquirrh Formation have since been completed (Bissell 1936b, 1952, 1959a, 1959b; Nygreen 1958; Steele 1960; Tooker and Roberts 1961; Welsh and James 1961; and Wright 1961). A general discussion and overview of the Pennsylvanian-Permian Oquirrh basin in Utah has also been compiled by Bissell (1962a).

Studies of the basal member of the Oquirrh are limited. The lower limestone member of the Oquirrh was formally named the Bridal Veil Limestone Member by Baker and Crittenden (1961). The first detailed map of the Cascade Mountain area was published by Baker (1972). Franson (1940) did a general geologic study of the basal Oquirrh in limited areas of its exposure in Provo Canyon, but advanced little information as to the depositional environment. Nygreen (1958) studied the lower Oquirrh, including the basal limestone member, in the type locality (Oquirrh Mountains), making comparisons with a section near Logan, Utah, and described some sedimentary characteristics of the unit in those areas.

Statement of the Problem

The purpose of this paper was to make petrologic and petrographic studies of the environment of deposition of the Bridal Veil Limestone Member of the Oquirrh Formation at Cascade Mountain east of Provo, Utah. Attention was directed to both detailed field and laboratory studies of a carefully measured section not only to determine the conditions of sedimentation of the exposed Bridal Veil Limestone Member, but to form a working model of the ancient sedimentary environment. This study helps fill the need for detailed investigations of rocks deposited in the Oquirrh and many other Late Paleozoic basins to determine tectonic and depositional settings.

Acknowledgments

The writer wishes to thank Dr. Harold J. Bissell, who suggested this problem and served as thesis chairman, and whose guidance, suggestions, and assistance on petrography of thin sections were always present and appreciated. Thanks also are accorded to Dr. Morris S. Petersen for serving as committee member and making many helpful suggestions during the thesis preparation. Mr. Kim Harris, Mr. David Noble, and Mr. Stewart Duncan assisted in part of the fieldwork, thereby providing valuable help. I am very grateful to my wife, Sue, for her patience, work, encouragement, and the personal sacrifice she willingly made to make possible the completion of this project.

METHODS

Methods of study of the Bridal Veil Limestone Member of the Oquirrh Formation were divided into field and laboratory investigations. Field studies were conducted from September through November 1977, with brief revisiting in June of 1978. Preliminary measurement of the stratigraphic section was accomplished by the use of a steel tape and a Brunton compass with corrections made for true thickness. Numbered divisions at major lithologic breaks were made and marked with bright orange spray paint. Detailed measurements were made using a 6-meter steel tape accompanied by extensive field description. Rock samples were collected at every marked break in lithology further subdividing the preliminary subdivisions into 81 separate lithologic field units. Collection of 130 samples was made, beginning from the upper Manning Canyon Shale through the Bridal Veil Limestone Member and into the overlying medial, predominantly quartzitic, member of the Oquirrh. Exact location of each collection site is labeled on the stratigraphic column (fig. 3). Rock color was determined for all units by comparison with the rock-color chart distributed by the Geological Society of America (1970). Photographs of important field locations were taken in conjunction with sampling of the measured section and also during later visits. Altogether, 146 thin sections (25.4 × 50.8 mm) were prepared. Alizarine Red S was used to stain slides suspected of containing dolomite to determine true amounts of dolomite and calcite (Friedman 1959). Description and analysis of thin sections were done by a thorough investigative study of each slide to learn relative amounts of and types of (1) skeletal, pelletal, intraclastic, oolitic, clastic admixtures, and other components; (2) textural characteristics; (3) matrix; (4) recrystallization or other diagenetic effects; (5) energy which affected the ancient sea bottom; and (6) environment in which the sediments were possibly deposited. Identification of textural types and skeletal fragments was facilitated by the use of excellent carbonate texts by Bissell (1970), Horowitz and Potter (1971), Majewske (1969), and Scholle (1978). No single classification was used to name the various carbonate rocks in thin section. A base name for all carbonates was taken from Dunham's classification (1962) with modifiers from the classifications of Leighton and Pendexter (1962) and Rich (1963) being placed in front of the base name.

GEOLOGIC SETTING

Bridal Veil Limestone Member of the Oquirrh Formation at Cascade Mountain was deposited in the Late Paleozoic Oquirrh basin, where subsidence and sediment infilling occurred in the easternmost part of the Cordilleran miogeosyncline. In Mississippian time the area became a sediment-receiving area called the Madison-Brazer basin and was a forerunner of the Oquirrh basin. The Deseret Limestone, Humbug Formation, Great Blue Limestone, and the Manning Canyon Shale were deposited in this incipient Oquirrh basin. The actual Oquirrh basin in which the Oquirrh Formation was deposited began to form in Early Pennsylvanian time as sediments accumulated at an accelerated rate and waters spread throughout its extent. Epeirogenic upwarping of certain adjacent landmasses occurred, and areally extensive blankets of carbonates, shales, and sands accumulated. The Oquirrh basin soon became

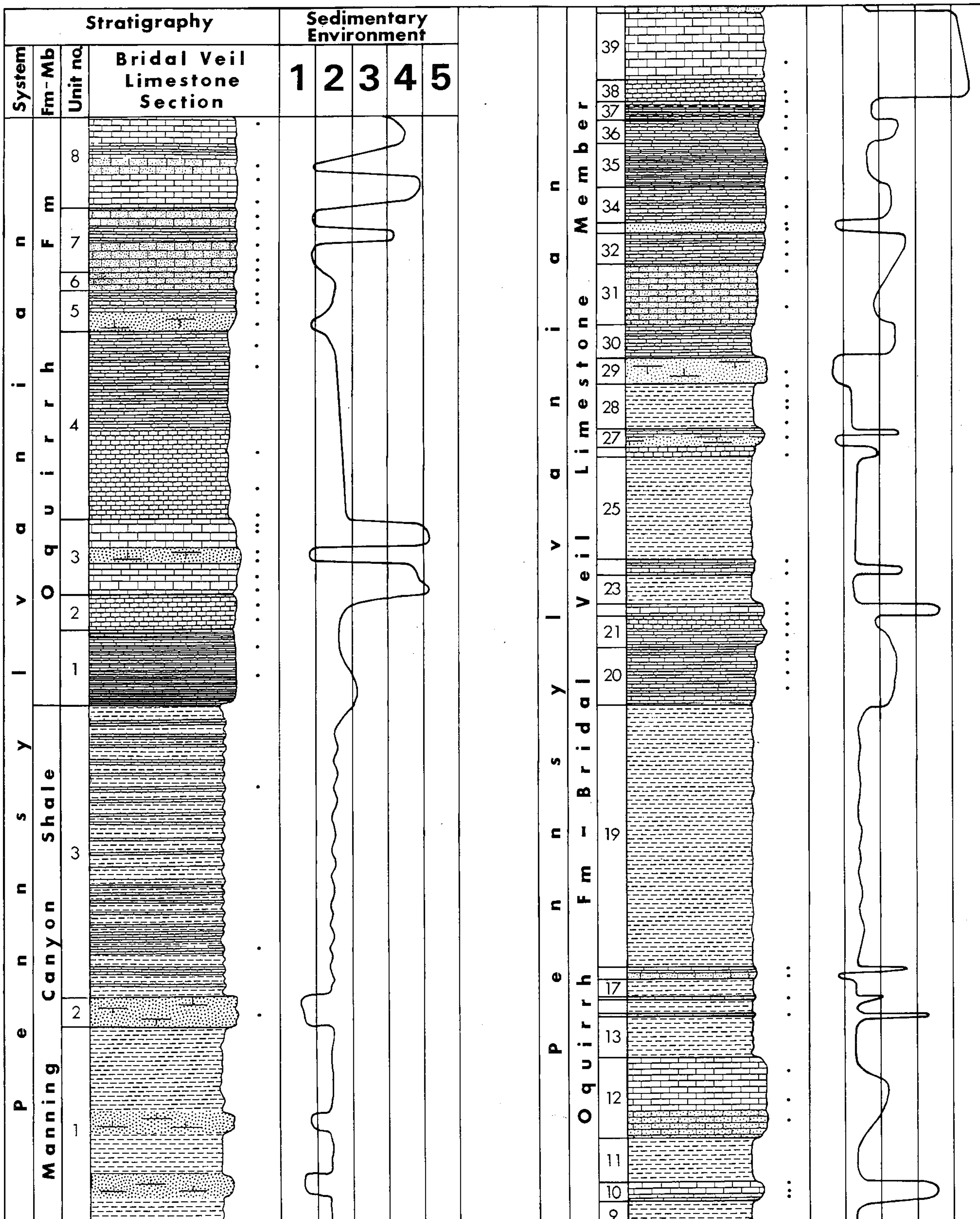
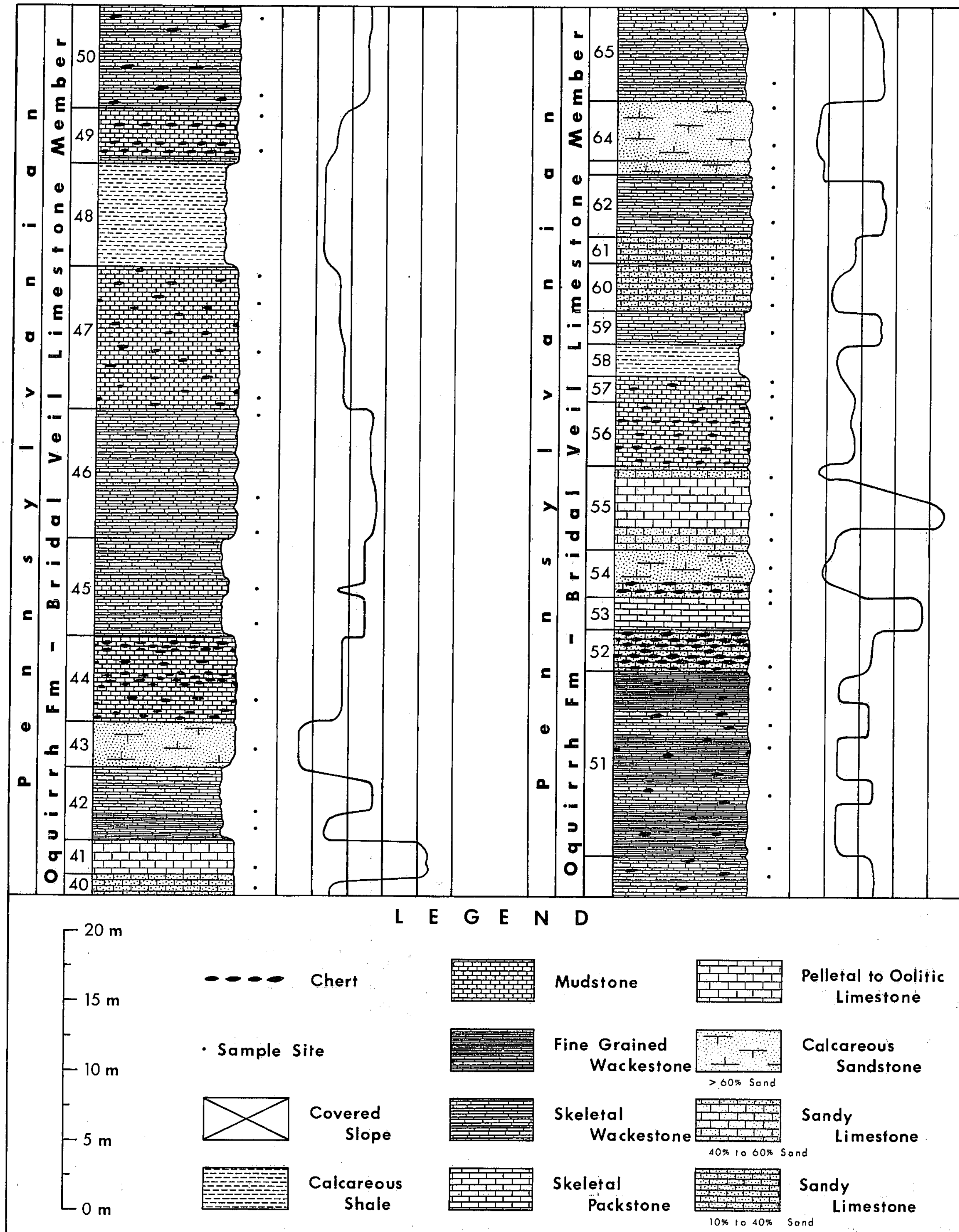


