Cambrian and Ordovician Rocks of Southern Arizona and New Mexico and Westernmost Texas

GEOLOGICAL SURVEY PROFESSIONAL PAPER 873

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By PHILIP T. HAYES

assisted by GEORGE C. CONE

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A stratigraphic and petrologic study of lower Paleozoic rocks in the Mexican Highland physiographic section as a framework for evaluating their oil and gas possibilities

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CAMBRIAN AND ORDOVICIAN ROCKS OF SOUTHERN ARIZONA AND NEW MEXICO AND WESTERNMOST TEXAS

By PHILIP T. HAYES, assisted by GEORGE C. CONE

ABSTRACT

The area of study is defined by the Mexican-United States border on the south, roughly by lat 34° N. on the north, and roughly by long 105° and 112° W. on the east and west, respectively. This area is chiefly in the Mexican Highland section of the Basin and Range province but includes parts of adjoining physiographic subdivisions.

The study, which was designed to aid in the evaluation of the oil and gas possibilities of the region, involved much library research, the examination of 76 outcrop localities, the laboratory study of about 750 outcrop samples, and the examination of cuttings from a few oil exploration holes.

Cambrian and Ordovician rocks in the report region are included in two main depositional sequences that are separated by a regional unconformity: Cambrian and Lower Ordovician rocks of the Sauk sequence at the base and a Middle and Upper Ordovician sequence assigned to the Montoya Group above.

The rocks of the Sauk sequence result from deposition in and on the margins of a shallow shelf sea that transgressed across the region from the west and southwest. As a result, the base of the sequence is of probable early Middle Cambrian age at the west edge of the region and of early Early Ordovician age at the east edge. Post-Early Ordovician regional emergence and consequent erosion at the top of the Sauk sequence was greater in the west and north than in the east and south, with the result that rocks just beneath the upper unconformity are locally as old as late Middle Cambrian in the west and as young as late Early Ordovician in the southeast. The rocks of the Sauk sequence are locally more than 1,500 feet thick at several localities near the south edge of the region, and they thin to a wedge edge at the north.

In most of southern Arizona the rocks of the Sauk sequence are included in the Bolsa Quartzite of Middle Cambrian age and the overlying Abrigo Formation. The Abrigo is divided into a lower member of Middle Cambrian age and three members of Late Cambrian age—the middle, upper sandy, and Copper Queen Members. All the members of the Abrigo are increasingly sandy toward the north and east.

Progressing east-northeastward the Bolsa Quartzite thins to a depositional wedge edge by onlap, and the lower three members of the Abrigo Formation grade into the Coronado Sandstone of easternmost Arizona and westernmost New Mexico. In that area, rocks equivalent to the Copper Queen Member of the Abrigo are assigned to an informal lower member of the El Paso Limestone which overlies the Coronado Sandstone. Above the somewhat sandy lower member of the El Paso in that area is a nonsandy upper member of Early Ordovician age. Farther eastward the Coronado Sandstone thins by onlap, and the upper part of the Coronado and lower member of the El Paso Limestone grade into the Bliss Sandstone.

In most of southern New Mexico and western Texas the rocks of the Sauk sequence are assigned to the Bliss Sandstone and the overlying El Paso Group which is made up, in ascending order, of the Hitt Canyon Formation, McKelligon Limestone, and Padre Formation. Both the base and the top of the Bliss are younger eastward. Whereas the Bliss is probably entirely of Late Cambrian age in far western New Mexico, it is entirely of Early Ordovician age in the eastern part of the report region. All formations of the El Paso Group are made up dominantly of carbonate rocks which become increasingly sandy eastward.

The Montoya Group of Middle and Late Ordovician age disconformably overlies Lower Ordovician rocks in much of western Texas and southern New Mexico but only barely extends into Arizona; the rocks of the group are limited by erosional wedge edges on the north and west. The maximum thickness of the group is slightly more than 500 feet. Throughout the region the group is divided in ascending order into the Second Value Dolomite, the Aleman Formation, and the Cutter Dolomite. In much of the region the Second Value Dolomite is divided into the Cable Canyon Sandstone Member and the overlying Upham Dolomite Member, but the Cable Canyon is missing in some large areas.

Our stratigraphic and petrologic studies indicate that, although the Cambrian and Ordovician rocks of the region cannot be regarded as having a high potential as oil- or gas-bearing rocks, possibilities for petroleum reservoirs do exist. The Abrigo Formation could contain petroleum reservoirs in southernmost Arizona, and rocks of the El Paso and Montoya Groups could contain reservoirs wherever they occur. Perhaps the most favorable exploration target would be porous rock at the top of the El Paso Group in areas where it is unconformably overlain by shale-bearing Devonian beds.

INTRODUCTION

PURPOSE OF STUDY

As the nation's reserves of oil and gas diminish and the demand for petroleum products increases, the search for new reserves must extend into areas that have heretofore been considered to have only marginal potential. It is the purpose of this study to evaluate the possibilities for oil and gas production from lower Paleozoic rocks in one of these marginal areas, the Mexican Highland section of southern Arizona and New Mexico and westernmost Texas, and to provide sufficient data on the rocks for others to make their own evaluations or to stimulate further study. In addition, knowledge of the paleotectonic framework established in early Paleozoic time should provide a firmer basis to begin similar studies on younger rocks in the region.

The area studied (fig. 1) is bounded on the south by the Mexican border, on the east roughly by the 105th meridian west of Greenwich, on the west roughly by the 112th meridian, and on the north roughly by the 34th parallel north. These boundaries were chosen because lower Paleozoic rocks east of the study area are relatively well known from drill-hole data; lower Paleozoic rocks are absent over most of the area immediately north of the study area; and outcrops and drill-hole penetrations of Paleozoic rocks west of the study area are extremely sparse.

REGIONAL SETTING

PHYSIOGRAPHY

Most of the area covered by this report is a part of the Mexican Highland section of the Basin and Range physiographic province, but the area also includes a part of the Sonoran Desert section on the west, the Sacramento section on the east, and the southern margin of the Colorado Plateaus province on the north (fig. 1). The Mexican

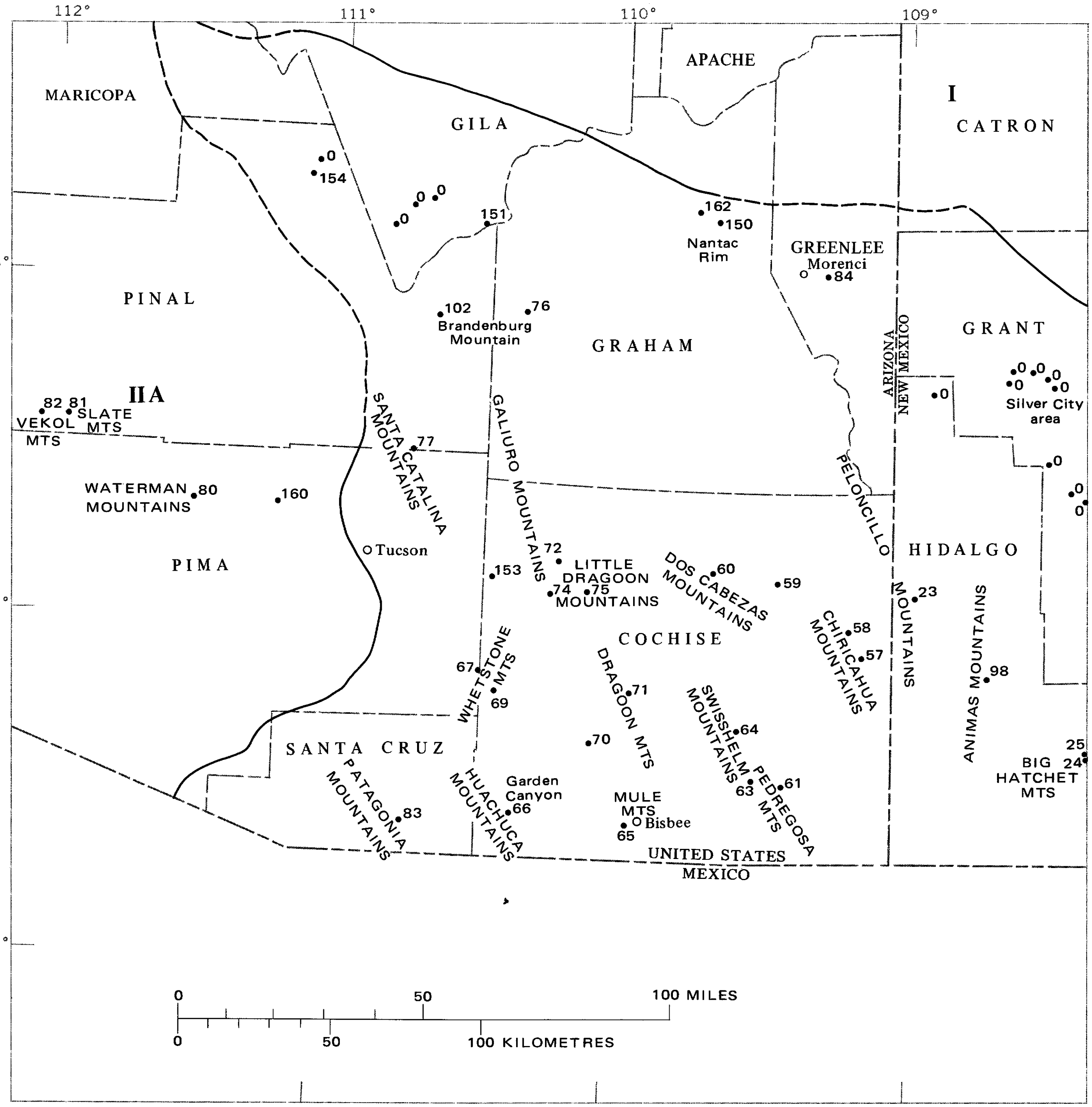
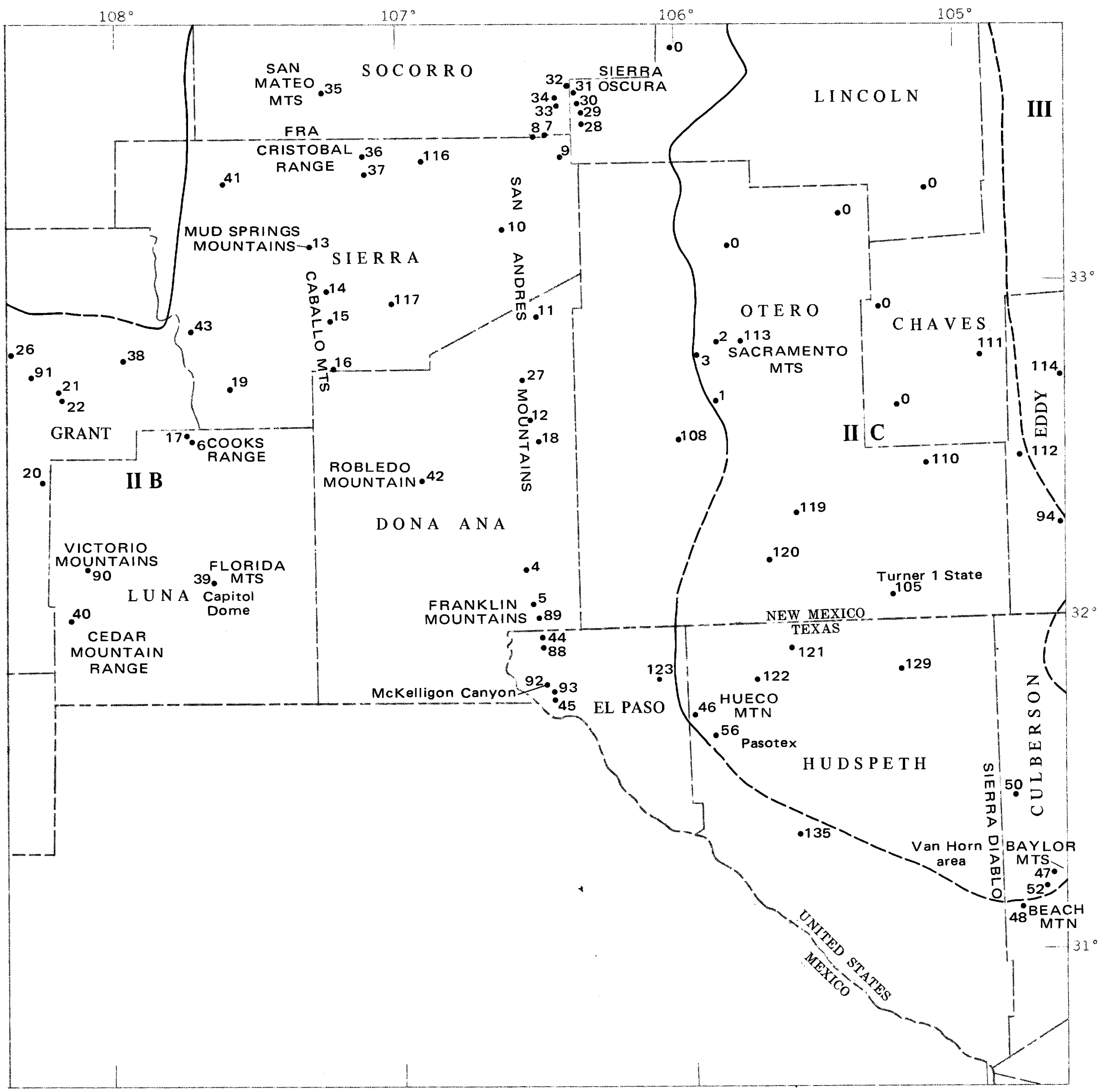


FIGURE 1.—Index map of the report region, showing county names, boundaries of physiographic subdivisions (dashed where approximate), province; IIB, Mexican Highland section of Basin and Range province; IIC,

Highland section is characterized by generally north trending upfaulted mountain ranges separated by broad intermontane basins which have been filled to varying degrees by alluvial debris from the ranges. The Sonoran Desert section is similar but is lower in overall altitude, the ranges are narrower, and the intermontane basins broader in proportion. The Sacramento section is characterized by broad moderately dissected ranges underlain by generally gently eastward-dipping rocks. The part of the Colorado Plateaus province included in the report area is dissected plateau country in which Paleozoic rocks are covered by Cenozoic volcanic rocks.

STRUCTURAL GEOLOGY

Local geologic structure in the Basin and Range province becomes increasingly complex from east to west



and localities (control points, table 1) referred to in the text. I, Colorado Plateaus province; IIA, Sonoran Desert section of Basin and Range Sacramento section of Basin and Range province; III, Great Plains province.

across the report area. In the Sacramento section the rocks for the most part are gently dipping and are interrupted only by gentle folds and high-angle normal faults of moderate displacement. Normal faults of larger displacement, more steeply dipping beds, and minor thrust faults are characteristic of the eastern part of the Mexican Highland section, but most individual ranges (and presumably the intervening basins) are relatively simple structurally as compared with those farther west. For the most part, local structure is complex in the western part of the Mexican Highland section, where there were repeated tectonic events throughout most of the Mesozoic and Cenozoic Eras. Structure in the Sonoran Desert section is not well understood but is complex also. Structure of the rocks underlying the thick volcanics of the southern margin of the Colorado Plateaus is unknown but may by simpler than that to the south.

Some workers (Muehlberger, 1965; Poole and others, 1967) have proposed that west-northwest- or northwest-trending right-lateral fault zones of up to 200 miles of displacement cross all or parts of the present report region in the Basin and Range province. Certainly there are important major structural lineations in the region that have such trends, such as the Texas lineament of western Texas (Albritton and Smith, 1965), but compelling evidence for large-scale wrench faulting has not been presented. Indeed, the distribution of Precambrian rocks in the region (fig. 3) and the isopach and facies maps prepared during this investigation seem to refute the existence of wrench faults with displacements of more than a few tens of miles at the most.

ROCKS

Rocks at the top of the crystalline basement are dominantly plutonic rocks of granitic to dioritic composition throughout the report region; but crystalline schists and gneisses are dominant over an extensive area in southeastern Arizona, and similar metamorphic rocks including quartzites are locally present throughout the region.

Sedimentary rocks with minor associated basalt that have been invaded by abundant diabase dikes and sills are present between the crystalline basement and the Paleozoic under an extensive area of Arizona. Similar Precambrian sedimentary rocks with locally associated rhyolite intervene between the basement and the Paleozoic in some areas in western Texas and eastern New Mexico. In most instances these Precambrian layered rocks display only slight angularity with the overlying Paleozoic.

The Paleozoic Era throughout the report region is represented by sedimentary rocks, dominantly carbonates, that were deposited in or on the margins of shallow shelf seas or, in the Pennsylvanian and Permian, in intracratonic basins.

Mesozoic rocks are very irregularly distributed in the region. Triassic and Jurassic rocks are missing over most of the region; however, there are some Triassic sedimentary rocks toward the north edge of the region in New Mexico, local but in places thick sequences of volcanic and epiclastic rocks of both Triassic and Jurassic age in southeastern Arizona, a few plutons of both Triassic and Jurassic age in the same area, and Jurassic carbonate rocks of marine origin along the Mexican border in western Texas. Lower Cretaceous strata of marine origin are widely distributed in western Texas and, with increasing proportions of nonmarine sediment, extend across southernmost western New Mexico and into southeastern Arizona. Upper Cretaceous strata partly of marine origin once covered most of the northern part of the region and are locally preserved. Nonmarine Upper Cretaceous beds are locally present in southeastern Arizona and extreme southwestern New Mexico. Volcanic rocks of latest Cretaceous age are present at many localities throughout the Arizona part of the region and in southwestern New Mexico. Plutonic rocks of latest Cretaceous age are fairly widely distributed in southeastern Arizona.

The character and distribution of Cenozoic rocks in the region are extremely variable. Cenozoic sedimentary rocks are entirely of continental origin and consist of debris shed from rising mountains; they are most abundant in the intermontane areas of the Mexican Highland and Sonoran Desert sections of the Basin and Range province. A wide diversity of Cenozoic volcanic rocks occurs throughout the region but are most abundant in the Colorado Plateaus province and most diverse in western parts of the Basin and Range. Both hypabyssal and plutonic igneous rocks of Cenozoic age are irregularly distributed throughout the region.

NATURE OF CAMBRIAN AND ORDOVICIAN OUTCROPS AND SUBSURFACE DATA

Cambrian and Ordovician rocks are at depth under much of the Sacramento section of the Basin and Range province, except where removed by later Paleozoic erosion; outcrops are limited to a few areas near the west and south margins of the section. Considerable information on the rocks, however, is available from exploratory drill-hole data.

Outcrops of Cambrian and Ordovician rocks occur in a large percentage of the mountain ranges of the Mexican Highland section, but drill-hole data for those rocks are sparse in the section, especially toward the west. In the eastern part of the section, outcrops are more extensive, are relatively free of internal structure, and are relatively free of hydrothermal alteration. Conversely, toward the western part of the section the outcropping rocks occur in shorter outcrop bands, are in many places severely faulted, and generally show the effects of mild to severe silicification, epidotization, and dolomitization.