FIGURE 3.–Stratigraphic column and proposed depositional environments of measured Rock Canyon section of Bridal Veil Limestone Member of the Oquirrh Formation. (Continued on next pages.)


Pennsylvanian
Oquirrh Fm - Bridal Veil Limestone Member
50
49
48
47
46
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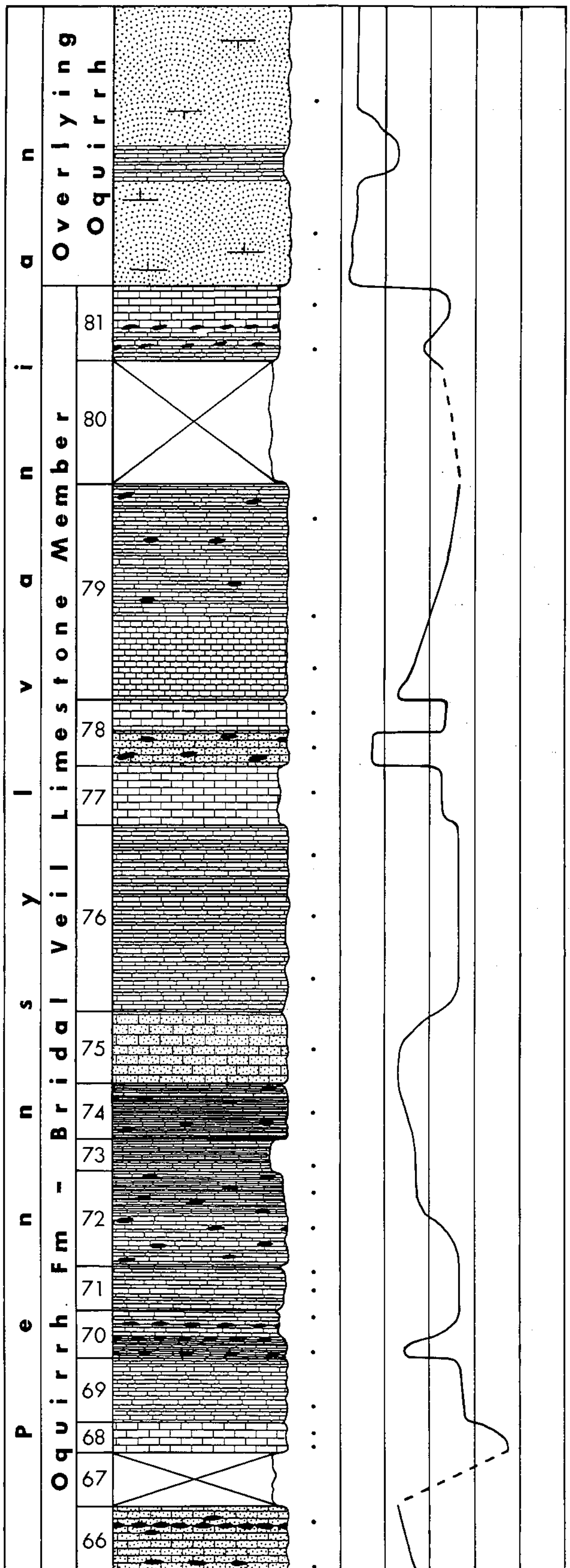
43
42
41
40
Pennsylvanian
Oquirrh Fm - Bridal Veil Limestone Member
65
64
62
61
60
59
58
57
56
55
54
53
52
51
LEGEND
20 m
15 m
10 m
5 m
0 m
Chert
Sample Site
Covered Slope
Calcareous Shale
Mudstone
Fine Grained Wackestone
Skeletal Wackestone
Skeletal Packstone
Pelletal to Oolitic Limestone
Calcareous Sandstone
> 60% Sand
Sandy Limestone
40% to 60% Sand
Sandy Limestone
10% to 40% Sand



broad with thick deposits of micritic, arenaceous, bioclastic, and other limestones and interbedded shale and sandstone occurring in a northwesterly trending trough in north central Utah. To the northeast, the Weber Shelf was a broad, stable to slightly unstable region situated between the subsiding miogeosyncline and the craton farther east. The Emery uplift to the south may have been incipient only and likely existed as a shallow submarine bank rather than as a pronounced positive block (Bissell 1962a). The Western Utah highland (Bissell 1962a), on the other hand, was rising and crowding against the west central part of the basin. The Northeast Nevada highland (Bissell 1962a) in northwestern Utah adjacent to the basin displayed most pronounced activity (Bissell 1962a) and controlled the sedimentary pattern in the basin to the north but probably did not provide significant amounts of clastic material to the west central part of the basin where the sediments of present-day Cascade Mountain were deposited. The probable accessway of most of the sands in the study area was through the Strawberry Accessway (Bissell 1960, p. 1426) or Doughnut Trough (Rose 1976). Detritus swept across this platformlike area was derived from the Weber Shelf and the craton on the northeast, the Emery uplift on the south, and the Uncompahgre uplift on the east. The Western Utah highland was also a likely source of much of the clastic material shed from the south and west directly into the basin.

Cascade Mountain occupies the south central portion of the Wasatch Front which is also the trace of what has been called the Wasatch hinge line, and has been the fulcrum of much tectonic activity. In Cretaceous time the hinge line served as an eastern terminus where thrusts carrying large slabs of crust came to rest after translating allochthonous blocks eastward. Cascade Mountain represents part of the allochthonous block thrust eastward upon the hinge line by the Charleston Thrust. Amount of displacement of the Charleston Thrust has been estimated to be up to 64 km (Crittenden 1961). Movement locally was probably less than 16 km (Johnson 1959 and Brady 1965). Evidence would then suggest that the Oquirrh Formation at Cascade Mountain was deposited relatively close to the hinge line and shelf sequence to the east.

Most recent diastrophism to affect Cascade Mountain was vertical uplift along the Wasatch Fault which raised the mountain to its present elevation. The uplift along the Wasatch Fault is associated with the breakup by block faulting of the Basin and Range which began in Miocene time and continues to the present, forming the Wasatch Mountains and the easternmost boundary of the Great Basin.

STRATIGRAPHY

The Oquirrh Formation was defined by Gilluly (1932, p. 34–38) in the Oquirrh Mountains, and was first used in the south central Wasatch Mountains area by Bissell (1936a). At Cascade Mountain, the two lowest members form superb outcrops.

The lowest is the Bridal Veil Limestone Member, named after Bridal Veil Falls on the south side of Provo Canyon in section 34, T. 5S, R. 3E, by Baker and Crittenden (1961). They indicate the thickness here to be 366 m. This basal sequence of units in the Oquirrh is one of the formation's most distinctive and mappable members and can be recognized in varying thicknesses throughout the Oquirrh basin. Age of the Bridal Veil Limestone Member is Morrowan as indicated by its fossil content, a fact pointed out by previous workers.

Sediments exposed at the measured Rock Canyon section of the Bridal Veil Limestone Member at Cascade Mountain reach a thickness of 320.8 m. At first appearance these sediments seem to be a sequence of relatively nondescript massive limestones, cross-bedded sandstones, and interbedded shales. However, detailed petrologic and petrographic studies indicate that marked variations in facies are typical, with interfingering of these facies occurring extensively throughout the section.

Stratigraphy of the measured Rock Canyon section at Cascade Mountain begins in the Manning Canyon Shale and extends upward conformably through the Bridal Veil Limestone Member into the overlying highly quarzitic medial member of the Oquirrh Formation. Manning Canyon Shale was named by Gilluly (1932) for a sequence of rocks exposed in Manning Canyon and in Soldier Canyon of the Oquirrh Mountains. The formation at Cascade Mountain is largely a covered slope former concealed by abundant vegetation which makes detailed study difficult. Three samples were collected from the upper Manning Canyon Shale in a gully at the base of the measured section where erosion and lack of vegetation provide good exposures of the top 36.5 meters. The formation, as exposed here, is composed predominantly of very fissile calcareous shale with three units of interbedded calcareous sandstone and orthoquartzite near the base, and interbedded mudstone above, comprising the remainder of the unit below the base of the Oquirrh Formation. General field color of Manning Canyon Shale is medium gray to medium bluish gray where weathered, and medium-dark to dark gray on fresh and broken surfaces. Interbedded calcareous sandstone is reddish brown to medium brown when weathered and medium gray on fresh surfaces. Sedimentary structures include ripple marks and low-amplitude cross-bedding in the calcareous sandstone. Bedding is thin, reaching high fissility in most of the shale units. Uppermost contact of the Manning Canyon Shale with Bridal Veil Limestone Member is placed at the abrupt change from interbedded mudstone and shale to massive limestone. The contact is distinct in the field with a sudden steepening of the moderate slope of Manning Canyon Shale into a steep, cliff-forming sequence. This contact reflects the abrupt transition from a dominance of shale to a dominance of more massive carbonate.

At the Rock Canyon section of Cascade Mountain, the first lithologic subdivision in the Bridal Veil Limestone Member of the Oquirrh Formation above the slope-forming Manning Canyon Shale is a medium-dark to dark gray, fine-grained wackestone-to-mudstone sequence that produces a steep cliff. Fossil size and content decrease upward with a fine-grained wackestone at the base grading into an unfossiliferous mudstone. At 7.2 m above the base of the member this sequence gives way to a sandy, skeletal packstone with some coated grains and pellets. The unit is 5.7 m thick with a medial 1-m-thick bed of calcareous sandstone. Color for the rock is medium-dark gray on fresh surfaces and medium-light gray on weathered surfaces; bedding is medium to thin. The section gives way upward to an 18-m-thick sequence of medium-dark to dark gray, ledge-and slope-forming, fine-grained wackestone to mudstone. Above this, a distinctive cliff-forming sequence of interfingering calcareous sandstone, sandy limestone, and skeletal packstone and wackestone dominates, showing a decrease in sand content upward. Bioclastic material in most of the unit is differentially concentrated and stratified with some zones containing abundant intraclasts of micrite. Worm burrows and trails, together with low-amplitude cross-bedding, are common in the calcareous sandstone and sandy limestone.

Slope-forming, medium-dark gray, calcareous shale becomes dominant at 41 m and remains so until a prominent calcareous sandstone is reached at 104.7 m. This predominantly shale unit is marked by interfingering, ledge-forming, skeletal wackestone and packstone, mudstone, calcareous sandstone, and sandy limestone beds. The skeletal wackestone and packstone predominate as ledge formers throughout the sequence, making up several thin interbedded layers, are closely associated, and are similar in appearance to a few smaller mudstone units. Their color ranges from medium to dark gray, and bedding is thin to thick. Skeletal rock-building components include brachiopods, crinoids, and bryozoans, with some small algal stromatolite buildups. Many of these units contain beds with abundant intraclasts and concentrations of iron oxide 3–5 cm in diameter staining the rock. Intervals ranging from sandy limestone to calcareous sandstone occur intermittently in the sequence and have a color of medium-dark gray on fresh surfaces, weathering light-olive gray to brown, with one interval weathering grayish orange. The rocks are thin bedded, and sedimentary structures include cross-bedding, flaser bedding, ripple marks, and worm trails. Brachiopods and crinoids are abundant in calcareous shale, and in many areas specimens weather out whole. Some identifiable brachiopods from this sequence include *Spirifer rocky montanus, Spirifer opimus, Composita ozarkana, Composita subtilita, Linoproductus ovatus, Derbyia robusta, Derbyia crassa, Composita trilobata,* and *Jerusania nebrascensis.*

Fine-grained and skeletal wackestone as a ledge- and slope-forming sequence occurs above the prominent calcareous sandstone cliff, which is 1.8 m thick. This unit occurs 101.5 m above the base of Bridal Veil Limestone and measures 19.4 m. A few beds high in quartz detritus occur as interbeds in the skeletal wackestone and exhibit undulatory bedding and some low-amplitude cross-bedding. Within this sequence, limestone varies between mudstone and skeletal wackestone with varying amounts of skeletal and some pelletal constituents. Near the top of this ledge- and slope-forming sequence is the first interval of stratified chert; bedding throughout is medium to thick. Medium-to-dark-gray color is common on fresh and broken surfaces of the rock, weathering lighter gray. Intervals containing abundant quartz weather to varying shades of brown to olive gray depending on quartz content.

A prominent cliff former is the next lithologic subdivision, which is composed of pelletal to oolitic limestone with a medial 2-m-thick bed of sandy limestone. The unit is thick bedded with thin to medium beds occurring in the medial sandy unit. Limestone is an admixture of pellets, coated grains, oolites, and skeletal fragments of crinoids, brachiopods, and sparse numbers of bryozoans, gastropods, and pelecypods. This limestone sequence is 9.1 m thick. Pelletal to oolitic limestone is medium gray and quartzose wackestone is medium gray to medium-dark gray in color; both weather light gray.

Interbedded units of skeletal wackestone, mudstone, shale, and fine-grained wackestone, with one 3.2 m unit of calcareous sandstone toward the base, make up the next sequence of rocks. These lithologies produce three prominent cliffs with three slope-forming units occurring below each one to form the profile of the sequence. Rock types in the cliff-forming units are skeletal wackestone, mudstone, and calcareous sandstone. Color of the units is mostly medium-dark to dark gray on fresh surfaces and lighter grays on weathered surfaces. Calcareous sandstone weathers light brown. Bedding is mostly medium to thick, and chert nodules are very prominent in most of the cliff-forming units, showing both random and stratified occurrences. In the upper part of the first cliff-forming unit, chert nodules occur commonly in a cone or horn shape with the open end always up. These appear to be some type of burrowing structure replaced by silica. Slope-forming intervals are made up of less resistant mudstone and fine-grained wackestone, skeletal wackestone, and calcareous shale. Bedding is medium to thin, with medium to medium-dark gray color common to fresh surfaces and lighter grays on weathered surfaces. No chert nodules are present in these slope-forming units. The total thickness for this cliff and slope sequence is 76.2 m.

An increase in both skeletal and detrital constituents marks the next sequence in the section. Rock types are sandy limestone with interbedded skeletal packstone, pelletal to oolitic limestone, and calcareous sandstone. Colors range from medium-light gray to dark gray, with lighter grays and olive gray on weathered surfaces. Bedding is medium and thick; abundant stratified chert nodules are present in the lower sandy limestone units.

Upper 106.2 m of the Bridal Veil Limestome Member form a steep cliff with only occasional thin slope-forming units. Dominant rock type in this unit is skeletal wackestone, with interbeds of mudstone, thin calcareous shale, sandy limestone, and calcareous sandstone in thin to moderately thick units occurring throughout the sequence. Skeletal wackestone and packstone are mostly medium-dark to dark gray on fresh and broken surfaces weathering medium-light to light gray. Bedding is medium to thick with some thin bedding in less resistant units. Toward the top, skeletal wackestone contains some randomly scattered chert nodules, and skeletal rock-building constituents are predominantly bioclasts of crinoids, brachiopods, and bryozoans. In units high in crinoid bioclasts a strong fetid odor is given off when the rock is crushed. Mudstone and shale are prominent in both upper and lower parts with some fine-grained wackestone interfingering with skeletal wackestone toward the top. Bedding throughout is thin to medium, and rock color is medium to medium-dark gray on fresh surfaces, weathering to lighter grays. Randomly scattered chert nodules are also common in the fine-grained wackestone. Sandy limestone and calcareous sandstone interbeds are present throughout this sequence. Colors, depending on the amount of quartz sand, range from medium-dark to dark gray to light-olive gray on fresh surfaces, and weather yellowish brown to dark brown. Bedding is thick to medium, with some thin bedding in the sandstone. Low-amplitude cross-bedding is present in the thick-bedded sandy limestone.