In the Sonoran Desert section the rocks are even more

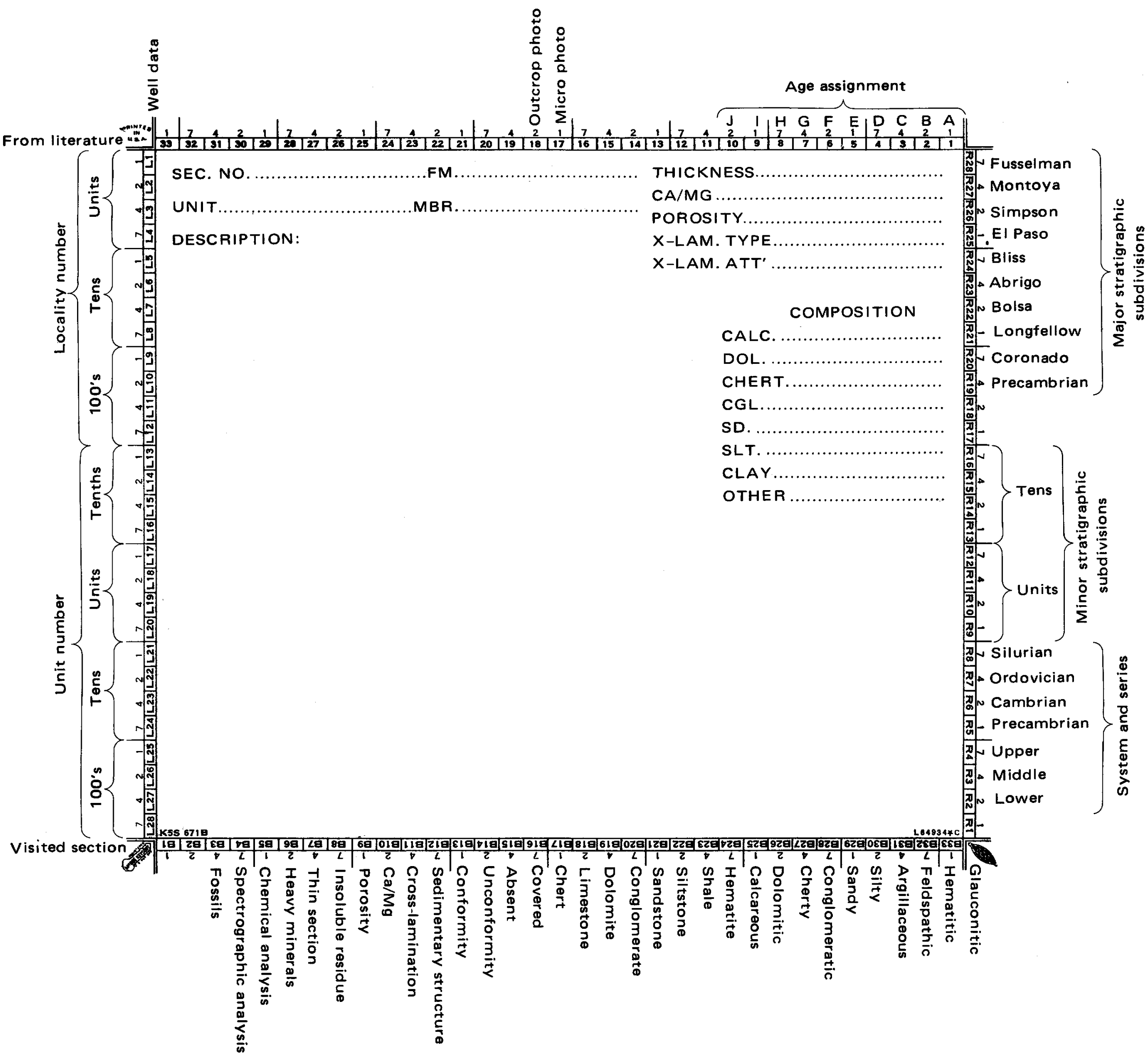


FIGURE 2.—The keysort card on which detailed information on rock units in stratigraphic sections was recorded.

severely faulted and altered, and outcrops are widely separated. No exploratory drill holes for oil and gas had been drilled at the time of writing (1973).

Cambrian and Ordovician rocks are not exposed in the part of the Colorado Plateaus province that lies in the report region, nor are there drill holes to provide information in that area. The nature and distribution of Cambrian and Ordovician rocks underlying that area, therefore, is entirely speculative.

PREVIOUS WORK

The following summary of previous work on Cambrian and Ordovician rocks in the report region will give some idea of the large foundation on which the present work is based. Without this foundation, it would not have been feasible to have undertaken the present study.

Rocks of Cambrian and (or) Ordovician age have been known to occur in the report region since the days of the early reconnaissance surveys of the West (Parry, 1857; Shumard, 1858; Jenney, 1874; Gilbert, 1875) but were not described in detail at any locality until the early years of the present century. Descriptions of these rocks and the concurrent naming of rock units by Richardson (1904, 1908) in the Franklin Mountains of extreme western Texas (fig. 1, loc. 45), by Ransome (1904) in the Mule Mountains of southern Arizona (fig. 1, loc. 65), and by Lindgren

(1905) in the Morenci area of eastern Arizona (fig. 1, loc. 84) established the basic nomenclature that, with modification, has been used throughout the region since.

Early papers reporting on the regional distribution of these rocks, largely based on the personal observations of the authors, were by Richardson (1908) for western Texas, Ransome (1917) for Arizona, and Darton (1917a) for New Mexico. Somewhat later regional papers that still were based largely on the authors' personal observations were by Darton (1928) for New Mexico, Darton (1925) and Stoyanow (1936) for Arizona, and Darton and King (1932) for western Texas.

Most important to the present study are numerous reports that have described the Cambrian and (or) Ordovician rocks in nearly all the outcrop areas in the region; some of these papers have speculated on regional correlations and depositional environments. Most of these reports are cited where appropriate within the body of this report.

A detailed regional stratigraphic paper by Cloud and Barnes (1946) on some Ordovician rocks in western Texas and an early attempt at broad-scale paleogeographic synthesis in Arizona by McKee (1951) set the stage for modern regional stratigraphic studies. Since then many regional syntheses have been made. Among the more significant of these are reports on Arizona by Epis and Gilbert (1957), McClymonds (1959b), and Krieger (1968e); on New Mexico by Flower (1959, 1969); on western Texas and southeastern New Mexico by Barnes and others (1959); and on western Texas by Jones (1953). Two excellent reports dealing strictly with Middle and Upper Ordovician rocks are by Howe (1959) and Pratt and Jones (1961).

The most authoritative reports to date on distribution, facies, and thickness of the subject rocks in southern New Mexico and adjacent areas are those by Kottlowski (1963, 1965). Similarly, the most authoritative papers on regional correlations and interpretations of depositional environments of Cambrian rocks throughout the region are those by Lochman-Balk (1970, 1971). Recent reports of interest on interpretations of depositional environments of Ordovician rocks in the region based largely on petrographic studies of carbonates are those by Lucia (1969, 1971) and Toomey (1970) and one by LeMone (1969) on the early phases of his detailed studies in the Franklin Mountains.

Generalized papers mentioning the oil and gas potential of Cambrian and Ordovician rocks in southwestern New Mexico and southeastern Arizona have been written by Kottlowski (1959), Wengerd (1962), and Greenwood (1969).

PRESENT WORK

INITIAL OFFICE WORK

The initial background library research for the project began in the summer of 1969. It quickly became apparent that some type of organized data storage and retrieval system would be required for the large amount of specific lithologic, paleontologic, and other sorts of information that were already available in the literature and that would become available as a result of our work. The system adopted centered on a numerical file system for general locality data and keysort punch cards for more specific detailed information.

Each locality for which lithologic data were already available, generally from a stratigraphic section or a drill hole, was assigned an arbitrary number, plotted on a 1:1,000,000 mylar index map, recorded on an individual page of a log book, and allotted a space in an expanding file. On the log-book page for each locality were recorded precise locality data, bibliographic reference data, and usually some general comments. The space in the expanding file accommodated copies of written or graphic sections or well logs, any other written material on the locality, and usually a copy of the part of any geologic or topographic map that included the locality.

The keysort cards chosen were 6½- by 7½-inch cards with a single row of punch holes around the perimeter. The cards were imprinted as needed by three rubber stamps that provided blank spaces for entering specific types of lithologic data for each unit in a measured section. The holes on the left side of the card were used for punching locality and unit numbers, the holes on the bottom left were used for punching specific types of data, the holes on the bottom right were used for lithic composition (this information proved to be of little value), the holes on the right were used for age and stratigraphic assignment, and the holes on the top were reserved for any use that we might later find desirable. (See figure 2.)

Before any fieldwork was undertaken, all the information that we could glean from the published literature, available theses, files of the U.S. Geological Survey, and drill-hole data available at the Denver offices of the U.S. Geological Survey was recorded on the master map, in the log book, and on the keysort cards. With this information alone, compilation of a report resembling the present one could have been made, but except in form, the report would have offered little that was not already fairly accessible for a large part of the report area. However, having all the available information in compiled form would enable us to approach the fieldwork more systematically and to systematically supplement or replace the data thus compiled as fieldwork and laboratory work progressed.

FIELDWORK

Upon visiting a stratigraphic section, our first course of action was to walk over it and determine the best route for measurement and observation. We then began to simultaneously measure, describe, and collect the section. For previously described sections (the majority), we checked

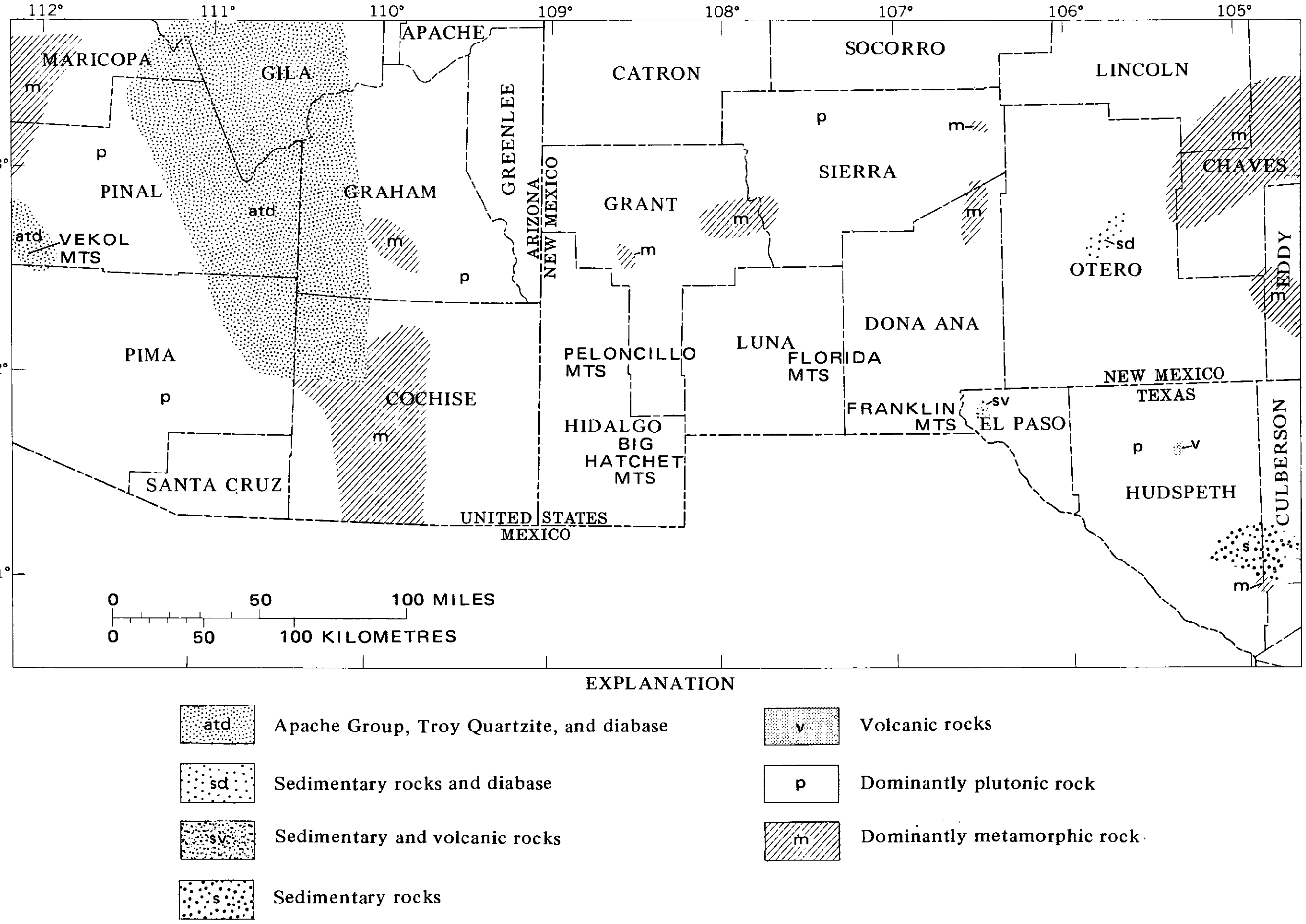


FIGURE 3.—Generalized map showing nature of rocks at the top of the Precambrian surface. Order of rock units does not necessarily reflect the relative ages of the rocks.

our measurements and observations against the published ones. If the measurements of the lower few units consistently agreed within 3 or 4 percent, we stopped measuring and concentrated on description and sampling. Some sections were entirely remeasured and redescribed, some were partially remeasured but entirely redescribed, some were only very slightly modified by our own additional observations, and all that we visited were sampled to greater or lesser extent. We omitted previously planned visits to several previously described sections after determining that we were in very close agreement with the measurements and descriptions of other sections described in the same report.

In all, 76 surface localities of Cambrian and (or) Ordovician rocks were visited in or near the project area during the course of the fieldwork; 13 of these were revisited one or more times. The fieldwork was done in the fall or 1969, the spring and fall of 1970, and the fall of 1971.

Wherever possible, sections were measured upward with clinometer and Jacob staff at right angle to the dip on steep front slopes. Measuring was only done on dip slopes if the beds could not be followed around a slope into a topographic saddle where upward measurement could resume. By being particularly careful to be accurate and consistent in our measurements we felt reasonably confident that significant differences in thickness of units measured by us in different sections were real. In several cases, at least, we were thus able to judge with some degree of confidence that previously reported thicknesses that seemed anomalously thick or thin for their locations were, in fact, probably in error or at least were measured by much different techniques than ours.

LABORATORY WORK

About 1,000 rock samples were collected in the field, and most of these were studied in one or several ways in the laboratory. Thin sections were made from three-fourths of the samples, calcite-dolomite ratios were determined for 190 carbonate samples, laboratory porosity tests were made on 183 samples, oxygen and carbon isotope analyses were made on 34 carbonate samples, and special elemental tests were made on 14 selected sandstone samples.

In addition, most samples were checked under ultraviolet light for oil stain.

All the thin sections were examined by me, and most of the sections of sandstone were point counted by Mr. Cone. Notes were made on carbonate petrography mainly by utilizing the carbonate rock terminology of Dunham (1962). In addition, notes were generally made on the nature of the porosity of the carbonates by utilizing the classification of Choquette and Pray (1970). Most of the sandstone point counts were made on only 200 points, which seemed adequate to determine a close approximation of the composition and porosity. The last several hundred thin sections prepared were first impregnated with a blue-dyed plastic that aided in spotting pore spaces during microscopic examination. This work was done by Melvin E. Johnson of the U.S. Geological Survey.

Calcite-dolomite ratios were determined on 96 carbonate samples by Robert F. Gantnier of the U.S. Geological Survey, utilizing a colorimetric titration technique. Thirty-seven of the same samples and an additional 94 samples were also analyzed for calcite and dolomite by Cone, utilizing X-ray diffraction methods.

At the outset, total porosity determinations were made of 99 samples by a wet kerosene displacement method described by the American Petroleum Institute (1960). Nineteen of the samples were run twice as a check. Later, we decided that effective porosities determined by the simpler Kobe mercury porosimeter, as described by the American Petroleum Institute (1960), would be more meaningful; and this method was then used on 93 samples. Of these, nine had previously been run by the kerosene displacement method. All the porosity determinations were made by Cone.

The oxygen and carbon isotope determinations and the various elemental tests were done by standard methods by various workers in U.S. Geological Survey laboratories. These workers and their results are cited, where appropriate, in the text.

Besides the rock samples collected and studied, numerous fossil collections were made; these were examined and reported upon by a dozen paleontologists.

In addition to the field samples studied, the cuttings from four oil test holes were examined under binocular microscope.

COMPILATION

Many data were accumulated during the investigation, but inclusion of all in this report was obviously impractical. Of the many stratigraphic sections we measured, generalized descriptions of only five that have not previously been described in the literature are included. Descriptions of 10 other sections, where our measurements or descriptions differ appreciably from previously published descriptions, are on open file (Hayes, 1975). Most other data that are not presented either in this report or in open file are stored in the U.S. Geological Survey acchives. General descriptions of all the localities used as control points and the information available on them appear in table 1.

ACKNOWLEDGMENTS

We particularly appreciate the help given us by Dr. David V. LeMone of the University of Texas at El Paso, who, as we were beginning the project, gave of his time in the field and office to introduce us to some of the Cambrian and Ordovician rocks and to some of the problems in their interpretation. We also greatly appreciate the help of Dr. Rousseau Flower of the New Mexico Bureau of Mines and Mineral Resources, who introduced us to the key Ordovician fossils both in his laboratory and in the field. Reuben J. Ross, Jr., and Michael E. Taylor of the U.S. Geological Survey on separate occasions each spent several days on the outcrop with us helping us make key fossil collections in Ordovician and Cambrian rocks, respectively. Medora H. Krieger of the U.S. Geological Survey spent 2 days in the field with us showing us details of a part of the section with which she was intimately familiar in Arizona. We are, of course, grateful to other geologists and students who, through discussion and the giving of unpublished information, helped us in our work.

Thanks are given to the Commanding Officer and security personnel of the White Sands Proving Ground, to officials of the San Andres National Wildlife Refuge, to officials of the Phelps Dodge Copper Co., and to the many ranchers and other property owners who allowed us access to important outcrops.

ROCK-STRATIGRAPHIC UNITS

PRECAMBRIAN ROCKS

CHARACTER AND DISTRIBUTION

Because the nature of the Precambrian rocks and the relief of the surface at the top of the Precambrian has had some effect on the character and distribution of some of the Lower Cambrian and Ordovician units, a brief résumé of the Precambrian of the region is presented here. Figure 3 is a highly generalized map showing the distribution of major rock types at the top of the Precambrian in the region.

The oldest Precambrian rocks known in the report region are diverse schists, gneisses, quartzites, and greenstones probably of late Precambrian X or early Precambrian Y age. An interim scheme for subdivision of Precambrian time recently adopted by the U.S. Geological Survey is as follows:

Precambrian Z — base of Cambrian to 800 m.y.

Precambrian Y — 800 m.y. to 1,600 m.y.
Precambrian X — 1,600 m.y. to 2,500 m.y.
Precambrian W — older than 2,500 m.y.

Rocks of definite late Precambrian X age are known to the northwest of the region in Arizona (Anderson and others, 1971); but as of this writing (1973) it is not certain, to my knowledge, whether rocks so old are present in the report region; all in the region may be of early Precambrian Y age. These schists and gneisses are the dominant rocks at the top of the Precambrian in a large area in southeastern Arizona, where they are referred to the Pinal Schist, and occur widely over the remainder of the region (fig. 3). In part of western Texas similar metamorphic rocks are referred to the Carrizo Mountain Formation (King, 1965). In most other areas they are unnamed.

The older metamorphic rocks were intruded by plutonic rocks ranging in composition from granite to gabbro (coarsely crystalline quartz monzonites and granites are the most abundant), and in most of the region these rocks are now much more widely distributed than are the older metamorphic rocks (fig. 3). Although these plutonic rocks are not all synchronous with one another (some being younger and some older than the rocks described below), they are probably all of Precambrian Y age.

Overlying the metamorphic and crystalline rocks in some areas are younger Precambrian Y sedimentary rocks (fig. 3). Some of these are of special interest here.

The thickest and most widely distributed Precambrian sedimentary rocks are in Arizona (fig. 3), where they are assigned to the Apache Group and to the unconformably overlying Troy Quartzite. These rocks, as described by Shride (1967), are shale, siltstone, conglomerate, arkose, quartzite, limestone, and some basalt. Wherever these Precambrian sedimentary rocks occur in southern Arizona they have been invaded by dikes and sills of Precambrian Y diabase. The Troy Quartzite at the top of the Precambrian in some places underlies the Cambrian with only slight angularity and is enough similar to basal Cambrian quartzite that it was formerly erroneously assigned to the Cambrian (Darton, 1925). The relations between the Troy and overlying Cambrian rocks and the distinctive lithologic features of each have been described by Krieger (1961).

Precambrian sedimentary rocks in extreme western Texas (fig. 3), as first described in detail by Harbour (1960), are generally similar to those of Arizona but have not been invaded as extensively by diabase; instead they were invaded by granite porphyry, covered by rhyolite, and invaded again by granite.

More extensive exposures of Precambrian sedimentary rocks and associated basic volcanics in Texas are preserved in the Sierra Diablo and have been described by King (1965).

Figure 3 shows two other small areas in the eastern part of the region, one in Otero County, N. Mex., and one in Hudspeth County, Tex., where virtually unmetamorphosed sedimentary or volcanic rocks lie at the top of the Precambrian.

Apparently only the relatively large area of Precambrian sedimentary rocks in Arizona had any significant effect on the character of the overlying basal Cambrian or Ordovician formation. And only in Arizona has there been any difficulty in distinguishing between the Precambrian and the Cambrian.