The uppermost 15.9 m of the Rock Canyon section comprise the overlying highly quartzitic medial member of the Oquirrh above the Bridal Veil Limestone Member. The contact is placed at the point where a dominance of limestone (characterized by the Bridal Veil Limestone Member) changes to a dominance of calcareous sandstone and orthoquartzite. The measured portion of this upper unit at Cascade Mountain is predominantly a calcareous sandstone with one interbedded skeletal wackestone 6 m above the base. The sequence is thick bedded, and has a color of light-olive gray on fresh surfaces, and yellowish brown to dark brown on weathered surfaces. Moderate-to-low-amplitude cross-bedding is abundant.

PETROGRAPHY OF SEDIMENTARY FACIES

Four sedimentary facies characterize Bridal Veil Limestone Member of the Oquirrh Formation in the Rock Canyon section at Cascade Mountain. These facies are seen to vary laterally and vertically both subtly and moderately throughout the section and seemingly represent interfingering of facies in a carbonate shelf environment. Petrographic description and observation of Bridal Veil Limestone will be discussed on a facies-to-facies basis.

Four sedimentary facies to be discussed are as follows: (1) calcareous sandstone–sandy limestone facies; (2) mudstone–fine-grained wackestone facies; (3) skeletal wackestone–packstone facies; and (4) pelletal to oolitic limestone facies.

Calcareous Sandstone–Sandy Limestone Facies

This facies is composed of calcareous sandstone (fig. 4) and

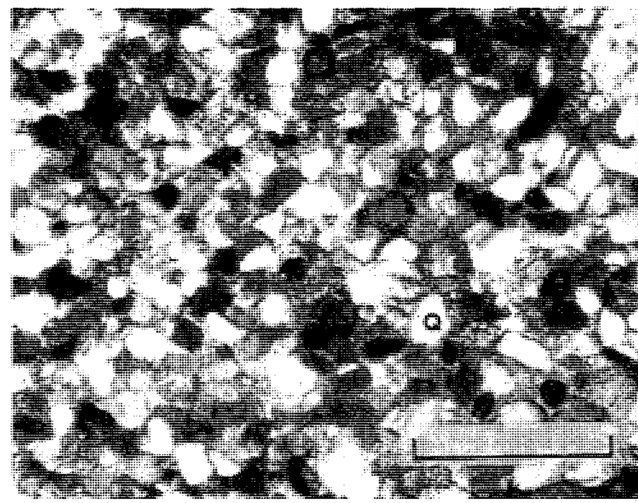


FIGURE 4.—Photomicrograph (crossed nicols) of calcareous sandstone subfacies. Scale is 500μ.

sandy limestone (fig. 5). These two compositional types are discussed together because they are commonly intimately associated in the section and are assumed to be closely related in the carbonate shelf environment. Clastic quartz shows a constant range in grain size from fine to very fine, being from 100μ to 200μ and averaging about 160μ, with some units being almost entirely composed of 100μ grains. Clastics are well sorted with little variation in grain size apparent throughout the section, and grains are mostly equant but angular to subangular. A few beds toward the top of the section contain as much as 10 per-

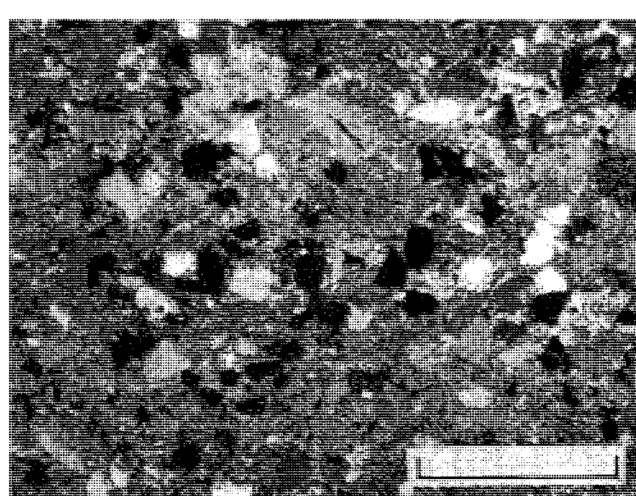


FIGURE 5.—Photomicrograph (crossed nicols) of sandy limestone subfacies. Scale is 500μ.

cent detrital feldspar. Matrix is formed of micrite mud that in many cases has been either partially or wholly recrystallized to fine microspar, but is not visible at low magnification. Where microsparitization has occurred, clastic grains have been partially invaded by microspar obscuring grain boundaries. Some sandy limestone contains up to 10 percent bioclastic material which is commonly well sorted. Crinoid and bryozoan fragments are usually sparse but comprise up to 10 percent of some units in this facies. Few beds contain fragments of brachiopods, possibly because the high clastic environment is not conducive to their occurrence; when brachiopods are present, it is only in units low in detrital quartz. Bedding in the facies results from variations in sand content, possibly indicating a periodic clastic influx creating an alternating high- and low-energy environment. In some cases an almost flaser-type bedding occurs with scattered lenses of lime mud in calcareous sandstone (fig. 6).

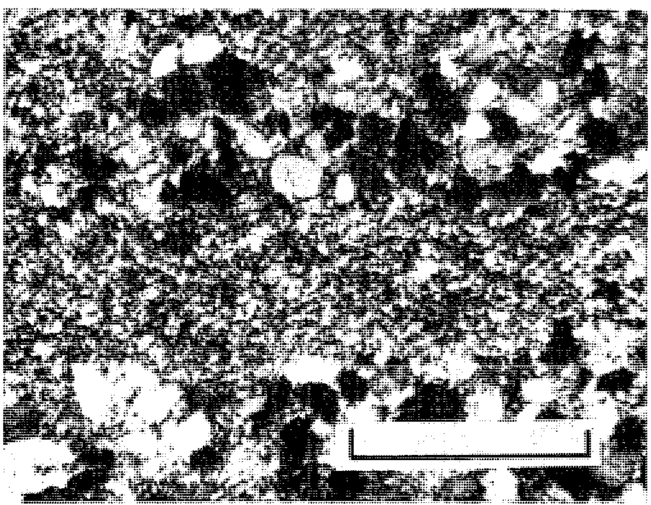


FIGURE 6.—Photomicrograph (crossed nicols) of scattered lenses of lime mud in calcareous sandstone. Scale is 500μ.

The combination of detrital quartz and concentrations of micrite mud shows what Wilson (1975) refers to as textural inversion, where the dominant particles are of a high-energy environment and have moved down a local slope to be deposited in quiet water. Micritic intraclasts are also abundant and contain no quartz detritus. Many of the sediments show burrowing with some feeding trails containing concentrations of authigenic iron oxide pseudomorphs after pyrite. In some cases burrowing appears to have completely obliterated bedding. Silicification is abundant in some units, with most of the fossil material present having been partially or wholly silicified, and occasionally matrix is completely replaced.

Twenty-two units of this facies occur in the section, ranging from 0.5 m to 5.4 m thick, totaling 53.9 thick, 17 percent of the Bridal Veil Limestone.

Mudstone-Fine-Grained Wackestone Facies

This facies is one of the more abundant and is characterized by sediments lacking in larger carbonate and detrital grains.

Mudstone subfacies is composed of very fine-grained micrite (fig. 7). Resistance to recrystallization suggests that it is of an algal origin, and small algal stromatolites occur periodically (fig. 8). Mudstone contains only small amounts of skeletal detritus and occasional whole brachiopod shells, usually completely silicified. Burrowing is extensive in many units, often containing concentrations of authigenic iron oxide and exhibiting partial recrystallization (fig. 9).

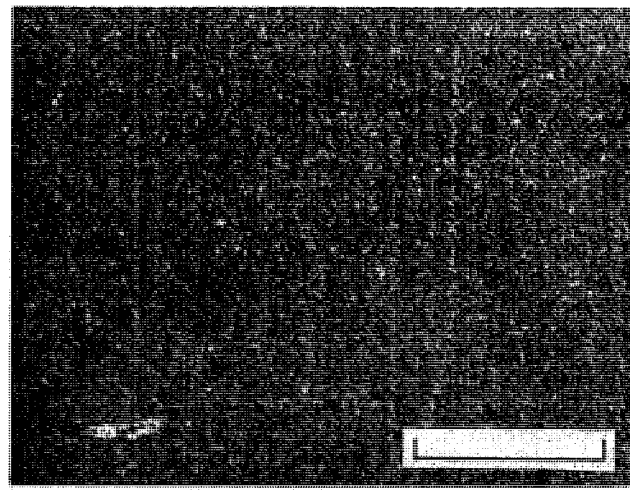


FIGURE 7.—Photomicrograph (crossed nicols) of mudstone subfacies. Scale is 500μ.

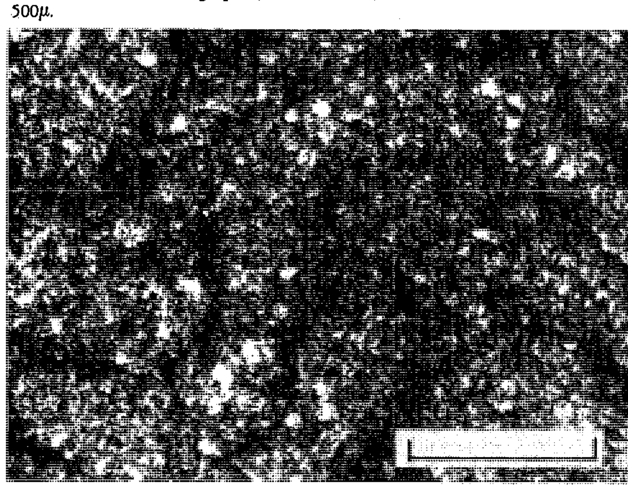


FIGURE 8.—Photomicrograph (crossed nicols) of algal stromatolite. Scale is 500μ.

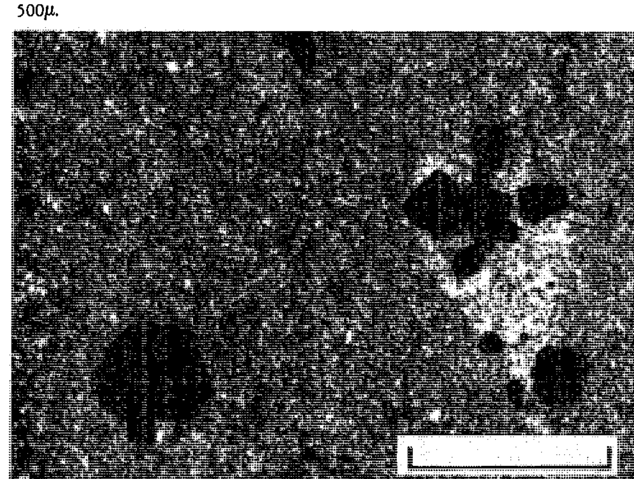


FIGURE 9.—Photomicrograph (crossed nicols) of burrowing trail showing recrystallization and concentration of iron oxide. Scale is 500μ.

Fine-grained wackestone (fig. 10) is a term used here to apply to rock with components of skeletal and clastic admixtures of less than about 100μ in size, being markedly different in size from grains prominent in other facies. Fine-grained wackestone has a matrix that is invariably replaced by microspar. Rock-building constituents include both fine-grained skeletal and detrital grains, with bioclasts of crinoids, brachiopods, bryozoans, and echinoderm spines commonly comprising 20 to 40 percent of the rock; large whole and fragmented brachiopods occur as scattered skeletal particles. Detrital, fine-grained quartz of from 50μ to 100μ comprises up to 20 percent of the wackestone. Much of the rock has been extensively burrowed with trails commonly highly silicified and sometimes apparent only as trails of authigenic iron (fig. 11). The larger skeletal fragments have commonly been replaced by silica, in the form of either crystalline quartz or chalcedony, and many later have experienced a replacement by crystalline calcite. Most quartz grains have also been partially invaded by microspar. Complete recrystallization of the rock is commonly seen to occur between low-amplitude stylolites, possible conduits for fluids that caused the change. Authigenic feldspar is abundant in the rocks of this facies, with some concentrations reaching as high as 30 percent (fig. 12).

Eleven units of this facies occur in the Rock Canyon section of the Bridal Veil Limestone and total 7.46 m and, with the 47.9 m of shale closely associated with rocks of this facies, comprise 38 percent of the member.

Skeletal Wackestone-Packstone Facies

This facies is characterized by skeletal wackestone and packstone (fig. 13) composed mostly of skeletal particles with some pelletal and intraclastic rock-building constituents set in a fine-grained groundmass ranging from true micrite mud to microspar with patches of primary spar cement in some packstones (fig. 14). Thirty-five units of this facies occur throughout the section ranging from 0.2 m to 13.8 m thick and totaling 123.5 m or 38 percent of the member making it equal in thickness to the mudstone-fine wackestone facies. Skeletal constituents include fragments of crinoids, brachiopods, bryozoans, and echinoderm spines, with some whole and fragmented gastropods and foraminifera. Crinoid arm and stem fragments are by far the most abundant and comprise up to 80 percent of certain

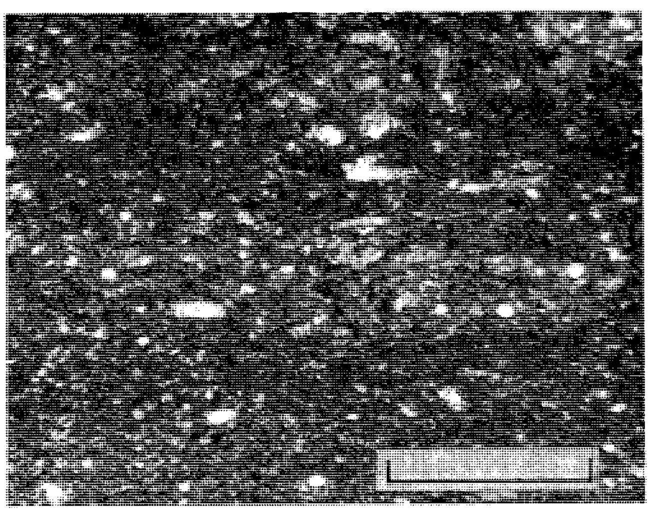


FIGURE 10.—Photomicrograph (crossed nicols) of fine-grained wackestone subfacies. Scale is 500μ.

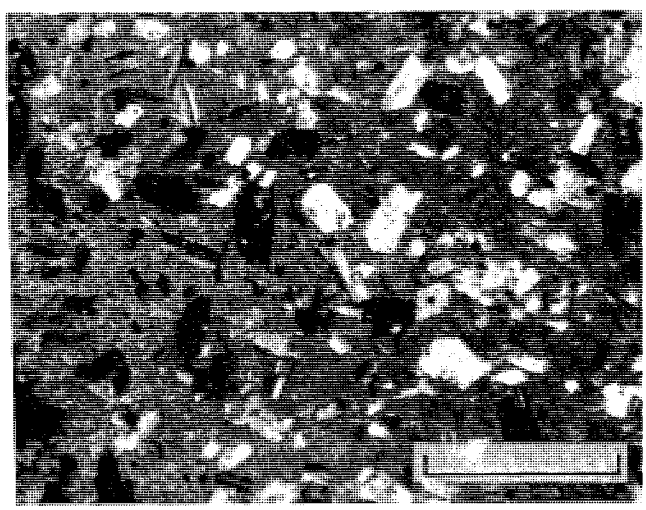


FIGURE 12.—Photomicrograph (crossed nicols) of authigenic feldspar in mudstone. Scale is 500μ.

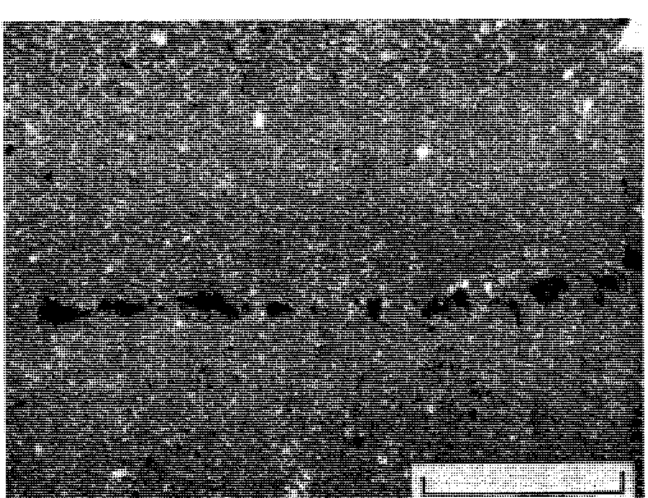


FIGURE 11.—Photomicrograph (crossed nicols) of burrowing trail marked by authigenic iron oxide. Scale is 500μ.

FIGURE 13.—Photomicrograph (crossed nicols) of skeletal wackestone-packstone facies. Scale is 500μ.

packstones; brachiopods are also occasionally concentrated. Fragments usually lack any orientation, but some units, especially those high in brachiopod fragments, show alignment of elongate grains parallel to bedding. Size sorting of bioclasts ranges from fair to poor, with wackestone generally exhibiting better sorting than packstone. Detrital quartz sand is often a secondary constituent, with skeletal material, and sometimes reaches as high as 30 percent; grain size is similar to that found in the calcareous sandstone to sandy limestone facies. An interesting phenomenon observed is that when quartz detritus is abundant, brachiopod fragments are minimal or nonexistent. Pellets, which are present in small quantities, are most abundant in sediments also high in skeletal detritus. Some intraclasts contain secondary euhedral quartz, primary quartz detritus, and skeletal fragments (fig. 15). There are at least three distinct stages of diagenesis that can be clearly recognized in this facies, but a definite order is not clear. The three stages were: (1) silicification of 20 to 50 percent of the fossil fragments (especially the brachiopods) and some matrix material; (2) microsparitization of much of the micrite, with partial invasion of the microspar into detrital quartz grains and silicified skeletal fragments; and (3) formation of abundant authigenic iron oxide pseudomorphs after pyrite, with iron probably originally coming from iron monosulfides deposited with the sediment. The formation of low-amplitude stylolites (fig. 16) appears to be an early occurrence, with the stylolites later acting as conduits for movement of solutions commonly causing recrystallization of much of the surrounding rock (fig. 17). Figure 18 shows distinctly the first two stages of diagenesis where the fossil has been replaced by chalcedony and later invaded by two euhedral calcite rhombs. Figure 19 also shows stages 1 and 2 in this replaced brachiopod shell. Authigenic albite feldspar crystals are abundant in many of the units comprising this facies (fig. 20) and are found replacing both skeletal fragments and matrix. Bryozoans seem to be the most common and saturated host when replaced, but all fossil types present show some feldspar replacement. Intraclasts, which could have possibly been derived from sediments deposited in an environment

FIGURE 14.—Photomicrograph (crossed nicols) of primary spar cement in skeletal wackestone. Scale is 500μ.

FIGURE 16.—Photomicrograph (crossed nicols) of low-amplitude stylolite. Scale is 500μ.

FIGURE 15.—Photomicrograph (crossed nicols) of intraclasts containing skeletal fragments and quartz detritus. Scale is 500μ.