RELIEF AT THE TOP OF THE PRECAMBRIAN

Over a major part of the region the relief on the Precambrian surface at the onset of Paleozoic deposition was low, amounting to no more than a few tens of feet. Hundreds of feet of relief remained, however, at least near the boundary of Gila and Pinal Counties in Arizona (fig. 1), where Peterson (1969) and Krieger (1968a, b, c, d) have shown great variations in the thickness of basal Cambrian units due to onlap onto hills carved on the Precambrian surface. Similar relief is present in northwestern Cochise County, Ariz., according to Cooper and Silver (1964) and in the Vekol Mountains (loc. 82, fig. 1) according to Chaffee (1974).

Considerable relief must have remained in or near the Big Hatchet Mountains in southwestern New Mexico (locs. 24 and 25, fig. 1), where Zeller (1965) noted large boulders of granite in the abnormally thin and arkosic basal Cambrian formation. A similar local Precambrian high with several hundred feet of relief persisted in the Franklin Mountains of Texas (fig. 1) into Early Ordovician time, as described by Kottlowski, LeMone, and Foster (1969). Considerable relief is also evident on the west side of the Florida Mountains in New Mexico (loc. 39) and, according to Gillerman (1958), in the Peloncillo Mountains in New Mexico (vicinity of loc. 23).

CAMBRIAN AND LOWER ORDOVICIAN ROCK UNITS

The Cambrian and Lower Ordovician rocks of the report region belong to a single major sedimentary sequence, the Sauk sequence of Sloss, Krumbein, and Dapples (1949) and Sloss (1963). In the report region the entire sequence becomes progressively younger from west to east. The base becomes younger eastward and northward because the seas along whose margins the sequence was deposited presumably transgressed onto this part of the craton from the southwest. The top of the sequence is older westward and, to some extent, northward because of deeper subsequent erosion of the sequence in those directions. Within the report region the sequence is thickest at the south and thins irregularly northward (fig. 4) owing in part to depositional thinning and in part to erosional truncation. In general, the sequence is divided into two major parts, a dominantly sandstone part below and a predominantly carbonate part above. Because of changes in facies and terminology from west to east, the rocks of the sequence are described separately for western, central, and eastern areas as shown in figures 5 and 6.

WESTERN PART OF STUDY REGION

BOLSA QUARTZITE

NAME AND TYPE LOCALITY

The Bolsa Quartzite was named by Ransome (1904) for exposures in the Mule Mountains, Cochise County, Ariz., and the type section on Mount Martin (fig. 4 and loc. 65, fig. 1) was remeasured by Hayes and Landis (1965).

GENERAL DESCRIPTION

Throughout the region where the Bolsa is recognized as a distinct unit it is made up dominantly of rather dark weathering resistant siliceous orthoquartzite that decreases in average grain size and bedding thickness from base to top. At most localities it is feldspathic in the lower part and relatively free of feldspar in the upper part. The formation ranges in thickness from 0 to 700 feet.

DISTRIBUTION AND STRATIGRAPHIC LIMITS

The name Bolsa Quartzite is confined to a rock unit in the western area as outlined in figure 6. The term has been used for similar but dominantly younger rocks in much of the central area (fig. 6), but in an earlier report, I (Hayes, 1972) extended the term Coronado Sandstone to replace Bolsa Quartzite in that area.

The Bolsa unconformably overlies Precambrian rocks throughout its area of occurrence and is overlain conformably by the Abrigo Formation (fig. 5).

PETROLOGY

The Bolsa Quartzite is made up of about 90 percent to nearly 100 percent siliceous sandstone or quartzite; the remainder of the Bolsa consists of small amounts of conglomerate at or near the base and interbeds of siltstone and shale, primarily in the upper part. Most of the quartzites are fairly thickly bedded and resistant and support steep cliffs or ridges. Most outcrops are color banded in colors ranging from yellowish gray and pale red to moderate yellowish brown and dark reddish brown, grayish orange pink is the dominant weathered color, and grayish pink is the dominant color of fresh rock. Rock color names used throughout this report are those of the Rock Color Chart (Goddard and others, 1948).

Beds separated by distinct parting planes mostly range in thickness from 6 to 60 inches; the thickest beds are in the lower part of the formation, and the thinnest are in the upper part.

Most sandstones in the Bolsa are orthoquartzites with siliceous cement, but there are exceptions; nearly all are grain-supported arenites as classified by Dapples (1972). The following comments on the composition and texture of Bolsa sandstones are based on the field examination of the formation at 12 localities and the examination of 34 thin sections, of which 30 were point counted.

Quartz cementation is so advanced in most samples that the boundaries of original grains and the quartz overgrowths are obscure or invisible (fig. 7*A*, *B*, *C*). Not distinguishing between the quartz grains and overgrowths, the average quartz content of the 30 point-counted samples is 87.1 percent, and the median is 83 percent.

Feldspar content in the lower part of the formation seems to be controlled by the composition of the underlying Precambrian terrane, but underlying terrane differences had no apparent effect on the feldspar content of the upper part of the formation. Samples from the lower one-third of the Bolsa in areas where it overlies crystalline rocks have an average feldspar content of 10.5 percent and a median of 9 percent. (See fig. 7*A*.) Samples from the upper two-thirds of the formation, or from the entire formation in areas where the Bolsa overlies a sedimentary Precambrian terrane, have an average feldspar content of 2.2 percent and a median of 1.5 percent. Sericite and other clay minerals that may, in large part, be alteration products of feldspars are generally present in small amounts, and the percentage of these also tends to be higher in samples from the lower one-third of the Bolsa where it overlies crystalline rocks than in other samples: 4.1 percent as opposed to 2.3 percent.

Recognizable lithic fragments from older sedimentary or metamorphic rock (fig. 7*B*) are very minor in the Bolsa, and their percentages tend to decrease upward in the section. The average content of such fragments in the lower, middle, and upper thirds of the formation, respectively, are 0.5 percent, 0.2 percent, and 0.2 percent.

Glauconite is sparse in the Bolsa and was seen in only two samples, both from near the top of the formation.

Iron minerals, most commonly in the form of hematitic dust but also in the form of discrete grains of magnetite, are present in small amounts in nearly all samples. A few thin beds at nearly all localities, especially in the upper part of the formation, are cemented partially or almost entirely by hematite (fig. 7*D*).

Carbonate cement is uncommon in the Bolsa and where present usually makes up only a minor part of the cement. Most occurrences of carbonate cement are in the upper part of the formation. Only in the Vekol Mountains (loc. 82), the westernmost locality visited, does carbonate, mostly in the form of dolomite, make up as much as 10 percent of the rock; this content is in the top 84 feet of the formation. Possibly these beds should be assigned to the overlying Abrigo Formation.

Grain size has a pronounced tendency to decrease upward in the Bolsa and size sorting of grains improves markedly upward. About half the localities examined had as much as 4 feet of pebble conglomerate at the base, one had 2 feet of cobbly conglomerate at the base, and most of the remainder had granule conglomerate at the base. Cooper and Silver (1964) reported as much as 40 feet of conglomerate, with boulders at the base, in the Johnny Lyon Hills (near loc. 74). Very coarse and coarse-grained sandstones are usually dominant in the lower part of the formation, and fine to very fine grained sandstone is dominant near the top (fig. 7*D*). Thin layers of granule conglomerate or gritty sandstone layers are most abundant in the lower part of the formation, but at some localities they occur as high as two-thirds of the way up in the formation.

Thin interbeds of shaly siltstone, silty shale, and shale commonly occur in the Bolsa, especially in the upper part, and in some areas make up as much as 10 percent of the formation. They seem to be most abundant in southwestern Cochise County (locs. 65, 66, and 69). Locally, where the Bolsa overlies Precambrian diabase, there is considerable siltstone in the lower part of the Bolsa (Krieger, 1968e).

SEDIMENTARY STRUCTURES

Cross-laminations are the most conspicuous sedimentary structures seen in the Bolsa Quartzite; nearly all are small- and medium-scale planar cross-laminations as defined by McKee and Weir (1953). Most beds are cross-laminated throughout the thickness of the Bolsa at some localities, but at most localities, at least the upper one-third of the Bolsa displays mostly parallel laminations. Some beds with parallel lamination are found throughout the formation in all areas. No detailed measurements of the attitudes of cross-laminations were made in the present study, but we noted that most dip in a general westerly direction at most localities and that in some localities a wide variety of attitudes are evident. Seeland (1968), in a study of basal Paleozoic paleocurrent directions in much of the United States, measured the attitudes of many sets of cross-laminations in the Bolsa in the Huachuca Mountains near our locality 66. In that area most cross-laminations dip N. 70° W.

Fucoidal tracks or trails on bedding surfaces and *Scolithus* tubes are sometimes seen in the upper part of the Bolsa and are locally abundant, such as at French Joe Canyon (loc. 69) in the Whetstone Mountains. The *Scolithus* tubes, typically about 1 cm in diameter and 15–20 cm long, are seen only in sandstone beds, whereas tracks and trails are seen both on sandstone beds and on shale interbeds.

Polygonal mud cracks were observed on the bedding surfaces of some shaly interbeds in the upper part of the Bolsa at a few localities.

POROSITY

The quartz cementation of most of the Bolsa Quartzite is so advanced that intergranular porosities are generally very low. The average effective porosity of four samples tested with the mercury porosimeter was 2.0 percent, the average total porosity of five other samples tested by the kerosene-displacement method was 2.7 percent, and the average porosity of six additional samples checked by point counting the voids in thin section was 1.6 percent. A single sample from near the top of the Bolsa at Brandenburg Mountain (loc. 102) had a porosity of 12.6 percent according to the kerosene-displacement method and 10 percent by point count. Wherever the Bolsa crops out at the surface it is fractured—locally intensely—but the fracture porosity in the Bolsa may not be important where the formation is deeply buried.

THICKNESS

The thickness of the Bolsa varies greatly, locally very abruptly; its thickness is greatest and most uniform in the southern part of the region. The thickest section we measured is the 499 feet at Garden Canyon (loc. 66) in the Huachuca Mountains, and the Bolsa's thickness is believed to be within 100 feet of that amount throughout the range. A greater thickness, 700 feet, was reported at Picacho de Calera (loc. 160) by Bryant (1952). We visited the locality but did not check the measurement. The Bolsa is 344 feet thick at its type section at Mount Martin (loc. 65) in the Mule Mountains and is believed to be between 300 and 450 feet thick throughout that range (Hayes and Landis, 1965).

From the Little Dragoon Mountains area (vicinity of locs. 72, 74, and 75) northward the thickness of the Bolsa is more variable locally, and its thickest sections are mostly thinner than those to the south. In the Little Dragoon Mountains area, where there is a great amount of relief on the underlying surface, Cooper and Silver (1964) reported thicknesses of Bolsa from 14 feet to 480 feet. In the northern Galiuro Mountains area (vicinity of loc. 102) the Bolsa is absent locally between the Precambrian and the overlying Abrigo Formation, but where present it is as much as 160 feet thick (Krieger, 1968a, b, c, d). Rocks reported by Peterson (1969) in the Superior area (loc. 154) to be Bolsa are here considered to be Abrigo; in that area, too, the Bolsa is interpreted to be absent between the Precambrian and Abrigo.

In the Vekol Mountains (loc. 82), far to the west, the Bolsa also locally laps out against old Precambrian hills (Chaffee, 1974). We measured 231 feet of the formation where it seemed to be relatively thick.

FOSSILS AND AGE

No fossils closely diagnostic of age have been reported from the Bolsa. Other than tracks and trails, vertical borings (*Scolithus* tubes), and occasional indeterminate phosphatic brachiopods, the Bolsa seems to be devoid of fossils.

Since the Bolsa was originally defined (Ransome, 1904), its age has been assigned as Middle Cambrian on the basis of its conformable relations with the overlying Abrigo Formation, whose lower part is known to be of late Middle Cambrian age. However, because the base of the Sauk sequence in the region is known to be progressively younger northward and eastward and because the basal Cambrian rocks of the Caborca area in Sonora (about 135 miles south of the Vekol Mountains, loc. 82) and of southern California are known to be of Early Cambrian age (Cooper and Arellano, 1956; Stewart, 1970), it seems very possible that at least part of the Bolsa of the western part of the report region (in the Slate and Vekol Mountains, locs. 81 and 82) is of Early Cambrian age.

CONTACTS

The basal contact of the Bolsa with underlying Precambrian rocks is everywhere unconformable and sharp. Only where the Bolsa overlies the Precambrian Troy

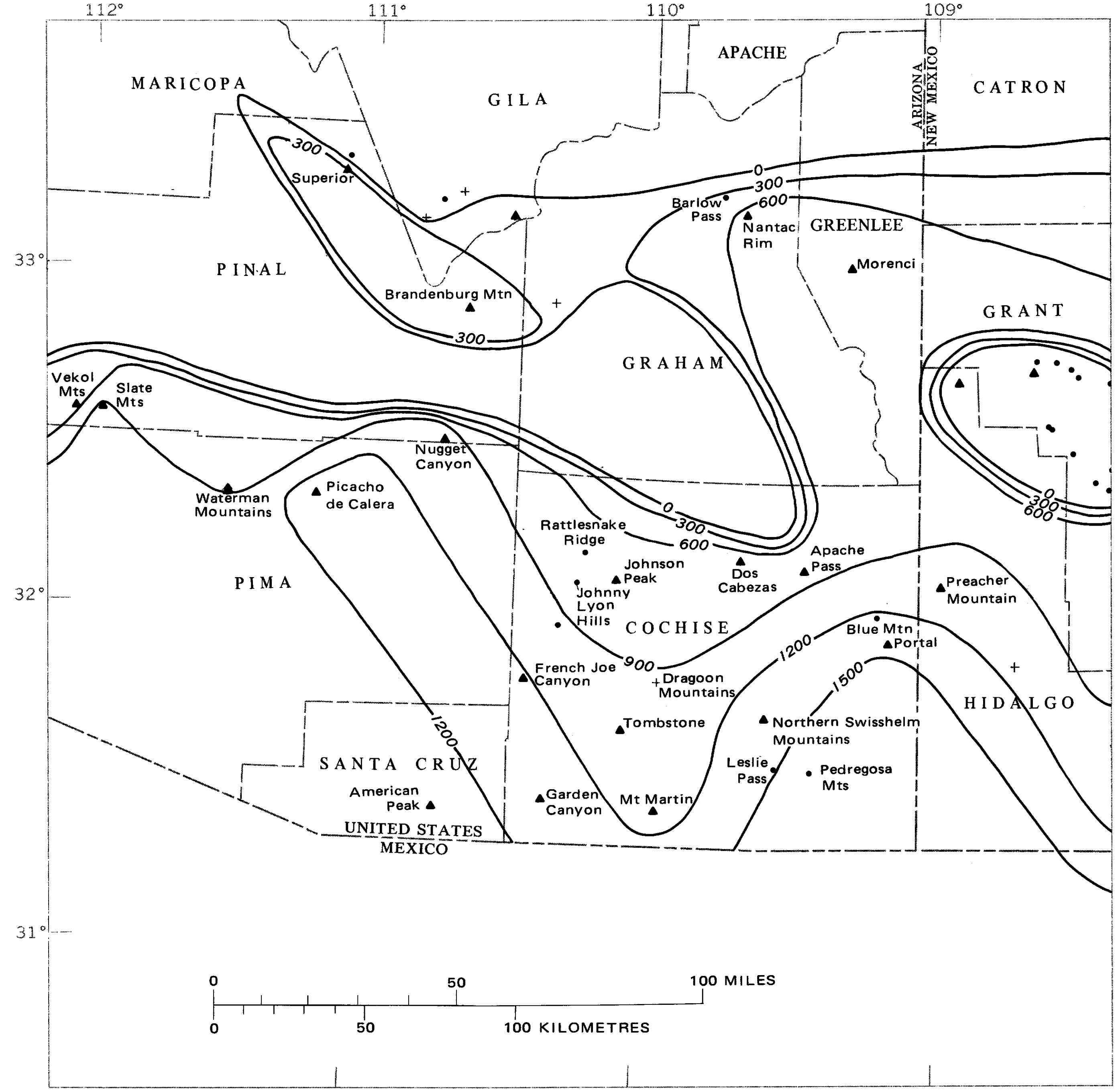
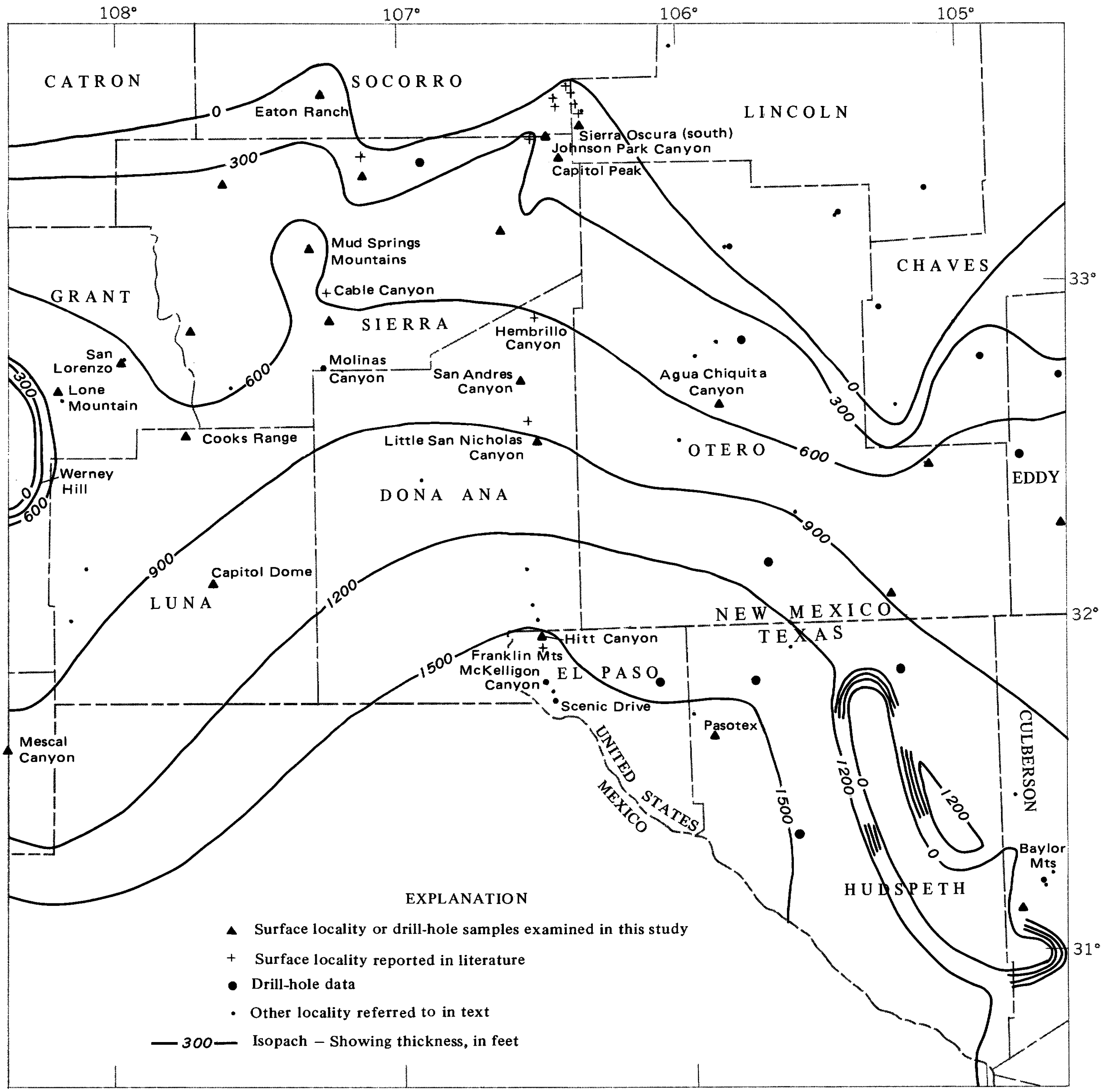


FIGURE 4.—Preserved thickness, in feet, of rocks of the Sauk

Quartzite with very low angularity is there any problem of identifying the contact. Krieger (1961) has described the similar but distinctive lithologies of the two formations.

The Bolsa is everywhere conformably overlain by the Abrigo Formation. The contact is gradational but in most places can be closely picked, the dominant quartzites of the Bolsa giving way abruptly to dominant shales or siltstones of the basal Abrigo. Locally, especially toward the south, the placement of the contact is more arbitrary because quartzite and shale may be interbedded in nearly equal proportions through a stratigraphic interval of as much as 150 feet. In such areas the contact is generally chosen at the top of the highest conspicuous quartzite bed below the lowest carbonate bed of the Abrigo.