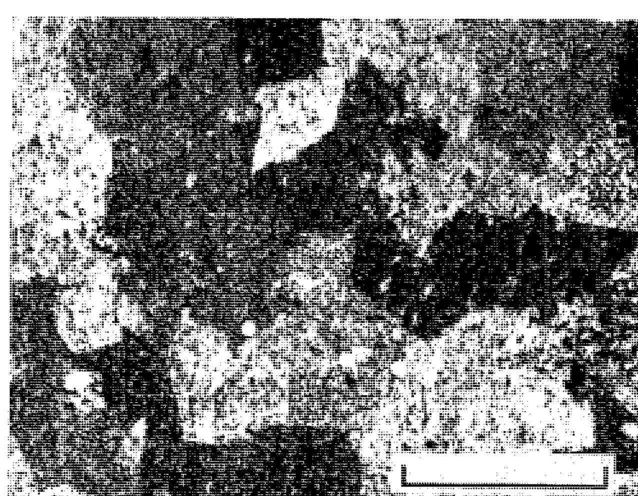


FIGURE 17.—Photomicrograph (crossed nicols) of recrystallized limestone closely associated with stylolitization. Scale is 205μ.

favorable to the formation of these low-temperature feldspars, are found in this facies containing 20 to 30 percent feldspar (fig. 21). Formation of euhedral authigenic quartz is also closely associated with the occurrence of authigenic feldspar in these rocks (fig. 22). It is difficult to determine the exact time of formation of the authigenic feldspar, but a relatively early formation before lithification seems likely because almost all crystals contain inclusions of micrite mud, and concentrations of these crystals often occur in burrowing trails.

Pelletal to Oolitic Limestone Facies

This sedimentary facies contains five units comprising 13.4 m, or 4 percent of the member, and is characterized by the presence of dark algal pellets, superficially coated grains, and oolites (fig. 23). Grains of this type make up from 10 to 40 percent of the rock, but are not necessarily the dominant rock builders, with skeletal fragments reaching as high as 30 percent and much of the facies containing from 5 to 10 percent detrital quartz. Algal pellets range from 2 mm to less than 100μ and are never recrystallized but do have occasional authigenic feldspar present. Within ooid-rich portions of this facies, well-sorted grains of both true oolites and coated grains occur with nuclei coated by one to several algal envelopes. Constituents forming nuclei are skeletal detritus, including whole foraminifera (*Plectogyra*?, fig. 24), and some detrital quartz. These rock-forming constituents rest in a matrix of microcrystalline calcite to micrite. The fact that detrital constituents in this facies occur in various ratios, either as nuclei for coated grains and oolites or with no algal envelope coating, indicates that interfingering of an oolite-generating environment with a skeletal environment is present. Thus within this facies most of the oolites and coated grains were deposited, not in an oolite-generating zone, but in an interfingering area where oolitic, detrital, and algal constitutents were produced and accumulated.

DEPOSITIONAL ENVIRONMENTS

The development of a working model to explain the origin of sediments from the Bridal Veil Limestone Member of the

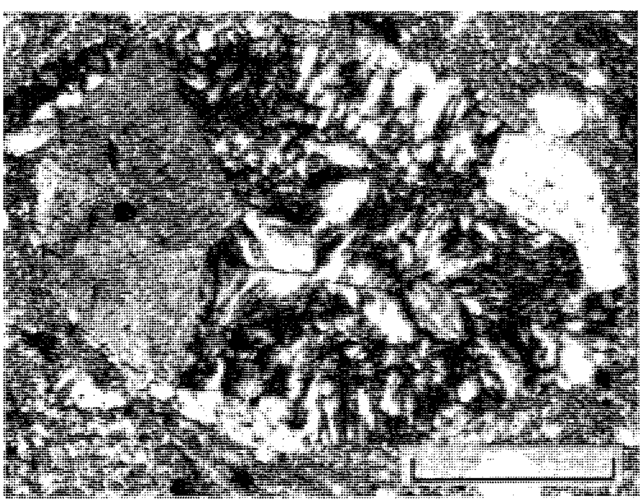


FIGURE 18.—Photomicrograph (crossed nicols) of fossil replaced by chalcedony and later invaded on left by euhedral calcite. Scale is 205μ.

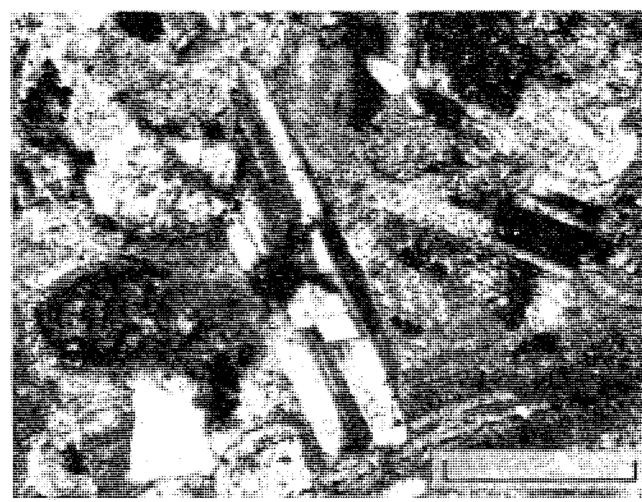


FIGURE 20.—Photomicrograph (crossed nicols) of authigenic feldspar in skeletal wackestone. Scale is 205μ.

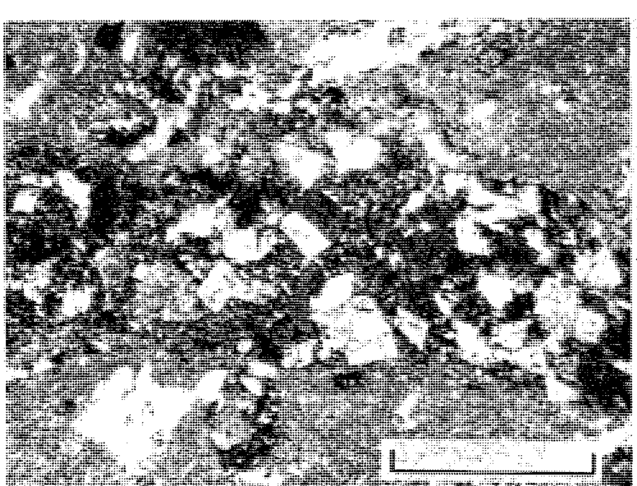


FIGURE 19.—Photomicrograph (crossed nicols) showing two stages of replacement: (1) silicification of fossil and (2) partial replacement by euhedral calcite. Scale is 500μ.

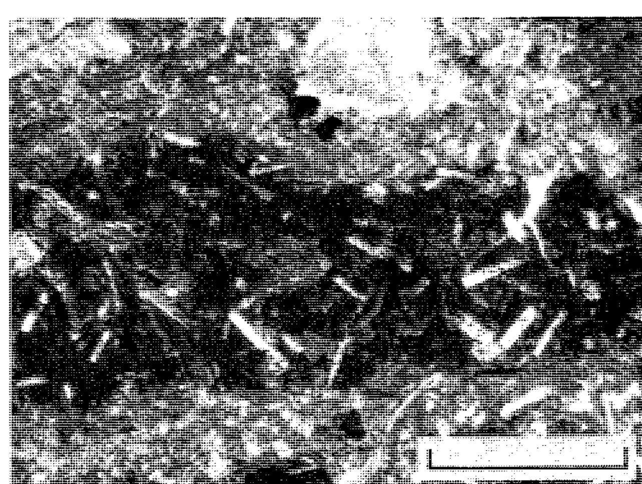


FIGURE 21.—Photomicrograph (crossed nicols) of interclast containing abundant authigenic feldspar. Scale is 500μ.

Oquirrh Formation at Cascade Mountain requires study and a review of present understanding of carbonate depositional environments including specific models proposed by other workers. In the last two decades, several studies of carbonate depositional environments or generalized environmental reconstructions and discussions have been published; those consulted in this study include (1) Heckel (1972), who described recognition of ancient shallow marine environments; (2) Wilson (1974, 1975), who discussed characteristics of carbonate-platform margins; (3) Irwin (1965), who proposed a general theory of epeiric sea sedimentation; (4) Shaw (1964), who also proposed a general theory of epeiric marine facies relations; (5) Purdy and Imbrie (1964), who described recent carbonate sediments in the Grand Bahama Bank; (6) Rees, Brady, and Rowell (1976), who proposed a model for an Upper Cambrian carbonate environment in west central Utah; (7) Jehn and Young (1976), who studied Mississippian deposition of the Pitkin Formation in northern Arkansas; (8) Mazzullo, Agostino, Seitz, and Fisher (1978), who described the stratigraphy and proposed a depositional environment for an Upper Cambrian–Lower Ordovician sequence in eastern New York; (9) Rose (1976), who discussed Mississippian carbonate shelf margins of the western United States; (10) Lindsay (1977), who studied Mississippian deposition of the Great Blue Formation in northern Utah, and (11) Bathurst (1975), who described recent carbonate environments of the Great Bahama Bank, Gulf of Batabano, Persian Gulf, British Honduras, and Florida.

In Lower Pennsylvanian time, Bridal Veil Limestone Member of the Oquirrh Formation was deposited in oscillating epeiric seas on a broad carbonate shelf margin in the eastern part of the Cordilleran miogeosyncline. At Cascade Mountain, interfingering depositional facies of a carbonate shelf margin are recorded in this Pennsylvanian rock sequence. Conditions of sedimentation in this environment resemble those which prevail in a broad shallow lagoon, with the virtual isolation of waters from the open ocean partly because of its shallowness and partly because of restriction caused by a fringing shoal of bioherms or knoll reef platforms (Wilson 1974) composed predominantly of crinoids, bryozoans, and algae.

In his work with shallow-marine sedimentation, Irwin (1965) recognized, covering broad areas within epeiric seas, three energy zones which he named X, Y, and Z. Zone X formed in deep-marine waters where waves did not affect the sea floor—essentially the starved part of the basin characterized by little sediment accumulation. Zone Y begins where water depths permit wave energy to reach the bottom. In this zone, sediments are disturbed as friction from wave energy is dissipated on the bottom. The end of zone Y is where wave action is minimal or absent. High amounts of energy in zone Y commonly produce ooids, particularly where upwelling occurs. Animal life is normally abundant with the formation of reefs on the cratonward side. Zone Z is formed between the high-energy zone Y and the strandline. Less circulation is present here because of loss of wave action, but local currents, storms, tidal changes, waves generated by local winds, and energy from the influx of fresh water of inflowing streams still affect this zone somewhat. At the strandline evaporites and dolomite often develop owing to the high rates of evaporation, but, as Irwin points out (p. 452), "If the climate is sufficiently humid and enough fresh water is added to the sea, dolomite and evaporate facies may not develop at all," allowing bioclastic carbonate and algal carbonate mud to grade shoreward into interfingering terrigenous clastics brought in by the inflowing streams. Seaward size of zone Z interfingers with zone Y to

FIGURE 22.—Photomicrograph (crossed nicols) with arrow pointing to authigenic quartz crystal. Scale is 205μ.

FIGURE 23.—Photomicrograph (crossed nicols) of pelletal to oolitic limestone facies. Scale is 500μ.

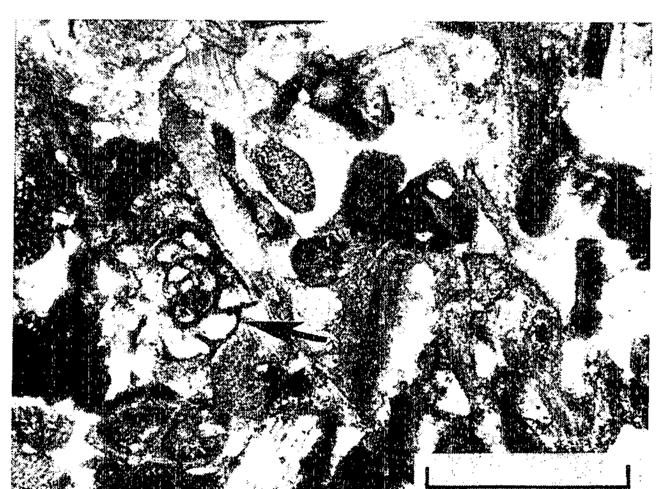


FIGURE 24.—Photomicrograph (crossed nicols) with arrow pointing to *Plectogyra* ? foraminifera. Scale is 500μ.

produce reefs or shoals with tidal inlets scattering skeletal debris back into zone Z. Lagoonal conditions form between the shoal environment and the area of clastic influx. As these zones migrated back and forth because of slight fluctuations in water depth or subsidence rates, they interfingered various parts of the rock-forming environments to produce an interbedded depositional complex of several smaller environments. Zone Z and minor occurrences of zone Y are recognized at Rock Canyon section of Cascade Mountain. As a result of detailed thin-section analysis, field investigations, and review of the literature, the following depositional model for this particular part of the limestone depositional complex of the lower Oquirrh Formation is herein proposed (fig. 25).

Depositional environment in which the Bridal Veil Limestone Member of the Oquirrh Formation at Cascade Mountain was deposited is interpreted to be the product of five shifting depositional zones within zones Y and Z of Irwin (1965). Specific characteristics of each zone together with interrelationships with other zones in the depositional environment will be discussed.

Zone 1

Zone 1 is situated closest to the paleostrandline, but could have extended a considerable distance seaward as is interpreted to be the case in sediments of this section. Terrigenous clastic influx of only fine-to-very-fine-grained sediment dominates this zone. Sands were commonly received in surges spreading clastic tongues well into the depocenter, forming broad lenses up to 5.4 m thick. These periodic influxes of clastics possibly occurred in response to minor epeirogeny in positive areas adjacent to the basin. Sand grains are also scattered throughout the section as minor rock-building constituents in limestone deposited in other zones in this shelf environment. These randomly dispersed sands were probably transported by local currents and storms that distributed them throughout the depocenter. This zone was well oxygenated but not very hospitable to marine life, possibly due in part to a shifting substrate evidenced by the presence of ripple marks and low-amplitude cross-bedding; some units exhibit abundant bioturbation, however. In thin-bedded sandstone and siltstone units, mud cracks occasionally occur, indicating that areas of this zone could have at times been exposed at low tide.

Zone 2

In Zone 2, fine sediments forming mudstone, calcareous shale, and fine-grained wackestone accumulated in the broad, quiet parts of the marine lagoon behind higher energy environments, characterized by larger allochemical and detrital grains. Water depth was probably as much as a few tens of meters. This was an area of deposition of carbonate mud in which waters were not turbulent, and cool seawater was occasionally swept to be warmed, to be evaporated to an extent, and to come in contact with algae and bacteria. These agencies all remove dissolved carbon dioxide from the water, thereby increasing pH (Irwin 1965), providing for the abundant amount of calcium carbonate that was precipitated. Salinities in the restricted lagoon probably varied from essentially normal marine to possibly quite high. Small patches and lenses of clastics commonly occur with sediments deposited here, showing interfingering with zone 1. Rare occurrences of stromatolites developed in zone 2, being associated with the interfingering clastics where they were affected by intermittent currents. Indigenous faunas are limited to moderately abundant occurrences of brachiopods together with moderate numbers of crinoids in some calcareous shale units. Burrowing traces, however, are numerous and show no one predominant grazing path orientation, with tracks in horizontal, vertical, and oblique directions. Occasional units of zone 2 sediments contain abundant intraclasts of micrite, suggesting turbulence caused possibly by storms or intermittent currents which ripped up the substrate and introduced allochems and clastics from other zones. Iron is disseminated in much of the micrite mud deposited in this zone and is probably iron monosulfide. Because of reducing conditions which probably existed in this quiet lagoonal environment, much of the disseminated iron formed pyrite cubes and pyrithodrons which have later been oxidized forming pseudomorphs. Authigenic feldspar reaches its greatest abundance in this zone with isolated areas rising as high as 30 percent feldspar.

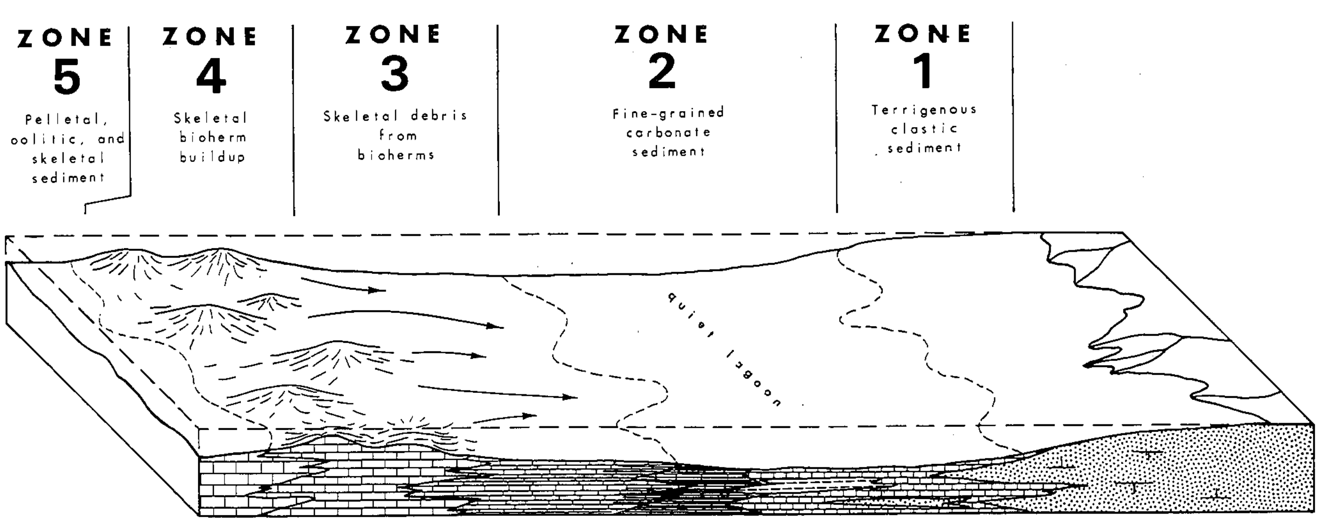


FIGURE 25.–Depositional model for Bridal Veil Limestone Member of the Oquirrh Formation at Rock Canyon section of Cascade Mountain, with proposed depositional zones 1–5.

Zone 3

Zone 3 is characterized by limestone deposited in shallow, mostly quiet, marine waters behind a restricting shoal of bioherms. Skeletal detritus, intraclasts, pellets, and some quartz sand are the dominant grains in a matrix of micrite to microspar. Abundant bioclasts of crinoids, brachiopods, and bryozoans are present and are derived mostly from biohermal communities. Because these grains have likely been transported predominantly by currents caused by energy not dissipated by the bioherm shoal, skeletal fragments are commonly worn and have lost much of their original robust character. The variety of crinoids, bryozoans, and brachiopods present suggests that deposition in these moderately well-circulated marine waters had a maximum water depth of probably only a few meters, but abundance of carbonate mud indicates predominantly low-energy conditions. Infrequent occurrences of intraclasts and quartz sand detritus are most likely deposits formed during short periods of high turbulence from storms. Skeletal fragments probably become progressively finer textured shoreward from the bioherm source, grading into the fine-grained wackestone of zone 2. Iron and authigenic feldspar are common with feldspar-replacing fossils and some dark intraclasts extensive.