Over much of the region the top of the Bolsa seems to be at approximately the same stratigraphic position, but



sequence of Sloss, Krumbein, and Dapples (1949) and Sloss (1963).

careful comparison of detailed graphic sections on which all diagnostic fossils of the Abrigo are noted indicates that the top of the Bolsa in easternmost areas may be younger than to the west. (See pl. 1.)

ABRIGO FORMATION

The Abrigo Limestone was named by Ransome (1904) for exposures in the Mule Mountains, Cochise County, Ariz., and the type section was remeasured and divided into four members by Hayes and Landis (1965) at Mount Martin (fig. 4 and loc. 65, fig. 1). Called Abrigo Formation everywhere but at the type locality, the Abrigo crops out at many places in the western area as shown in figure 6 but does not occur farther east. The four members of the type section were extended over all the eastern part of the western area by Hayes (1972) and called, in ascending order, lower member, middle member, upper sandy member, and Copper Queen Member. In this report the informal members are extended, with reservations, to the western part of the western area and are described separately on the following pages.

LOWER MEMBER

General Description

The lower member of the Abrigo Formation is a moderately nonresistant unit several hundred feet thick that in outcrop generally forms a slope between the much more resistant underlying and overlying units. Lithologically, the member varies markedly from one area to another but, in general, is made up dominantly of fine-grained terrigenous clastic rocks.

Distribution And Stratigraphic Limits

The lower member of the Abrigo Formation is present wherever Cambrian rocks occur in the western area as shown in figure 6. In most areas it conformably overlies the Bolsa Quartzite and is conformably overlain by the middle member of the Abrigo. Locally, in the northern and western parts of the western area where the Bolsa is absent over old Precambrian hills, the lower member unconformably overlies Precambrian sedimentary rocks.

Petrology

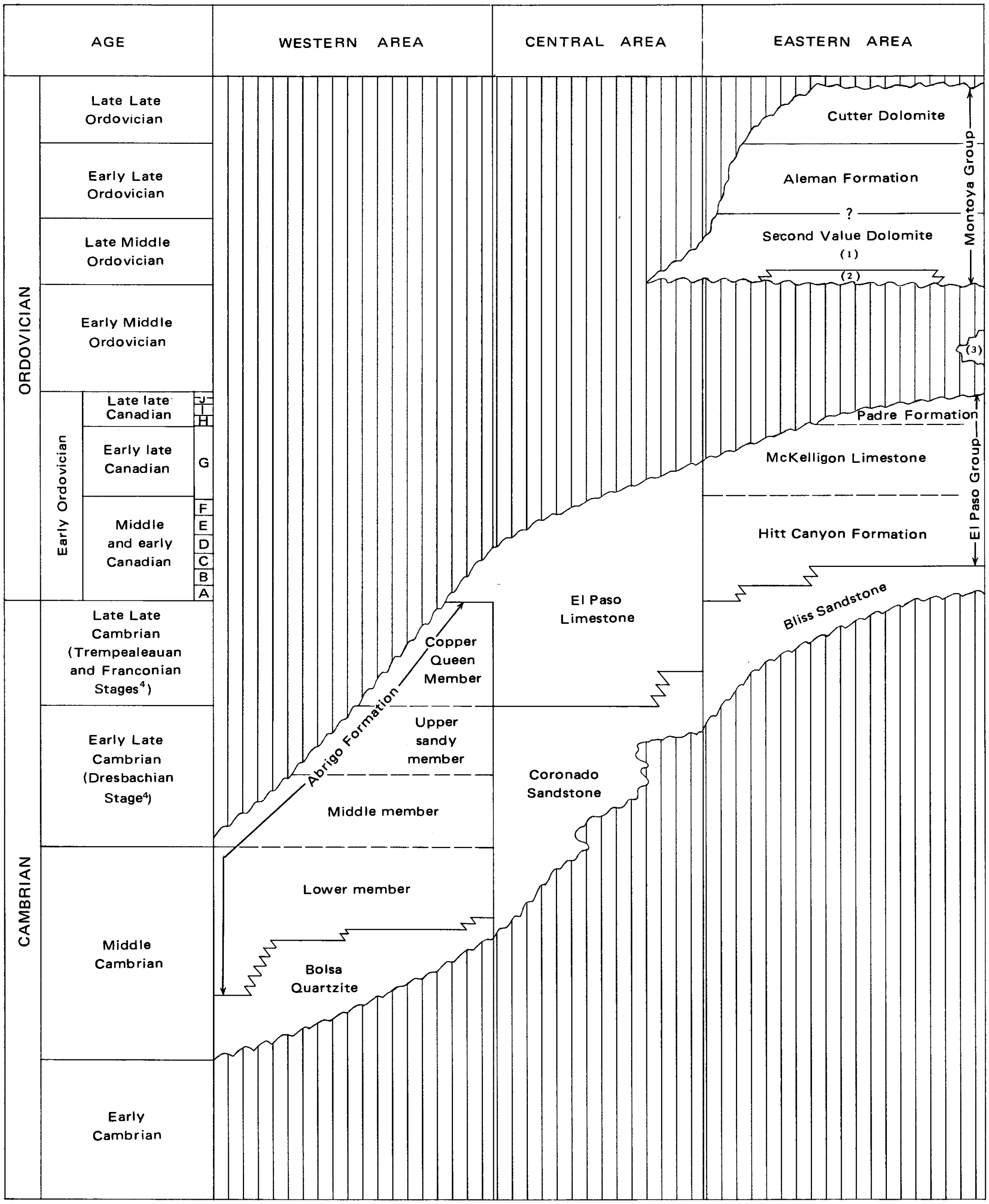
The lithologic characteristics of the lower member of the Abrigo Formation change almost completely from the southern part of the region to the northern part. In the Mule, Huachuca, and Patagonia Mountains at the south (locs. 65, 66, and 83) the member is made up almost entirely of roughly equal proportions of micaceous silty shale and thin-bedded limestone, but a few thin beds of quartzite and brown-weathering dolomite are generally near the base. In the Santa Catalina and Galiuro Mountains and Superior area (locs. 77, 102, and 154) the member is made up almost entirely of siltstone and fine-grained sandstone. In the intervening area the member is intermediate in composition but in an irregular manner. Toward the east in the intervening area abundant shales extend farther north than they do to the west, whereas abundant carbonates extend farther north in the western part of the intervening area. The following comments on the petrology of the lower member are based on the outcrop examination of the unit at 18 localities and on the examination of 80 thin sections. Limestones were studied most carefully and shales least.

Shale in the lower member is in general fissile. It is commonly micaceous and usually silty and slightly calcareous. It is mostly medium gray to olive gray where fresh but weathers to a yellowish brown. In mineralized and slightly metamorphosed areas, such as the Tombstone area (loc. 70), shale in the member has been altered to hornfels.

Limestone in the lower member of the Abrigo Formation rarely occurs in units more than a few feet thick and is generally thinly or very thinly bedded; it is commonly irregularly laminated as well. Most is medium gray on fresh surfaces and light gray or yellowish gray on weathered surfaces. Yellowish-gray-weathering limestone is typically fairly silty, whereas light-gray-weathering limestone is mostly free of terrigenous silt. Silty and relatively silt-free limestone are commonly irregularly interlaminated. Variably silty and (or) argillaceous laminated lime mudstone is the most common limestone type in the member (fig. 8*C*). Some lime mudstones appear in thin section to have been peloid, and others show lithiclasts that may have been desiccation chips. Lithiclast lime wackestones to packstones made up of chips of lime mudstone in lime mudstone matrix (fig. 8*A, B*) are also common, as are algal grainstones (fig. 8*D*). Fossil-bearing lime mudstones and skeletal wackestones are present but not common. Both glauconite (fig. 8*A*) and hematite (fig. 8*D*) are common as impurities in lower member limestones.

Dolomite in the lower member is most abundant in the facies intermediate between the southern shale and limestone facies and the northern siltstone and sandstone facies. Where present it is medium gray and generally weathers to a dark yellowish brown. It is commonly silty or sandy and is generally thinly laminated. Some dolomite in the Slate and Vekol Mountains (locs. 81 and 82) is sandy dolomite chip conglomerate which has chips of laminated hematitic dolomitic sandstone in a matrix of sandy fine-grained dolomite.

The coarse siltstones and fine-grained sandstones that make up most of the member in the north and part of it elsewhere are in general yellowish to reddish gray on fresh surfaces and weather to a wide variety of colors ranging from yellowish gray to dark reddish brown. It is thinly to thickly bedded, commonly laminated, locally cross-laminated, commonly friable, and mostly only weakly resistant. Siltstone exceeds sandstone in abundance at most



[1] Upham Dolomite Member
[2] Cable Canyon Sandstone Member.
[3] Unnamed rocks of early Middle Ordovician age.
[4] Of Howell and others (1944)

FIGURE 5.—Stratigraphic nomenclature and correlations used in this report for Cambrian and Ordovician rock units. The locations of the western, central, and eastern areas are shown in figure 6. The letters on the right edge of the left column show correlations with Ordovician fossil zones of Utah (Hintze and others, 1969).

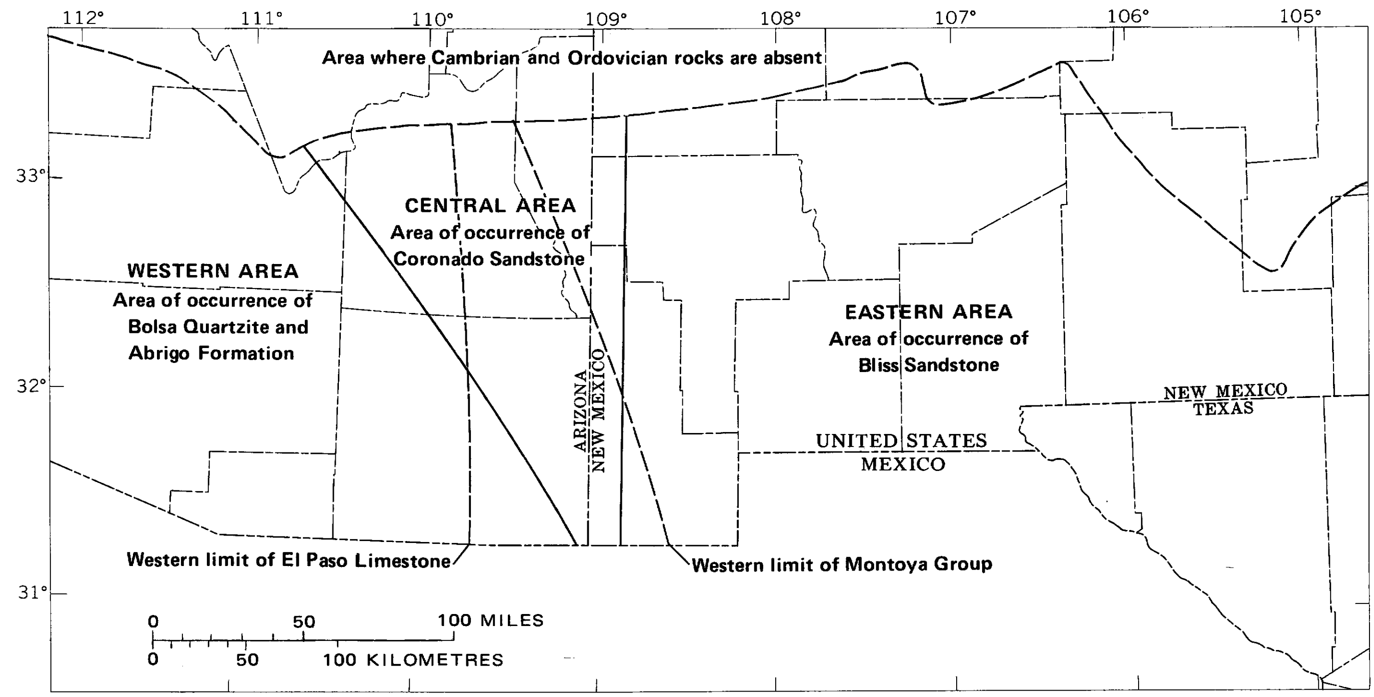


FIGURE 6.—Distribution areas of major stratigraphic units discussed in text and shown in figure 5.

localities (fig. 8*E*); most of the sandstones present are fine to very fine grained, but some are medium grained. Grain-size sorting is mostly fairly good, but sorting ranges from very good to very poor. The grains are mostly quartz; but feldspar grains are fairly common, and grains of glauconite, calcite, dolomite, and chert also occur. Most of the siltstones and sandstones are cemented with quartz, calcite, or dolomite, but clay minerals and iron oxides are commonly present in the matrix.

SEDIMENTARY STRUCTURES

The most notable sedimentary structures observed in limestones and dolomites of the lower member of the Abrigo Formation are mud cracks and intraformational chip conglomerates. Burrowed lime mudstone was noted at a few localities.

Tracks and trails are abundant and conspicuous on the bedding surfaces of many siltstone and fine-grained sandstone beds, and *Scolithus* tubes as much as 1 cm wide and 25 cm long are commonly noted in sandstone beds.

Many sandstone beds show conspicuous small- and medium-scale cross-laminations. At Nugget Canyon (loc. 77) in southeastern Pinal County most of the cross-laminae are inclined toward the southwest.

Slump structures were noted in siltstone beds at a few localities.

POROSITY

Porosities in carbonate rocks of the lower member of the Abrigo Formation are very low, but some sandstones and siltstones have moderate porosity. The effective porosities of two limestone samples checked were 1.4 and 2.1 percent, and the effective porosities of two silty dolomites checked were 0 and 1.1 percent. Six siltstone and sandstone samples were checked for total porosity, and the resultant porosities ranged from 7.3 to 13.9 percent and averaged 9.5 percent. The effective porosities of six sandstone and siltstone samples were also checked, and the resultant porosities ranged from 1.3 to 7.0 percent and averaged 4.5 percent.

THICKNESS

The lower member of the Abrigo Formation ranges in thickness from 238 feet at Johnson Peak (loc. 75) in northwestern Cochise County to 665 feet at Waterman Mountains (loc. 80) in northern Pima County; it is 252 feet thick in the type section of the Abrigo at Mount Martin (loc. 65). The great thickness at locality 80 is probably due to westward thickening at the expense of the underlying Bolsa Quartzite. The lower member is less than 480 feet thick at all other localities.

FOSSILS AND AGE

On the basis of fossils, chiefly trilobites, found by various workers in Cochise and Pima Counties, Ariz., at or near the northern Swisshelm Mountains, Mount Martin, French Joe Canyon, Tombstone, Johnson Peak, and the Waterman Mountains (locs. 64, 65, 69, 70, 75, and 80), the age of the lower member of the Abrigo Formation is Middle Cambrian and probably mostly late Middle Cambrian. Fossils from the northern Swisshelm Mountains and French Joe Canyon (at or near locs. 64 and 69) have

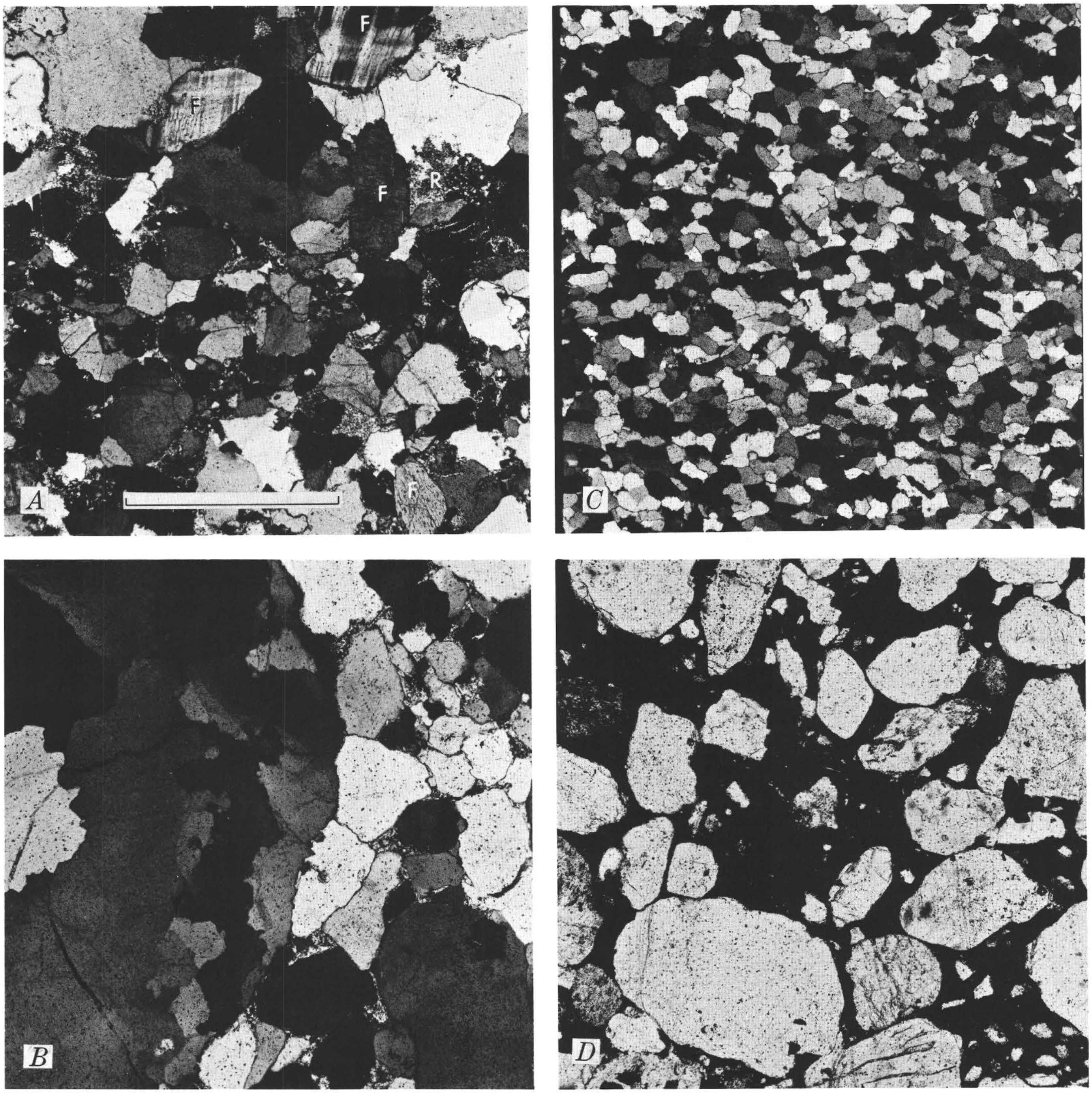


FIGURE 7.—Photomicrographs of Bolsa Quartzite. Bar in *A* is 1 mm; all views are same scale. *A*, Poorly sorted arkosic quartzite from near base of formation in the northern Swisshelm Mountains (loc. 64). Such rock is abundant in the lower part of the Bolsa wherever it overlies a crystalline terrane. Besides abundant feldspar (F), mostly microperthite, the section contains rock fragments (R), magnetite, and considerable sericite in the matrix. Note the intergranular welding of quartz grains especially in the upper part of the picture. Crossed nicols. *B*, Poorly sorted granule-bearing quartzite from 299 feet above base of formation at Garden Canyon (loc. 66). Large fragment of quartzite at left was derived from the underlying Precambrian. Like most quartzite from this high in the Bolsa, this rock is virtually devoid of feldspar. This quartzite is less perfectly welded than most in the Bolsa, and there is some sericite between many quartz grains. Crossed nicols. *C*, Very well sorted siliceous fine-grained orthoquartzite from upper part of formation at Nugget Canyon (loc. 77). Rock such as this is characteristic of the upper part of the Bolsa wherever it occurs. The original grain boundaries are nearly all lost. Crossed nicols. *D*, Poorly sorted quartzose sandstone cemented with hematite from upper part of formation at Mount Martin (loc. 65). This rock type is present at nearly all Bolsa localities but makes up a very minor part of the sequence. Such rock is much more prevalent in the Bliss Sandstone. Plain light.

been reported on by A. R. Palmer (in Gilluly, 1956), and more collections from those localities were made during this study and reported on by M. E. Taylor of the U.S. Geological Survey (written commun., Aug. 16, 1971, and Jan. 24, 1973). Fossils from or near Mount Martin (loc. 65) in the Mule Mountains have been reported on by Stoyanow (1936) and by A. R. Palmer (in Gilluly, 1956). Fossils from the Tombstone area and Johnson Peak (at or near locs. 70 and 75) have been reported on by A. R. Palmer (in Gilluly, 1956). Collections were made from the lower member during this study in the Waterman Mountains (loc. 80) and contain several genera of trilobites indicative of a late Middle Cambrian age, according to M. E. Taylor (written commun., Aug. 16, 1971, and Jan. 24, 1973). Fossils collected from the member during this study are given under "Fossil Lists" near the end of the report.

The age of the lower member at northern localities where no diagnostic fossils have been found is presumed to be Middle Cambrian on the basis of stratigraphic position and presumed equivalence to the lower member of southern localities.

Upper Contact

The contact of the lower member of the Abrigo with the overlying middle member is gradational but at most localities can be placed rather precisely. In the southernmost localities, where considerable shale is present in the lower member, the contact is placed at the top of the highest shale or siltstone bed beneath the 100 feet or more of limestone that makes up the middle member. Farther north, where the lower member consists largely of siltstone and fine-grained sandstone and the upper member contains resistant sandstone or quartzite at the base or is made up entirely of such rock, the contact is placed where siltstone or weakly resistant fine-grained sandstone gives way abruptly upward to relatively resistant coarser grained sandstone or quartzite.

MIDDLE MEMBER

General Description

The middle member of the Abrigo Formation, like the lower member, changes completely in lithologic character from south to north but can be recognized by its stratigraphic position and its contrast to the underlying and overlying units. In the south the member is made up almost entirely of distinctively ribbed limestone or dolomitized limestone. In the northernmost localities it is made up almost entirely of resistant sandstone. In intervening areas it is resistant sandstone at the base and chiefly dolomite in the upper part. The middle member nearly everywhere contrasts fairly sharply with the relatively nonresistant fine-grained clastic rocks of the underlying member and with the sandy dolomites and dolomitic sandstones of the overlying member. Wherever completely preserved, the member is more than 100 feet thick and is nowhere much more than 300 feet thick.

Distribution And Stratigraphic Limits

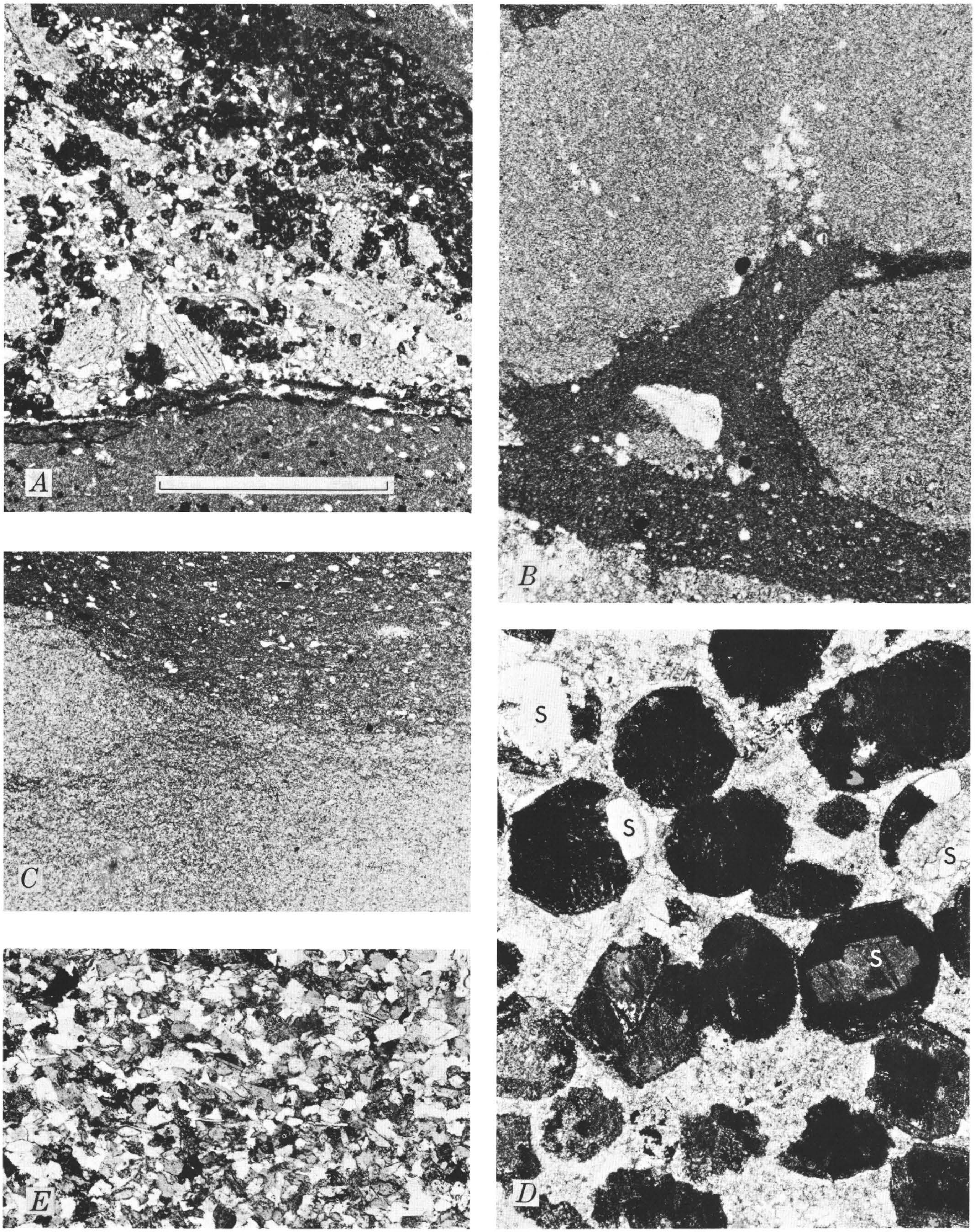
The middle member of the Abrigo Formation is confined to the western area as outlined in figure 6. It is present throughout that area except where removed or not deposited at the extreme north, where removed by Mesozoic erosion in much of the central part of the area, and where locally removed by pre-Late Devonian erosion in the west.

The middle member of the Abrigo wherever seen overlies the lower member with conformable contact. It is conformably overlain by the upper sandy member of the Abrigo in most areas except in the far west (Slate and Vekol Mountains, locs. 81 and 82), where it is overlain disconformably by the Martin Formation of Devonian age. The middle member grades laterally northeastward into the Coronado Sandstone of the central area.

Petrology

The middle member of the Abrigo Formation consists almost entirely of distinctively ribbed limestone or dolomitized limestone in and west of the Mule Mountains (loc. 65). Not far to the north and east of the Mule Mountains, in the Swisshelm and Little Dragoon Mountains (locs. 64 and 75), limestone is predominant, but a few thin sandstone beds are present. Farther north and west, in southern Pinal County (locs. 77, 81, and 82), sandstone is dominant in the lower part of the member, and carbonate, in that area chiefly dolomite, is dominant in the upper part. Still farther north, at and near Brandenburg Mountain (loc. 102), the member consists entirely of sandstone. The following descriptions of the rocks of the middle

FIGURE 8.—Photomicrographs of lower member of Abrigo Formation. Bar in *A* is 1 mm; all views are same scale. *A*, Coarse lithiclast lime packstone from 105 feet above base of member at French Joe Canyon (loc. 69). Parts of two large rounded lithiclasts (upper right and bottom) and all of one rounded lithiclast (upper left) of slightly silty lime mudstone are visible. Matrix (in upper middle) is sparrite containing quartz silt (white spots) and glauconite (dark circular spots). Plain light. *B*, Coarse lithiclast lime grainstone from 322 feet above base of member at Garden Canyon (loc. 66). Parts of three lithiclasts made up of slightly silty lime mudstone are visible. Matrix material is silty and argillaceous lime mudstone. Many of the thin limestone beds in the lower member in the southern part of the region are made up of such rock. Plain light. *C*, Laminated lime mudstone (below) and silty argillaceous lime mudstone (above) from 300 feet above base of member at French Joe Canyon (loc. 69). This thinly laminated rock is very similar to that of the lithiclasts in *B*. Such rock is more common in the middle member of the Abrigo. Plain light. *D*, Ferruginous grainstone from 204 feet above base of member at Garden Canyon (loc. 66). The spheroidal grains are largely made of iron oxide but many contain sparry calcite (S). They may be altered grains of glauconite, completely replaced ooids, or largely replaced algal structures (*Girvanella*?). Such rock occurs sparingly in the lower member at several localities. Crossed nicols. *E*, Well-sorted porous slightly ferruginous quartz siltstone from Brandenburg Mountain (loc. 102). Most dark spots are pore spaces but some are grains of iron oxide. Most of the lower member is made up of such rock near the transition of the Abrigo into the Coronado sandstone. Crossed nicols.


A
B
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member are based on outcrop examination of the member at 17 localities and on the examination of 26 thin sections.

Most of the limestone in the middle member either is distinctively ribbed with layers of medium-light-gray-weathering limestone and slightly more resistant light-brown-weathering silty limestone (fig. 9*A*) (both medium gray on fresh fracture) or is irregularly laminated in a distinctive manner (fig. 9*B*). Much of the limestone is lime mudstone or vaguely peloid lime mudstone that may or may not be fossil bearing. Also common are skeletal lime wackestones (fig. 10*A*), algal(?) and oolitic lime packstones (fig. 10*B*), and lithiclast lime wackestones that contain large disk-shaped clasts of lime mudstone in lime mudstone or sparry calcite matrices (fig. 10*C*). At American Peak (loc. 83) and some other areas the limestones are partially or completely dolomitized but retain their distinctive ribbing or laminations.

Dolomite greatly dominates limestone in the intermediate facies between the southern limestone facies and the northern sandstone facies. In this intermediate area the dolomites are nearly all thinly laminated and some are cross-laminated. They are commonly brownish gray on fresh surfaces and yellowish brown on weathered surfaces. Most of the dolomites are either sandy or silty and commonly occur as interlaminated sandy and very fine to medium-grained dolomites. Beds of edgewise chip conglomerate containing chips of laminated sandy or nonsandy dolomite or of dolomitic sandstone in a dolomite matrix are conspicuous in the member in the intermediate facies.

The sandstone that makes up the middle member at the north is light to medium gray on fresh surfaces and weathers to a banded gray or yellowish brown. It is fairly well sorted fine- to medium-grained orthoquartzite cemented by quartz. Most beds are fairly resistant but some are friable. The more resistant beds commonly have "case-hardened" weathered surfaces but are less well cemented away from the weathered surfaces. Many beds are cross-laminated.

Sandstones that occur to the south in the intermediate facies are largely concentrated at the base of the member where they have been included in a local Southern Belle Member (Creasey, 1967a). The sandstones of the inter-

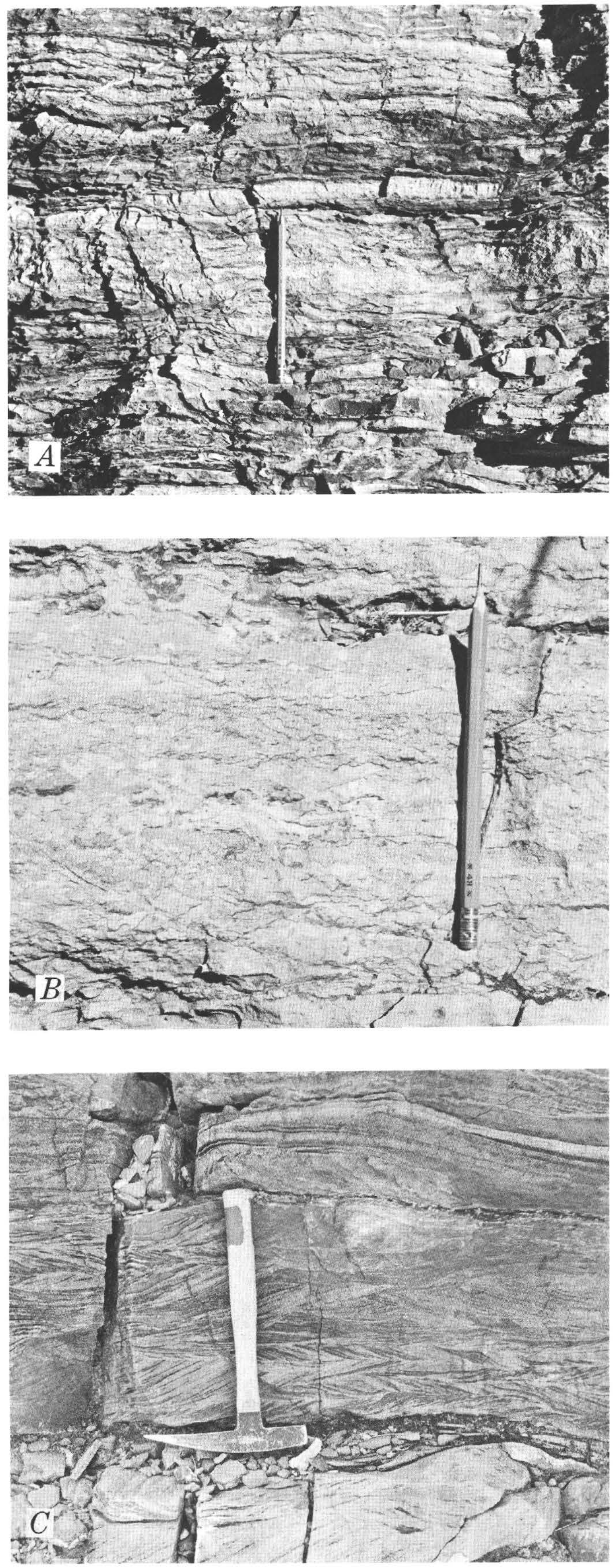


FIGURE 9.—Outcrops of middle member of Abrigo Formation. *A*, Silty and nonsilty limestone about 180 feet above base of member at French Joe Canyon (loc. 69). Pencil gives scale. "Ribbed" limestone like this is characteristic of the middle member in southern and western Cochise, eastern Pima, and Santa Cruz Counties, Ariz. (fig. 1). *B* Thinly layered slightly silty limestone with irregular very silty laminae in Pedregosa Mountains (loc. 61). Note similarity of this outcrop to that of Hitt Canyon Formation shown in Figure 18*A*. *C*, Cross-laminated slightly glauconitic calcareous sandstone in Vekol Mountains (loc. 82). Rock such as this is tentatively assigned to the middle member, but the member has this lithology only in the Slate and Vekol Mountains (locs. 81 and 82).

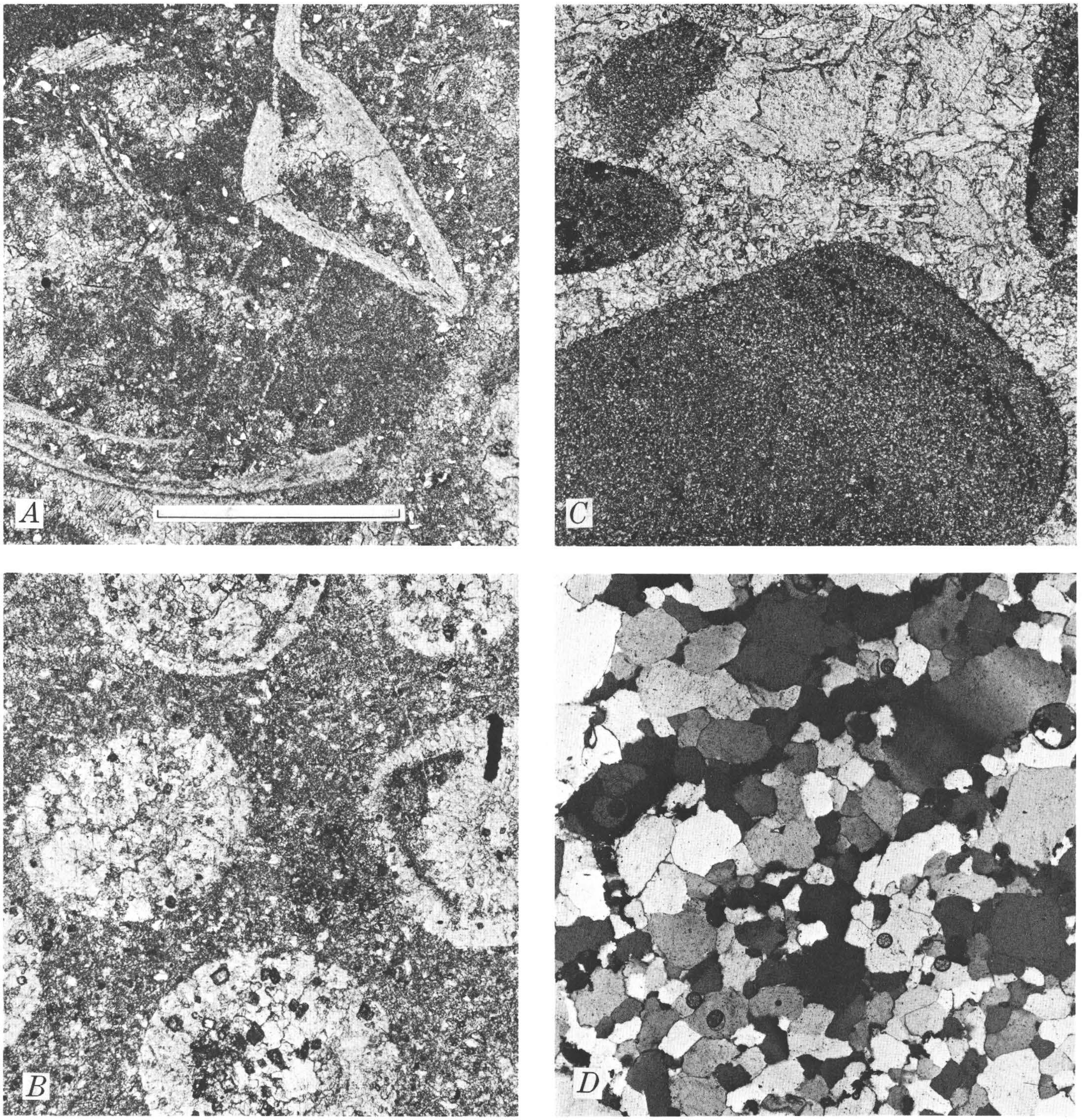


FIGURE 10.—Photomicrographs of middle member of Abrigo Formation. Bar in *A* is 1 mm; all views are same scale. *A*, Partly dolomitized slightly silty skeletal lime wackestone from 85 feet above base of member in northern Swisshelm Mountains (loc. 64). Such rock is abundant in the middle member in all southern localities. Plain light. *B*, Partly dolomitized silty oolite lime packstone from 150 feet above base of member at Garden Canyon (loc. 66). The oolites are largely dolomitized, whereas the silty micrite matrix is not. Oolitic rock such as this occurs commonly only in the Huachuca and Patagonia Mountains (locs. 66 and 83). Plain light. *C*, Lithiclast lime grainstone from base of member at Mount Martin (loc. 65). Clasts are slightly argillaceous lime mudstone, and matrix is mostly sparry calcite. (Compare fig. 8*B*.) Such rock is common in the middle member in southern localities. Plain light. *D*, Poorly sorted siliceous orthoquartzite from lower part of member at Nugget Canyon (loc. 77). Quartzite such as this is not present in the member at southern localities but is conspicuous at most northern and western localities. Crossed nicols.

mediate area tend to be less well sorted than to the north (fig. 10*D*). In the western part of the intermediate area the sandstones commonly have calcareous or dolomitic cement and weather dark red to moderate brown; some of them are glauconitic and many are hematitic.

Sedimentary Structures

Limestone or dolomite chip conglomerates or edgewise conglomerates occur in carbonate beds in the middle member of the Abrigo at all localities except at the far north, where the member is made up entirely of sandstone. Burrowed lime mudstone is occasionally seen in the member.

Sandstone beds of the northern and intermediate areas commonly are conspicuously cross-laminated. Most cross-laminations are small- to medium-scale planar type, but some trough cross-laminations are present in western sections (fig. 9*C*). Dolomite beds of the intermediate area also commonly display small-scale cross-laminations.

Tracks and trails may be noted on the top surfaces of sandstone beds in the northern and intermediate facies, but they are not abundant.