Zone 4

Zone 4 is a shoal environment of bioherms forming at outer edges of the shelf margin and protecting the lagoon by absorbing probably limited wave action. Areal extent of bioherm development must have been extensive judging from the size and abundance of crinoids and bryozoans in the sediments, but intrabioherm material is volumetrically much greater than patches of boundstone framework. Most debris is skeletal and was derived from breakdown of organisms growing prolifically atop bioherms. Wave or current action was sufficiently great to remove only the finest debris. Skeletal bioherm talus appears to have undergone little transport; yet this is a death assemblage, not a life assemblage. Material was probably well protected from strong currents by the bioherms. Debris from bioherms often fell into waters with currents vigorous enough to wash out most fines, but not strong enough to carry away large fragments. Lack of any massive reef-building organisms in Bridal Veil Limestone is probably due to the absence of strong waves and currents and is one of its most distinguishing characteristics as a carbonate unit. Rugose and tabulate corals that are usually abundant in sediments of this type from the Paleozoic, where they often form reefs, are absent or extremely rare in this member. In several beds of this zone, sediments contain abundant amounts of crinoid material, enough to be indicative of a crinoid garden present, possibly near the backslope of bioherms.

Zone 5

Zone 5 is an environment closely associated with the bioherm shoal on its seaward side and is the only zone located in Irwin's (1965) zone Y. There is a relative scarcity of zone-5 sediments in the section which, together with the lack of abundant oolites and other coated grains and the fact that many of the grains lack coatings or sign of a turbulent environment, indicates that zone 5 was not one of abundant energy or even constant energy from waves and currents. This could have been caused by a very low slope or because the zone does not represent the actual ooid-generating environment which was located farther basinward. Scattered algal mats possibly existed in zone 5 because there are numerous rounded, dark algal pellets in sediments that were possibly derived from turbulent conditions over the mat surface.

Through the complete Rock Canyon section, units of Bridal Veil Limestone show sharp contacts between rock types, reflecting relatively quick changes in sea level and other fluctuations abruptly shifting zones within the depositional model. Limestone beds, which are abruptly overlain by sandstone units, may be indicative of small-scale hiatus development between two rock units (Dunbar and Rogers 1957).

Chert was found to be common in much of the sediment proposed here to have been deposited in the quiet lagoon environment. The chert is found mainly as nodular, bedded, or randomly scattered masses. Its presence, with the fact that extensive silica replacement of skeletal fragments has occurred, indicates that high concentrations of silica entered the depocenter. Abundance in certain parts of the section indicates much of the influx was rather sporadic. Possible sources of the chert include rivers draining the craton bringing enrichments of silica into the shallow-marine environment (Bien, Contois, and Thomas 1959) or siliceous material produced from volcanism in the Antler orogenic belt to the west (Bissell 1959c). In these same sediments iron oxide pseudomorphs after pyrite are abundant, especially along burrowing trails. Many of the mudstones show a yellowish-brown iron staining in thin section. The presence of the iron indicates a reducing condition in the restricted waters of the lagoon (Brener 1963, 1964, 1970).

Authigenic, low pressure and temperature feldspar is a relatively unique constituent of the Bridal Veil Limestone and is found in sediments from zones 2 and 3 of the quiet lagoon environment. With the use of extinction angles and refractive index, it was determined that feldspar was albite in composition which is very common in other reported occurrences of authigenic feldspars in limestone. The facts that feldspars replace fossils extensively (fig. 26) and that crystalline outlines have straight edges (fig. 27) and sharp corners (fig. 28) indicate growth in place. Formation of albite was probably an early diagenetic process in unconsolidated sediment where intercommunication with the original environment was still possible (Daly 1917, Tester and Atwater 1934, Degens 1965). It has been tentatively suggested that the authigenic feldspar formation results from a situation where a carbonate-water solution existed with alkalinity sufficiently high to stabilize feldspar at low temperatures. High salinity environments also seem to

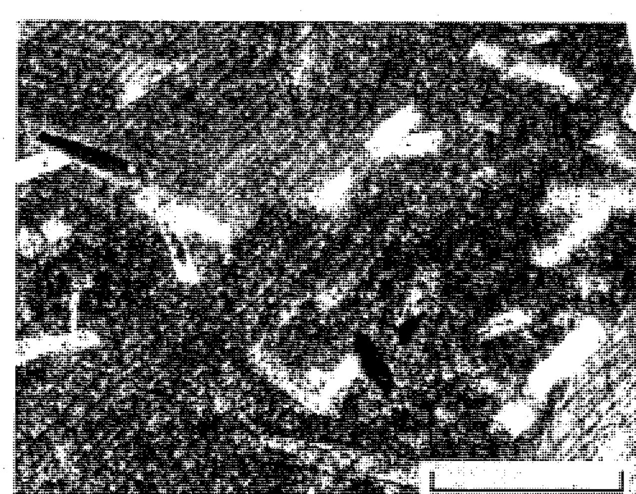


FIGURE 26.—Photomicrograph (crossed nicols) of authigenic feldspar partially replacing fossil fragment. Scale is 205μ.

favor the authigenesis of feldspar (Degens 1965). Indications are that the restricted lagoon was a highly saline and alkaline environment at times.

CONCLUSION

Bridal Veil Limestone Member of the Oquirrh Formation at Rock Canyon of Cascade Mountain is herein interpreted as having formed in a shallow-marine environment typified by epineritic conditions. Presence of crinoids, brachiopods, bryozoans, foraminifera, and stromatolites indicates warm water with some gentle agitation and at times vigorous turbulence acting on terrigenous, detrital, bioclastic, and precipitated sediment. The environment is characterized by four facies composed of several subfacies. The major sedimentary facies include: (1) calcareous sandstone-sandy limestone facies; (2) mudstone-fine-grained wackestone facies; (3) skeletal wackestone-packstone facies; and (4) pelletal to oolitic limestone facies. These facies accumulated in an environment which can be divided into five depositional zones: (1) an area of terrigenous clastic influx; (2) a broad, quiet lagoonal zone marked by deposition of fine carbonate sediments; (3) an area of skeletal detritus scattered behind a bioherm shoal; (4) a fringing belt of bioherms with abundant intrabiohermal skeletal detritus; and (5) interfingering oolite, coated-grain, and algal-pellet-producing marine waters seaward of the bioherms. Facies patterns experienced shifts within the five zones in an oscillating depositional pattern within an unstable portion of the eastern part of the Cordilleran miogeosyncline, as shown by the abundant interfingering of varied rock types in the section.

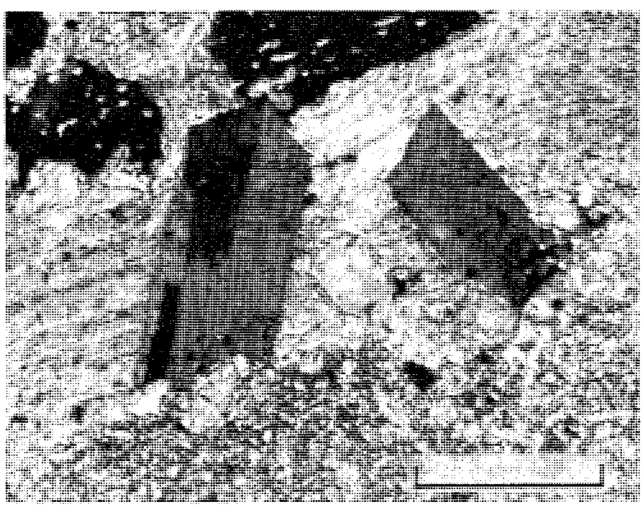


FIGURE 27.—Photomicrograph (crossed nicols) of authigenic feldspar showing clean, straight, euhedral crystal edges. Scale is 81μ.

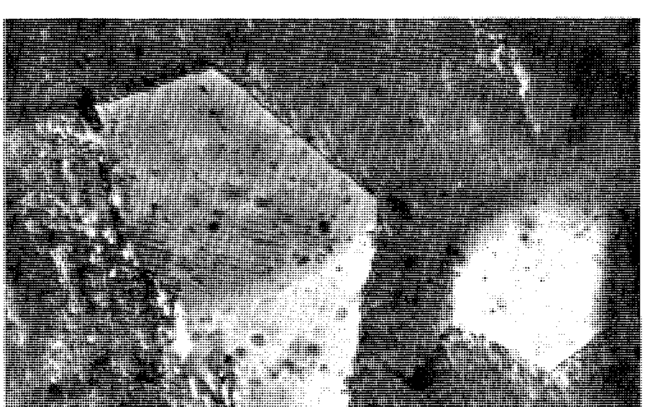


FIGURE 28.—Photomicrograph (crossed nicols) showing sharp euhedral form of twinned feldspar crystal. Scale is 32.5μ.

The appendix to this paper, manuscript pages 41–52, "Measured Rock Canyon Section of the Bridal Veil Limestone Member of the Oquirrh Formation, Second Left Fork, Rock Canyon, Utah," is on open file in the Geology Department, Brigham Young University, Provo, Utah 84602, where a Xerox copy may be obtained.

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