Porosity

The limestones of the middle member of the Abrigo Formation mostly seem to be very low in porosity, as indicated by thin-section examination. Pores formerly present in the unit are now largely cement filled, as seen in outcrop samples. Cement-filled or cement-reduced moldic and microfracture porosity are the most commonly noted types. One exceptional sample from Johnson Peak in the Little Dragoon Mountains (loc. 75) which showed conspicuous fenestral porosity in thin section was checked for effective porosity and found to have 7.1 percent.

Dolomite from the intermediate facies is also seen to be very low in porosity. One sample tested from the Vekol Mountains (loc. 82) showed 1.9 percent effective porosity.

Some of the well-sorted and imperfectly cemented sandstone from Brandenburg Mountain (loc. 102) shows considerable porosity in thin section. Two samples checked for total porosity showed 6.0 percent and 13.6 percent.

The more poorly sorted sandstones from the intermediate area seem to be lower in porosity than the northern sandstones. One sample checked had 4.6 percent total porosity, and another had only 1.5 percent effective porosity.

Thickness

Where the middle member of the Abrigo Formation is completely preserved and has not been thinned by post-Cambrian erosion, it ranges in thickness from 139 feet in the northern Swisshelm Mountains (loc. 64) to 306 feet at Garden Canyon in the Huachuca Mountains (loc. 66); it is 201 feet thick at the type section of the Abrigo at Mount Martin (loc. 65). Despite the large differences in thickness there seems to be no regionally consistent pattern of thickening and thinning.

Fossils And Age

The middle member of the Abrigo Formation is mostly of Dresbachian (of Howell and others, 1944) or early Late Cambrian age on the basis of fossil—chiefly trilobite—collections made at or near the northern Swisshelm Mountains, Mount Martin, French Joe Canyon, Tombstone, Dragoon Mountains, Johnny Lyon Hills, Johnson Peak, and the Slate Mountains (locs. 64, 65, 69, 70, 71, 74, 75, and 81). At Mount Martin (loc. 65) in the Mule Mountains the basal few feet of the member is apparently of latest Middle Cambrian age (Hayes and Landis, 1965), and the same is true in the northern Swisshelm Mountains (loc. 64), where fossils possibly assignable to the *Bolaspidella* zone were collected 8 feet above the base of the member (M. E. Taylor, written commun., Jan. 24, 1973). Fossils collected during this study within 18 feet above the base of the member in the Slate Mountains (loc. 81) (see "Fossil Lists"), however, are definitely of early Late Cambrian age (M. E. Taylor, written commun., Jan. 24, 1973). On the basis of fossils from Cochise County reported by A. R. Palmer (in Gilluly, 1956) from at or near localities 64, 65, 69, 70, 71, and 75; by Cooper and Silver (1964) from locality 74; and by us at localities 64, 65, and 69 (see "Fossil Lists"), forms that are representative of the *Cedaria* zone of the Dresbachian Stage are seen to be characteristic of most of the middle member. The younger Dresbachian fossils are found near the top at localities 65 and 74.

The age of the middle member of northern areas where diagnostic fossils have not been found is assumed to be very nearly the same as that of southern areas because of conformable stratigraphic position beneath the upper sandy member.

Upper Contact

The contact between the middle member and the overlying upper sandy member is conformable but generally fairly sharp. In the south, where the middle member is made up of gray ribbed limestone, the contact is marked by a rather abrupt change to reddish-brown-weathering sandy dolomite and dolomitic sandstone of the upper sandy member. In the north, where the middle member is made up of gray- to pale-yellowish-brown-weathering siliceous sandstone, the contact with the upper member is also easily recognized by a fairly abrupt upward change to brown-weathering dolomitic sandstone and sandy dolomite.

Only in the area of the intermediate facies of the middle member where brown-weathering sandy dolomites and subordinate dolomitic sandstones make up much of the upper part of the middle member is the contact subtle. Indeed, Creasey (1967a) reasonably included the upper part of the middle member and the overlying beds in his Peppersauce Member in the Santa Catalina Mountains (loc. 77). However, I believe that a contact within the Peppersauce at that locality can be recognized at a horizon where there is an abrupt upward change to conspicuously sandier and darker brown-weathering beds. This is very nearly at the same horizon as the top of the middle member to the north and south. On the basis of thickness and lithology in the Slate and Vekol Mountains (locs. 81 and 82) in the intermediate area, the upper sandy member seems to be missing, and the middle member is disconformably overlain by the Martin Formation of Devonian age.

UPPER SANDY MEMBER

General Description

The upper sandy member of the Abrigo Formation, 100–180 feet thick where completely preserved, is made up entirely of brown-weathering dolomitic sandstone and brownish-gray-weathering sandy dolomite. The member is very persistent in lithology throughout its area of occurrence but contains more dolomite toward the south and west and more sandstone toward the north and east.

Distribution And Stratigraphic Limits

The upper sandy member is confined to the western area as shown in figure 6. It is missing because of post-Cambrian erosion, however, over much of the western part of that area and over some of the central part.

The upper sandy member of the Abrigo conformably overlies the middle member and, where completely preserved, is conformably overlain by the Copper Queen Member. In most western sections the Copper Queen is missing because of erosion, however, and the upper sandy member of the Abrigo is disconformably overlain by the Martin Formation of Devonian age.

The upper sandy member grades eastward into the upper part of the Coronado Sandstone of the central area (fig.5).

Petrology

The upper sandy member of the Abrigo Formation shows very little diversity of lithology vertically or regionally. In southern sections, however, there tends to be an alternation of sandy dolomite and dolomitic sandstone, with dolomite being slightly dominant, whereas in the northernmost localities the unit is made up almost entirely of dolomitic sandstone. A few southern localities (Mount Martin, French Joe Canyon, and American Peak, fig. 4 and locs. 65, 69, and 83, fig. 1) contain some sandy or silty limestone. The following descriptions of the lithology are based on outcrop examination of the upper sandy member at 11 localities and on the examination of 20 thin sections.

Sandstones in the member are well-sorted very fine to medium-grained orthoquartzites with dolomite cement (fig. 11); some are glauconitic and a few are slightly hematitic. They are olive gray to pinkish gray on fresh surfaces

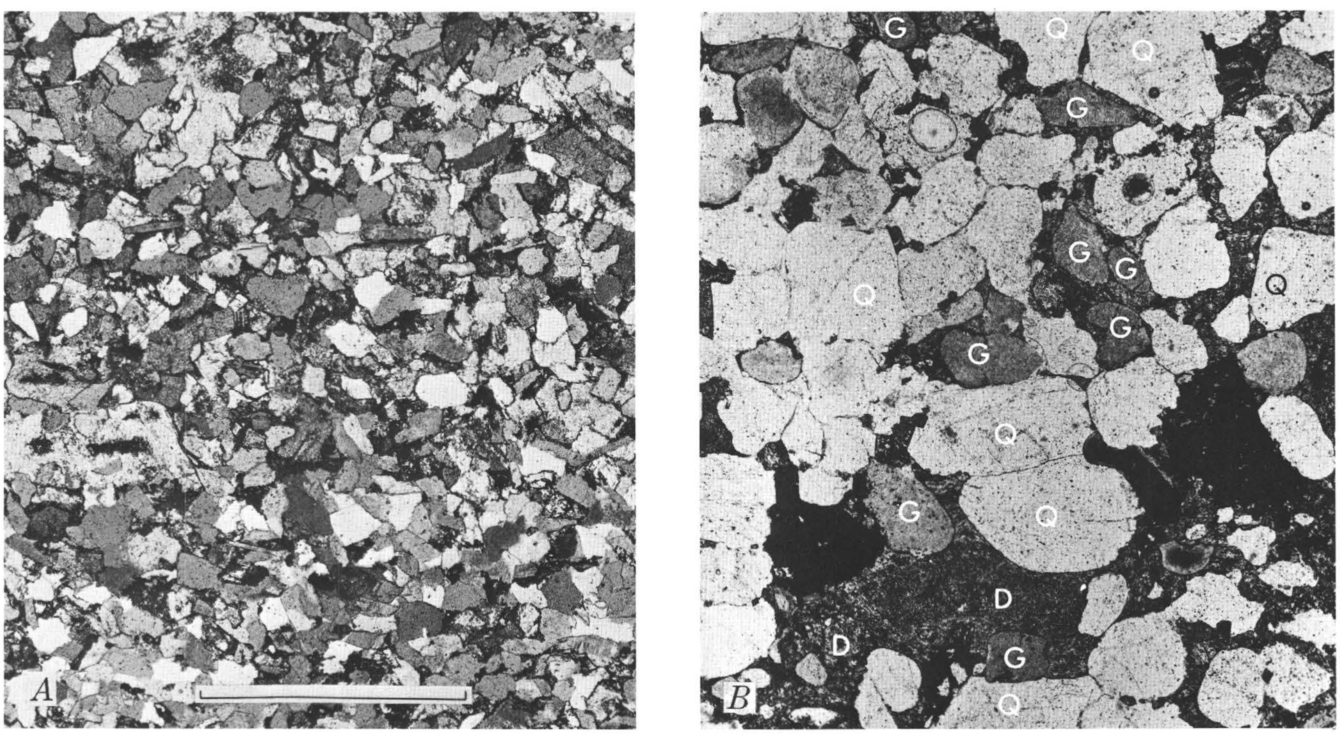


Figure 11.—Photomicrographs of upper sandy member of Abrigo Formation. Bar on *A* is 1 mm; views are same scale. *A*, Well-sorted fine-grained laminated dolomitic sandstone from lower part of member in northern Swisshelm Mountains (loc. 64). By point count this section contains 79 percent quartz, 20 percent dolomite grains, and 1 percent feldspar. This and *B* are the most abundant rock types in the member at most localities. Crossed nicols. *B*, Medium-grained glauconitic, hematitic, dolomitic quartz sandstone from Brandenburg Mountain (loc. 102). Quartz (Q) is most abundant, but rounded glauconite (G) grains are common, as is hematite (black) and dolomite (D) cement. Plain light.

and weather moderate brown or dark reddish brown. Most are cross-laminated (fig. 12) and are moderately resistant.

Dolomites in the upper sandy member are evenly very fine to medium grained lithiclast dolomite grainstones (dolarenites). They range from very slightly quartzose to extremely quartzose, and some are glauconitic. They are mostly olive gray on fresh surfaces and weather to light brownish gray. Many dolomite beds are cross-laminated and are moderately resistant.

The few limestones seen at Mount Martin, French Joe Canyon, and American Peak (locs. 65, 69, and 83) are very fine to medium grained lithiclast lime grainstones (calcarenites). Most contain quartz silt or sand and a few are glauconitic. Otherwise they are similar to the dolomites.

Sedimentary Structures

Cross-laminations are by far the most notable sedimentary structures of the upper sandy member (fig. 12). The cross-laminations are small to medium scale and are of the planar type. They occur throughout the member and throughout the region.

Dolomite edgewise conglomerates that are made up of clasts of dolomite in a dolomite matrix may be found in most Cochise, Santa Cruz, and eastern Pima County sections.

Porosity

Porosities in the upper sandy member of the Abrigo Formation are higher than in most of the rock units described in this report. The sandstones of the northern part of the region tend to be most porous, and dolomites of the southern part, least porous. Intergranular porosity is by far the most common type in sandstones, and both intergranular and fracture porosities are found in dolomites. Two sandstones checked from Nugget Canyon (loc. 77) had 13.3 and 14.2 percent total porosity; the one with 14.2 percent total porosity had 12.0 percent effective porosity. Two dolomites checked for total porosity had 2.1 and 8.8 percent. The effective porosities of three dolomites checked were 2.8, 4.2, and 6.7.

Thickness

Where overlain by the Copper Queen Member, and thus completely preserved, the upper sandy member of the Abrigo Formation ranges in thickness from 101 feet at Nugget Canyon in the Santa Catalina Mountains (loc. 77) to 180 feet in the northern Swisshelm Mountains (loc. 64); it is 166 feet thick at the type section of the Abrigo at Mount Martin in the Mule Mountains (loc. 65).

Fossils and Age

Fossils are not abundant in the upper sandy member of the Abrigo Formation, but trilobites have been reported from the unit in western Cochise County from at or near Mount Martin, Tombstone, Dragoon Mountains, and Johnson Peak (locs. 65, 70, 71, and 75) by A. R. Palmer (in Gilluly, 1956) and from the Johnny Lyon Hills (loc. 74) by Cooper and Silver (1964). In addition we collected trilobites from what appears to be the member from Picacho de Calera (loc. 160) in Pima County. (See "Fossil Lists.") All the collections reported that are without doubt from the member are assignable to the *Crepicephalus* or *Aphelaspis* zones of the Dresbachian Stage of the Late Cambrian.

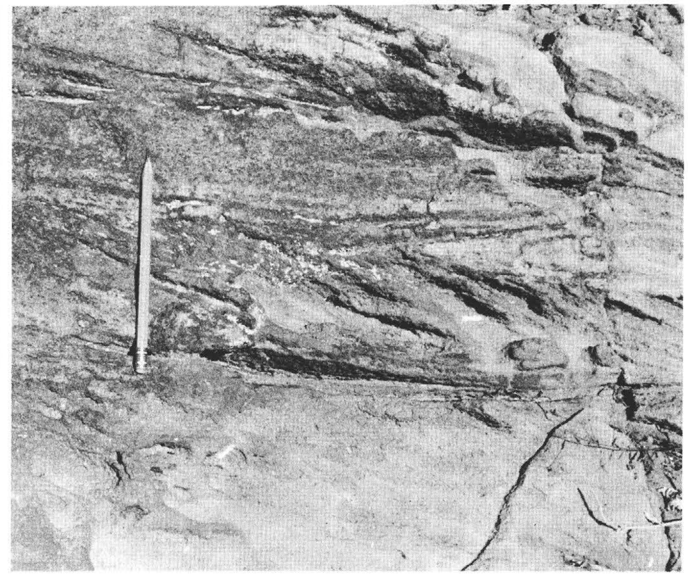


Figure 12.—Torrentially cross-laminated glauconitic and dolomitic sandstone in upper sandy member of Abrigo Formation at Brandenburg Mountain (loc. 102). Figure 11*B* is a thin-section photomicrograph of rock from this outcrop. Such rock is common in the member at all localities where the member is present. Note strong similarity of this outcrop to that of Bliss Sandstone in figure 16*A*.

Although some localities have not yielded fossils, on the basis of the uniformity of lithology and fauna over considerable distances the upper sandy member is assumed to be of closely similar age throughout the region.

Upper Contact

The upper sandy member is conformably overlain by the Copper Queen Member, or, where the Copper Queen has been removed by pre-Devonian erosion, it is disconformably overlain by the Martin Formation of Devonian age. The contact between the upper sandy member and the Copper Queen, though conformable, is marked by a generally abrupt change from sandstone or decidedly sandy dolomite to nonsandy or only slightly sandy dolomite or limestone. Where the Martin Formation overlies the upper sandy member, the precise position of the contact, though disconformable, is not everywhere immediately evident. In places where a thin conglomeratic zone is at the base of the Martin there is no difficulty in determining the contact, but there are many localities in which slightly sandy brown-weathering cross-laminated dolomite at the base of the Martin directly overlies sandy brown-weathering cross-laminated dolomite at the top of the upper sandy member of the Abrigo. If diagnostic fossils cannot be found, the Martin dolomites can most easily be recognized by the vague low-angle cross-laminations as contrasted to the higher angle planar cross-laminations of the upper sandy member. In addition, the Martin is dominantly yellowish brown or brownish gray, whereas the upper sandy member is mostly moderate brown. Where the contact is well exposed it can be seen to be knife sharp along a surface of a few inches of relief.

COPPER QUEEN MEMBER

Name And Type Area

The Copper Queen Limestone was named by Stoyanow (1936) for exposures in the Mule Mountain at Mount Martin (fig. 4 and loc. 65, fig. 1) as a separate formation but was considered by Hayes and Landis (1965) as the Copper Queen Limestone Member of the Abrigo Limestone in the same area. The member designation has since been extended to other localities in the western area (fig. 6) as the Copper Queen Member of the Abrigo Formation (Hayes, 1972).

General Description

At its type area the Copper Queen Member consists dominantly of thinly bedded laminated slightly sandy to silty limestone, and in all other areas it consists mostly of laminated slightly sandy dolomite.

Distribution And Stratigraphic Limits

The Copper Queen Member of the Abrigo Formation as currently defined is limited to the western area, as shown in figure 6. It is missing because of post-Cambrian erosion over most of the area but is preserved at a few localities in the eastern part.

The Copper Queen Member conformably overlies the upper sandy member of the Abrigo. At the extreme east in the Pedregosa and Swisshelm Mountains (as at locs. 61 and 64, fig. 1) it is conformably overlain by the El Paso Limestone, but farther west it is disconformably overlain by the Martin Formation of Devonian age.

The Copper Queen Member grades laterally eastward into an informal lower member of the El Paso Limestone in the central area (fig. 5).

Petrology

The Copper Queen Member is made up almost entirely of fairly resistant medium-gray to pinkish-gray limestone at and near the type area and of light-brownish-gray dolomite at other localities. A few thin beds of dolomitic sandstone are present at most places. The following descriptions of the rocks in the unit are based on the outcrop examination at five widely separated localities and on the examination of six thin sections.

The limestone at the type area is mostly laminated slightly sandy fine- to medium-grained lithiclast lime grainstone (calcarenite) and fossil-bearing lithiclast lime grainstone, but some interlaminated lime mudstone is present, as is oolite lime grainstone and packstone (fig. 13*A*).

The dolomite that makes up the member at most localities is either lithiclast dolomite grainstone (dolarenite) (fig. 13*B*) or dolomitized fine- to medium-grained lithiclast lime grainstone; most is slightly sandy or silty and some is thinly laminated.

The sandstone in the Copper Queen Member is well-sorted and brown-weathering generally cross-laminated dolomitic sandstone like that which makes up much of the underlying upper sandy member.

Sedimentary Structures

Notable sedimentary structures are virtually absent in the Copper Queen Member except for very minor dolomite intraformational conglomerate at Brandenburg Mountain (loc. 102) and for cross-laminations in most of the thin sandstone beds.

Porosity

The carbonate rocks of the Copper Queen Member appear on the outcrop and in thin section to be very low in porosity, although some dolarenites have considerable cement-filled intergranular porosity. One dolomite sample checked by the kerosene displacement method had 2.0 percent total porosity.

The very thin sandstone beds present at most localities may have porosities comparable to those of the sandstones of the upper sandy member but are probably much too thin to be effective reservoir rocks.

Thickness

Only two sections were examined in which the Copper Queen Member is conformably overlain by the El Paso Limestone and thus completely preserved from post-Cambrian erosion. In those sections, both in southeastern Cochise County, the Copper Queen is 120 feet thick (Pedregosa Mountains, loc. 61) and 148 feet thick (northern Swisshelm Mountains, loc. 64). At other localities the Copper Queen ranges in thickness from a few feet to slightly less than 100 feet.

Fossils And Age

Large numbers of trilobites and a few brachiopods have been collected from the type area of the Copper Queen Member at Mount Martin (loc. 65), where the unit is disconformably overlain by Devonian rocks (A. R. Palmer, in Gilluly, 1956; Hayes and Landis, 1965; this report, in "Fossil Lists"). These fossils are representative of zones of Franconian age (of Howell and others, 1944). The highest collection, from 16 feet below the top of the member, indicates an age very near the Franconian and Trempealeauan boundary (M. E. Taylor, written commun., Jan. 24, 1973). Species of the brachiopod *Billingsella* have been recovered from the lower part of the complete Copper Queen sequence in the northern Swisshelm Mountains (loc. 64) (Epis and Gilbert, 1957) and from the thin remaining part of the member at Brandenburg Mountain (near loc. 102) (Krieger, 1968e). *Billingsella* was also found with *Ptychaspis*-zone trilobites at the type area and is indicative of a Franconian age. It seems rather certain that the lower part of the Copper Queen is of Franconian age, and it is assumed that the upper barren part in the more complete sections may be of Trempealeauan (of Howell and others, 1944) or latest Cambrian age.

Upper Contact

At the extreme east the Copper Queen Member is conformably overlain by the El Paso Limestone with an indefinite contact. The contact used by Epis and Gilbert (1957) was placed at an upward change from dolomite to limestone, but I (Hayes, 1972) chose a contact 55-75 feet lower at a change from sandy but noncherty dolomite below to nonsandy but somewhat cherty dolomite above.

To the west the Copper Queen Member is disconformably overlain by the Martin Formation of Devonian age. The basal Martin beds in most places where they overlie the Copper Queen consist of cross-laminated sandy or silty dolomite. Not far above the base of the Martin in most sections is a distinctive bed of nearly white orthoquartzite.

EL PASO LIMESTONE

NAME AND TYPE LOCALITY

The El Paso Limestone was named by Richardson (1904, 1908) for exposures in the Franklin Mountains, El Paso County, Tex., near the Scenic Drive section (fig. 4 and loc. 45, fig. 1). At the type locality and throughout western Texas and much of southern New Mexico, the El Paso is now considered a group, but in westernmost New Mexico and in southern Arizona, its formational rank is retained. (See fig. 17 and attendant text discussion.)

GENERAL DESCRIPTION

The El Paso Limestone of the western area (fig. 6) consists almost entirely of thinly bedded limestone or dolomite that is slightly cherty at a few horizons.

DISTRIBUTION AND STRATIGRAPHIC LIMITS

In the western area (fig. 6) the El Paso Limestone is limited to a few exposures at and near the Pedregosa Mountains, Leslie Pass, and the northern Swisshelm Mountains (locs. 61, 63, and 64). It conformably overlies the Copper Queen Member of the Abrigo Formation and is disconformably overlain by strata of late Middle Devonian age.

PETROLOGY

The El Paso Limestone was given cursory examination at three localities in the western area. It does not differ appreciably from the upper part of the El Paso of the central area which is described later in this report. Most of the limestones are fine- to coarse-grained lithiclast or skeletal-lithiclast lime packstones to wackestones; some con-

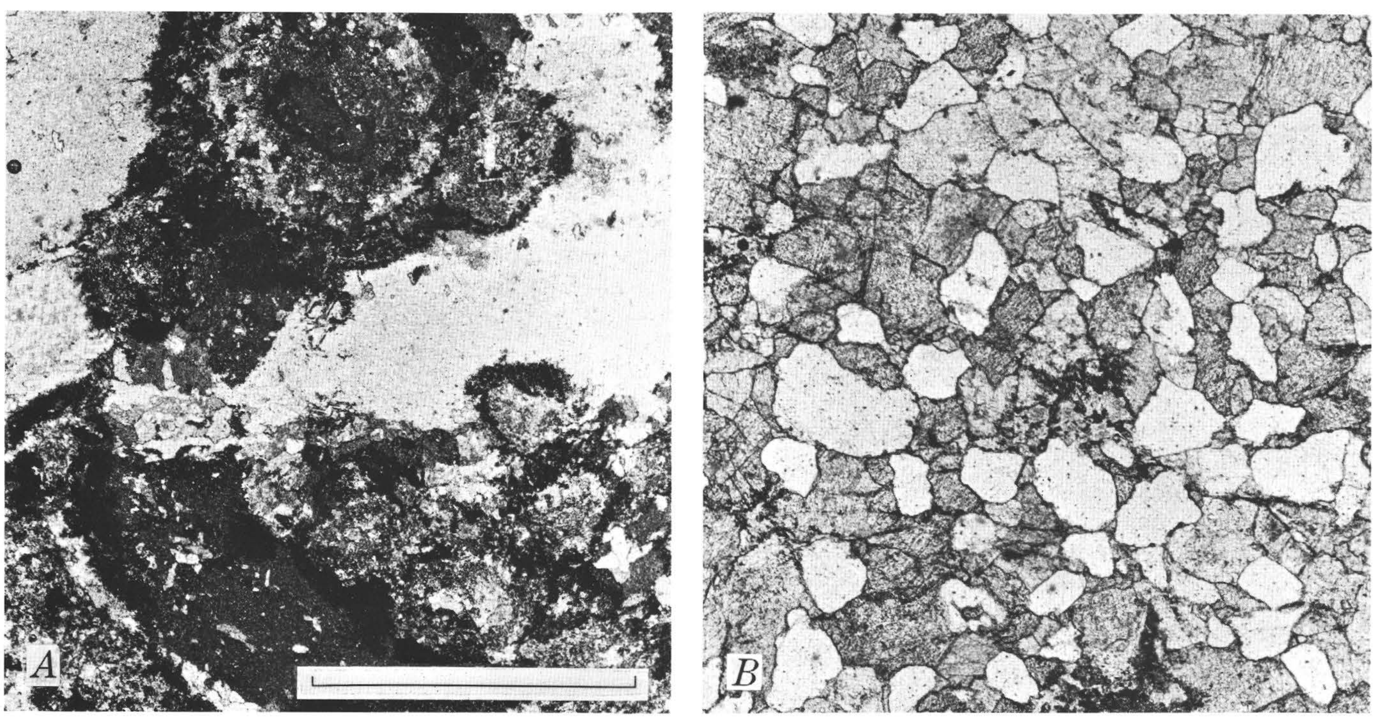


Figure 13.—Photomicrographs of Copper Queen Member of Abrigo Formation. Bar in *A* is 1 mm; views are same scale. *A*, Largely silicified oolite lime packstone from Nugget Canyon (loc. 77). White is chert, black is hematitic dust, and gray is chiefly dolomite. At most localities rock in this member is dolomitized and has no relict structure. In the Mule Mountains (loc. 65), where undolomitized, the member consists largely of lithiclast lime grainstone or fossil-bearing lithiclast lime grainstone. Plain light. *B*, Well-sorted quartzose lithiclast dolomite grainstone (dolarenite) from northern Swisshelm Mountains (loc. 64). This rock type is characteristic of the member at eastern localities. Plain light.

tain quartz silt. The lower 50-80 feet is dolomitized at most localities, and locally all of the El Paso is dolomite. Chert occurs in nodules and lenses.

SEDIMENTARY STRUCTURES

Sedimentary structures noted in the El Paso in the western area include minor small-scale cross-laminations in slightly silty dolomite at one locality, probable algal-mat dolomite in the lower part at most localities, and some beds of burrowed limestone at all localities.

POROSITY

No porosity measurements were made of El Paso Limestone from the western area; presumably it differs little in porosity from the El Paso of the central area described later in this report. On the outcrop, porosities apparently are very low.

THICKNESS

The thickest known section of El Paso in the western area is at Leslie Pass (loc. 63) in the Swisshelm Mountains, where Epis and Gilbert (1957) measured 435 feet of the formation. The El Paso thins abruptly westward to a wedge edge and is absent west of long 109°45′ W.

FOSSILS AND AGE

No guide fossils have been found in the basal 120 feet or more of the El Paso Limestone in the western area. Cephalopods reported by Epis and Gilbert (1957) from higher beds indicate an age for those beds no older than Early Ordovician zone D of Utah (Hintze and others, 1969) (fig. 5). Lithologic correlation with El Paso sections in the central area suggests, however, that the highest El Paso beds of the western area cannot be much younger than zone D and certainly are not as young as zone G. The barren basal beds of the El Paso may contain equivalents of one or all of zones A, B, and C and could conceivably contain beds of latest Cambrian age. The highest fossils known in the underlying Copper Queen Member of the Abrigo Formation are of Franconian age. Until further information is available, it is arbitrarily assumed that the uppermost beds of the Abrigo are of Trempealeauan age (latest Cambrian) and that the Cambrian and Ordovician boundary is near the arbitrary contact between the Abrigo and El Paso in the western area.

UPPER CONTACT

The contact of the El Paso with the overlying Devonian beds is disconformable and easily recognized; the relatively pure carbonate rocks of the El Paso contrast sharply with the soft-weathering siltstones and silty carbonate rocks of the Devonian.

EASTERN PART OF STUDY REGION

BLISS SANDSTONE

NAME AND TYPE LOCALITY

The Bliss Sandstone was named by Richardson (1904) for exposures in the Franklin Mountains, Tex. (between locs. 44 and 45, fig. 1); a formal type section was not designated. A section in McKelligon Canyon (fig. 14) (loc. 92) near the type locality is described and is designated the principal reference section in this report. (See description under "Selected Measured Sections.")

GENERAL DESCRIPTION

In its type locality and at all localities to the east of the longitude of the type locality, the Bliss is made up almost exclusively of sandstone. To the northwest and west of the type locality, significant amounts of sandy limestone or dolomite and (or) siltstone or shale are present at most localities. The Bliss ranges in thickness from 0 to about 375 feet, the thickest sections being toward the south.

DISTRIBUTION AND STRATIGRAPHIC LIMITS

The Bliss Sandstone is confined to the eastern area as outlined in figure 14. The name Bliss is now applied to the basal Paleozoic clastic formation throughout that area. Gordon and Graton (1907) used the term Shandon Quartzite for the unit in part of southwestern New Mexico, but it was never widely adopted. Darton (1917b) and Paige (1916) abandoned Shandon and extended Bliss into that area. Flower (1958) suggested that the term Shandon be revived and that the Bliss be only a part of the Shandon, but the term Bliss is well established, and such a division seems unnecessary, inappropriate, and undesirable.

The Bliss unconformably overlies Precambrian rocks wherever it occurs and is conformably overlain by the El Paso Group, except very locally at the extreme north (Mockingbird Gap and Fra Cristobal Range, locs. 34 and 37), where it is disconformably overlain by Pennsylvanian rocks.

PETROLOGY

In the type locality and in most areas east of long 107° W., the Bliss Sandstone is made up mostly of sandstone, generally more than 90 percent (fig. 14). The subordinate lithologies in these eastern areas include thin interbeds of siltstone or shale and, rarely, a thin bed or two of generally sandy limestone or dolomite. West of long 107° W., interbedded carbonate rock occurs in the formation in appreciable amounts at most localities and is the dominant lithology in some places. Siltstone and shale are important constituents of the formation at several localities northwest of the type locality, most notably at Eaton Ranch in the San Mateo Mountains and at Amphitheater Canyon in the Fra Cristobal Range (locs. 35 and 36, fig. 1) near the north wedge edge of the Bliss. Hematite is an important cementing agent of the Bliss in most areas, particularly west of long 106° W., and thin beds of oolitic hematite are interbedded with sandstone at many localities, especially toward the northwest. Glauconite-rich beds are common at all localities except at the extreme southeast (Beach Mountain, loc. 48) and southwest (Mescal Canyon, loc. 24) of the area of Bliss distribution in the report area. The presence of rather abundant hematite and

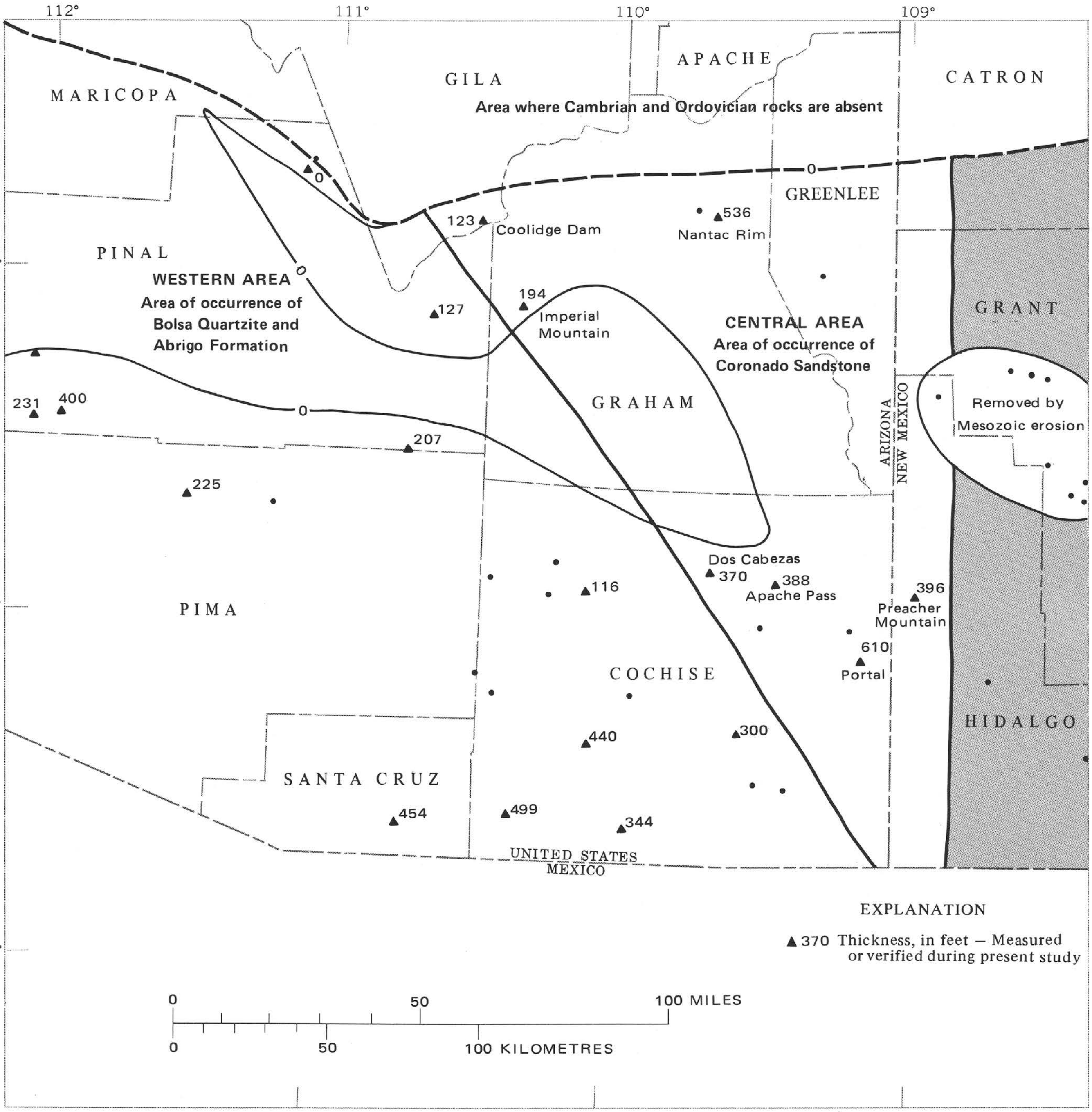
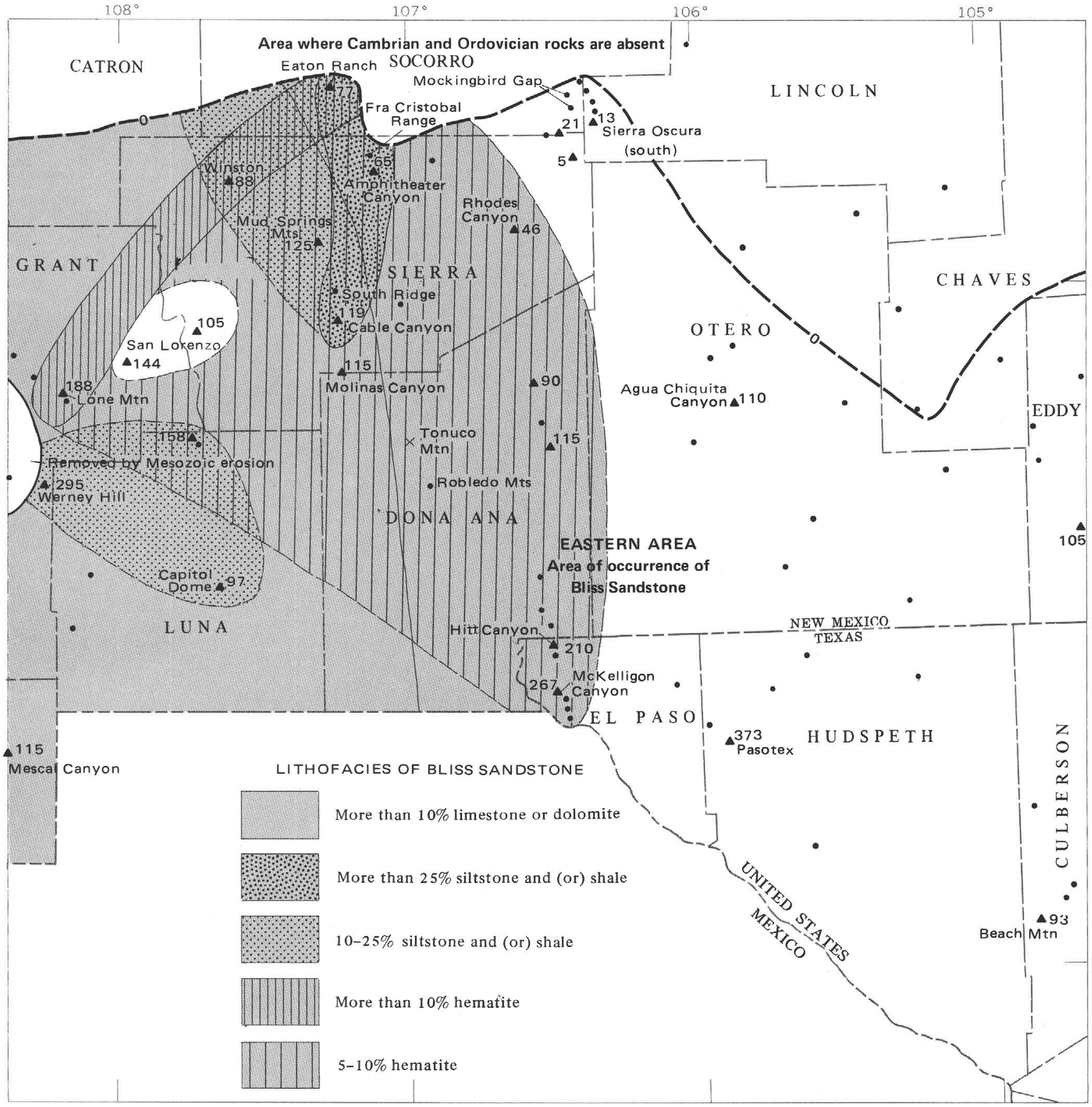


FIGURE 14.—Lithofacies of Bliss Sandstone and some thicknesses

glauconite in the Bliss gives a dark appearance to the formation as a whole, and, especially in western and northern localities, outcrops of the Bliss are conspicuously darker than overlying and underlying units. The weathered colors of individual beds range from blackish red and dark greenish gray to pinkish gray and yellowish gray, but most beds are in the dark-reddish-brown to pale-brown range. Freshly fractured rock is generally somewhat paler, and most is in the pale-red to pinkish-gray range.

The following statements on the texture and composition of sandstone and siltstone from the Bliss are based on field examination at 25 localities and on the examination of 84 thin sections, of which 70 were point counted. An additional 18 thin sections of carbonate rock from the Bliss were examined.

Nearly all sandstones in the Bliss are grain-supported arenites; most are orthoquartzites (fig. 15*H*) or feldspathic sandstones (fig. 15*A*), and a few, especially near the base, are arkoses (fig. 15*E*). Glauconite grains are present in



of Bolsa Quartzite, Coronado Sandstone, and Bliss Sandstone.

Bliss sandstones in small amounts at most localities, but such grains are known to occur in abundance only in two discrete areas: (1) a large area in south-central New Mexico and extreme western Texas bounded roughly by lines connecting Molinas Canyon, south Sierra Oscura, and Scenic Drive (locs. 16, 28, and 45); and (2) a smaller area in Grant County, N. Mex., including Werney Hill, Lone Mountain, and San Lorenzo (locs. 20, 21, and 38). Lewis (1962) discussed the occurrence of glauconite in the Bliss near Lone Mountain (loc. 21).

All observed sandstones of the Bliss are cemented by quartz (fig. 15*A*, *H*), carbonate (fig. 15*D*), or hematite (fig. 15*C*) or by a combination of these (fig. 15*F*, *G*). Quartz cement is the most abundant, but at nearly all localities either carbonate cement or hematite cement or both occur in significant amounts. No variation in the distribution of carbonate cement seems to be regionally consistent, but the decided tendency is for the cement to be more common in the upper part of the formation. On the other hand, hematite cement seems to be common only in north-

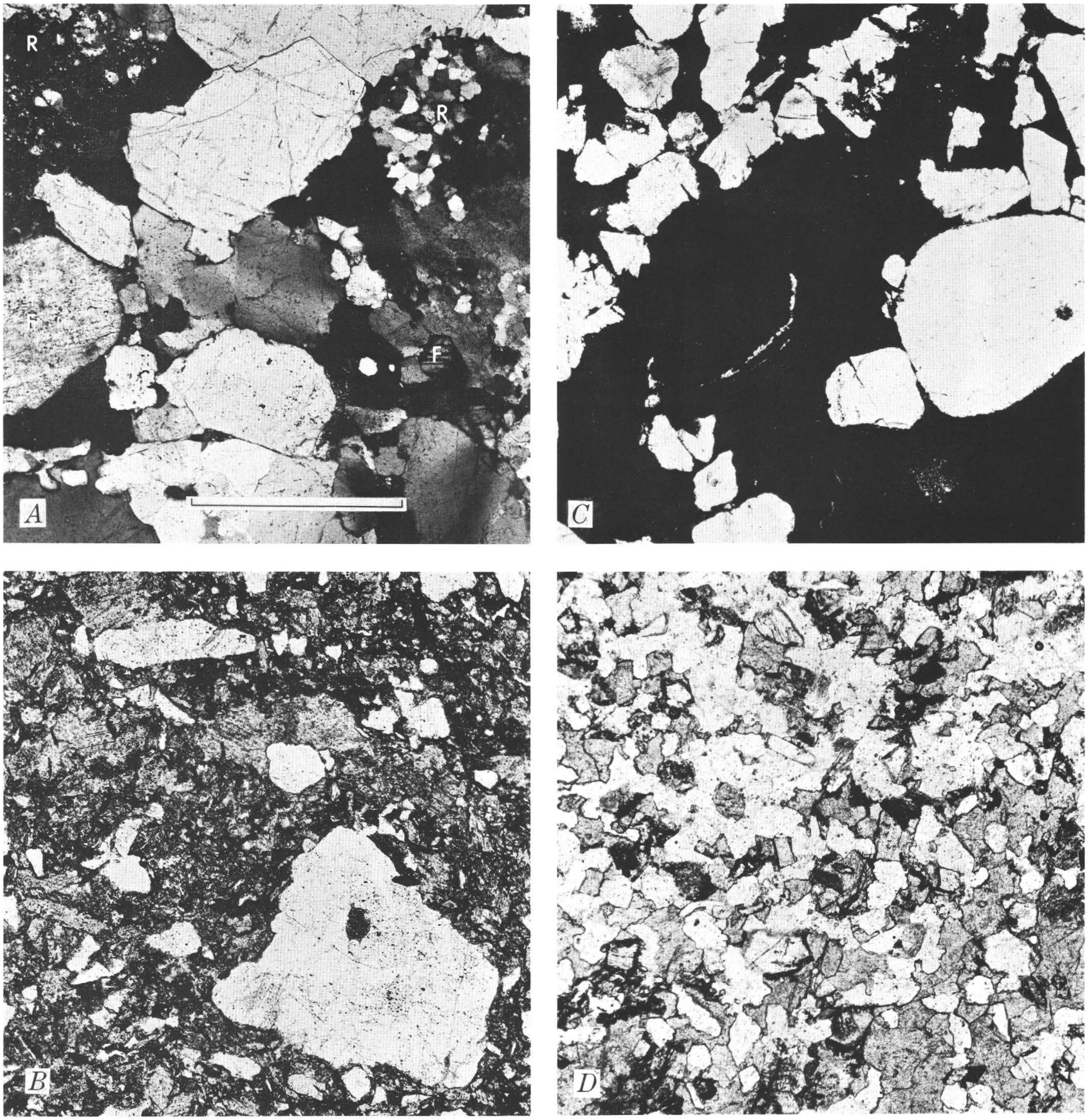
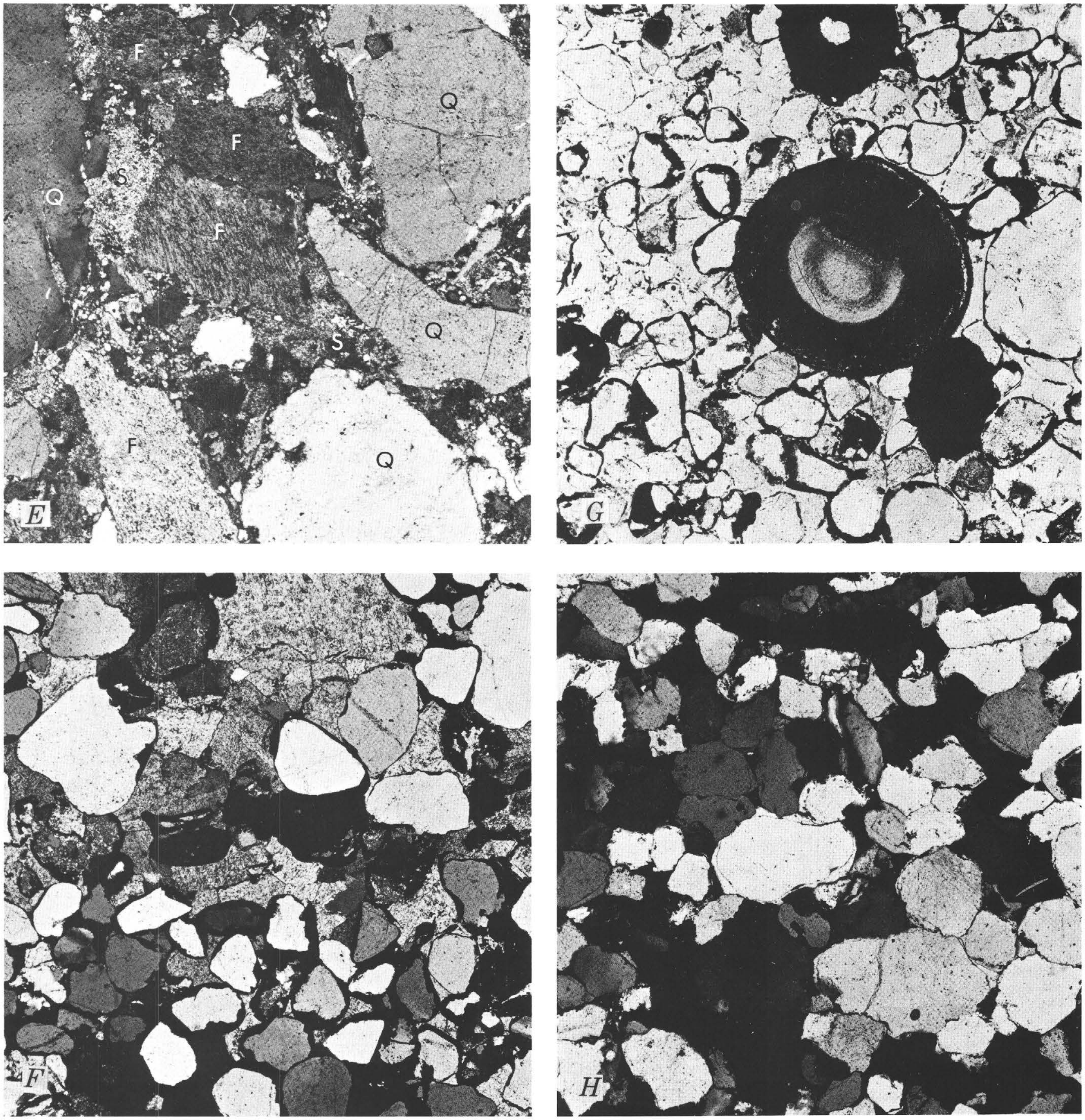


FIGURE 15. (Above and facing page).—Photomicrographs of Bliss Sandstone. Bar in *A* is 1 mm; all views are same scale. *A,* Poorly sorted very coarse grained sandstone from base of formation at Beach Mountain (loc. 48). This sandstone, which rests on Precambrian sedimentary rocks, contains large lithic fragments (R) of siltstone and quartzite as well as some feldspar (F). Cement is quartz, and original boundaries of quartz grains are largely obscured. Crossed nicols. *B,* Very sandy fine-grained dolomite from about 60 feet above base of formation at Capitol Dome (loc. 39). Rock as dolomitic as this is interbedded with sandstone in most western localities. The dolomite appears to be slightly metamorphosed. Plain light. *C,* Extremely hematitic sandstone from 2 feet above base of formation at Rhodes Canyon (loc. 10). Here hematite (black) occurs both as cement and as replacement(?) of quartz (white) grains. Similar hematitic sandstone occurs in both Cambrian and Ordovician parts of the Bliss in most northern localities. Plain light. *D,* Very dolomitic sandstone from lower part of rock assigned by Zeller (1965) to the Bliss Sandstone at Mescal Canyon (loc. 24). This rock is not overlain by less dolomitic sandstone and might more properly be assigned to the overlying Hitt Canyon Formation. Plain light. *E,* Poorly sorted coarse arkose from base of formation at Capitol Dome (loc. 39).



Feldspar (F) is nearly as abundant as quartz (Q). Matrix is largely quartz and feldspar silt but includes considerable sericite (S). Arkose such as this is common where the Bliss rests on a surface of moderately high relief carved in Precambrian granite. Crossed nicols. *F*. Calcareous and hematitic laminated sandstone from 30 feet above base of formation at Werney Hill (loc. 20). Here the hematite (black) apparently has replaced some of the sparry calcite cement around quartz grains. This type of sandstone is very common in the Bliss. Crossed nicols. *G*, Hematitic siliceous sandstone from 14 feet above base of formation at Cable Canyon (loc. 15). Here the chief cementing material is quartz, but hematite forms rings around most grains and also occurs as large hematitic ooids. Such rock occurs most commonly in more northern localities of the Bliss. Plain light. *H*, Porous well-sorted medium-grained siliceous sandstone from about 160 feet above base of formation at Werney Hill (loc. 20). This quartzose sandstone is cemented with quartz in optical continuity with grains, but most original grain boundaries are evident. Some of the black areas are porous voids, and others are quartz at extinction. Such sandstone is generally present in the Bliss but is not predominant in most areas. Crossed nicols.

western areas as shown in figure 14, where it may occur in any part of the formation from the base to near the top. Where various cements occur together, quartz cement generally replaces carbonate cement and hematite cement generally replaces both quartz and carbonate cement.

In addition to hematite cement in many of the sandstones of the Bliss, hematite ooids are commonly present in many northern and western localities (fig. 15*G*) and greatly predominate over quartz grains in some beds. Five selected samples that appeared to be particularly high in hematite were examined for total iron content by the atomic-absorption method by Violet Merritt of the U.S. Geological Survey. A sample from a poorly exposed bed about 25 feet above the base of the Bliss at Lone Mountain (loc. 21) in Grant County showed 41 percent iron as Fe_2O_3, and a sample from a 4-foot-thick bed 12 feet above the base of the Bliss at the Winston section in northeastern Sierra County showed 37.5 percent iron as Fe_2O_3. Kelley (1949) discussed the potential of some of these oolitic hematites of the Bliss as iron-ore deposits and described the brief mining of such ore in the Caballo Mountains, N. Mex. (near Cable Canyon, loc. 15).

Sandstone at the base of the Bliss is locally conglomeratic and is nearly everywhere very coarse and poorly sorted (fig. 15*A*, *E*). Near the top of the Bliss most sandstones are fine grained and fairly well sorted.

The areas where siltstone and shale are moderately abundant in the Bliss Sandstone are generally coincident with areas where hematite, glauconite, and carbonate are also moderately abundant. (See fig. 14.) Although none of the fine-grained rocks were examined in the laboratory, field examination indicated that most of the fine siltstones and the shales are calcitic, hematitic, or glauconitic, or all three.

Limestone and dolomite beds included in the Bliss Sandstone are for the most part, similar to those in the lower part of the overlying El Paso Limestone and are not described in detail here. Nearly all are quartzose (fig. 15*B*), many are glauconitic, and some are slightly hematitic. Most of the limestones are fine-grained lithiclast lime grainstones to packstones, some are coarse lithiclast lime wackestones, and a few are oolite packstones. Some of the dolomites appear to be true dolarenites, but most are probably dolomitized lithiclast limestones. Figure 14 and plate 1 together roughly show the lateral and vertical distribution of carbonate beds in the Bliss.

SEDIMENTARY STRUCTURES

Small- and medium-scale planar cross-laminations (fig. 16*A*) are the most conspicuous and most abundant sedimentary structures seen in the Bliss Sandstone. Cross-laminations can be seen in all parts of the sequence at all localities, although most of the sandstone beds in the formation are not cross-laminated at most places. Seeland (1968) measured the attitudes of inclination of numerous sets of cross-laminated beds in the Bliss for at least six localities within the present report area. A majority of those measured at two western localities (San Lorenzo and Capitol Dome, locs. 38 and 39) dip southwestward and agree rather closely with most sets he measured to the west in the Bolsa Quartzite and Coronado Sandstone. Sets that were measured farther east are less consistent from one place to another—slightly east of north at Agua Chiquita Canyon and near the Pasotex section (locs. 1 and 56), east-southeast near South Ridge and McKelligon Canyon (locs. 14 and 92), and southwest at Beach Mountain (loc. 48).

Other sedimentary structures seen at many places in sandstone of the Bliss are fucoidal tracks and trails on bedding surfaces and *Scolithus* tubes.

Intraformational chip conglomerates were noted in dolomite or dolomitic sandstone beds at several localities (fig. 16*B*).

POROSITY

Porosities of sandstones from the Bliss vary but, in general, are higher than those of the more siliceous Bolsa Quartzite. The average effective porosity of four samples tested with the mercury porosimeter is 3.4 percent; the average total porosity of eight other samples tested by the kerosene-displacement method is 7.6 percent; and the average porosity of five additional samples checked by point counting is 4.8 percent.

The total porosity of two carbonate samples tested from the Bliss is 3.5 percent and 4.7 percent. Most porosity observed in thin sections of carbonates from the Bliss is microfracture porosity; some carbonates showed vuggy porosity, and one lithiclast lime grainstone had intraparticle porosity.

THICKNESS

The thickness of the Bliss Sandstone ranges from depositional and erosional wedge edges to as much as 373 feet at the Pasotex section (loc. 56) in the Hueco Mountains, Tex. Erosional wedge edges occur along the north boundary of the Bliss distribution area and around a large Mesozoic highland in western New Mexico (fig. 14). In general, the thickest complete sections are in the southern part of the region, but even there, thicknesses change radically within a few miles owing to relief on the underlying surface. In the Franklin Mountains of western Texas the Bliss is locally absent because of nondeposition (Kottlowski and others, 1969; Harbour, 1972) between McKelligon and Hitt Canyons (locs. 92 and 44), where the formation is 267 and 210 feet thick, respectively (fig. 14).

FOSSILS AND AGE

Guide fossils are sparse in the Bliss Sandstone. Late Cambrian fossils have been found at some localities, and Early Ordovician forms have been found at others. Flower (1969) has discussed the problems relating to the age of the Bliss on a regional basis. As a whole, the faunal evidence available, together with lithologic correlations, indicates that the Bliss becomes younger from west to east.

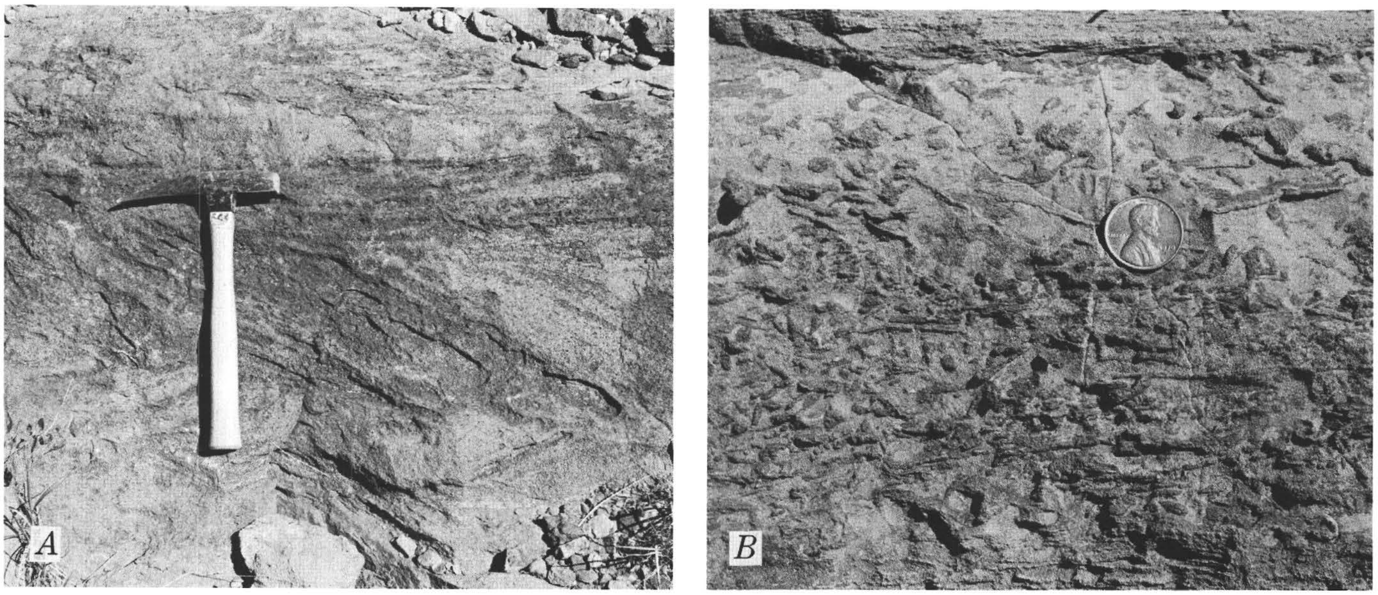


FIGURE 16.—Outcrops of Bliss Sandstone at Lone Mountain (loc. 21). *A*, Torrentially cross-laminated sandstone 112 feet above base of Bliss Sandstone. Such sandstone is common in the Bliss at most localities. *B*, Intraformational conglomerate about 150 feet above base of Bliss Sandstone. Penny gives scale. Here sandy dolomite clasts are in a dolomite matrix. This part of the Bliss at this locality is probably of earliest Ordovician age and thus somewhat younger than similar rock in the El Paso Limestone at Preacher Mountain (loc. 23). (See fig. 26*A*.)

At locality 20 (fig. 1) near Werney Hill in Grant County, one of the westernmost exposures of the Bliss, we found brachiopods about 30 feet above the base of the Bliss, which Reuben J. Ross, Jr. (written commun., May 11, 1970) identified as *Eorthis* sp. of Late Cambrian (Trempealeauan) age. Ballman (1960) had previously reported the Late Cambrian trilobite *Camaraspis* sp. from near the base of the Bliss at the same locality. The easternmost locality in which Cambrian fossils have been found in the Bliss is San Diego, or Tonuco, Mountain in Dona Ana County, about 12 miles north-northwest of Robledo Mountain (loc. 42), where trilobites of Late Cambrian (Franconian) age were reported to occur by Flower (1953). East of the longitude of San Diego (Tonuco) Mountain only Ordovician fossils have been reported from the Bliss.

There seems to be little doubt that the top of the Bliss is younger in the east than toward the west. According to Flower (1969) the upper Bliss of the Van Horn area in Texas (near Beach Mountain, loc. 48) contains impressions of cephalopods that indicate an age as young as that of beds 100 feet above the Bliss in areas to the west. King (1965) concluded that the entire Bliss of the Van Horn area is of Ordovician age. Earliest Ordovician fossils are known from the upper part of the Bliss at least as far west as the Mud Springs Mountains of New Mexico (loc. 13) (Flower, 1953).

All the faunal evidence available used in conjunction with lithologic correlations suggests that in the western part of the region the lower part of the Bliss is Late Cambrian (Franconian) in age and that the upper part is of Early Ordovician age. The evidence further indicates that at the easternmost localities the entire Bliss is of Ordovician age and that the top is younger than to the west. Exactly where the base of the formation becomes Ordovician eastward is unknown, but our interpretation is shown on plate 1 and in figure 46.

CONTACTS

The basal contact of the Bliss Sandstone with underlying Precambrian rocks is everywhere unconformable and sharp. In most places the Bliss overlies crystalline rocks, but even where it overlies younger Precambrian sedimentary rocks there is no problem in recognizing the unconformable contact because the basal Bliss contains pebbles of the underlying rocks (King, 1965).

The upper contact of the Bliss with the overlying Hitt Canyon Formation of the El Paso Group varies somewhat in nature from west to east. At most western localities the contact is intertonguing. At such places, as exemplified at Lone Mountain (loc. 21) in Grant County (pl. 1), where limestones lithologically similar to those of the basal Hitt Canyon Formation occur below sandstones like those of the Bliss, the contact is usually chosen at the top of the highest conspicuous sandstone. At most eastern localities the contact is gradational but fairly sharp—sandstone at the top of the Bliss gives way rather abruptly to sandy limestone or dolomite at the base of the Hitt Canyon. At most Texas localities the contact is very abrupt and has been interpreted as a disconformity (Richardson, 1904; Cloud and Barnes, 1946). As noted by King (1965), if the contact at

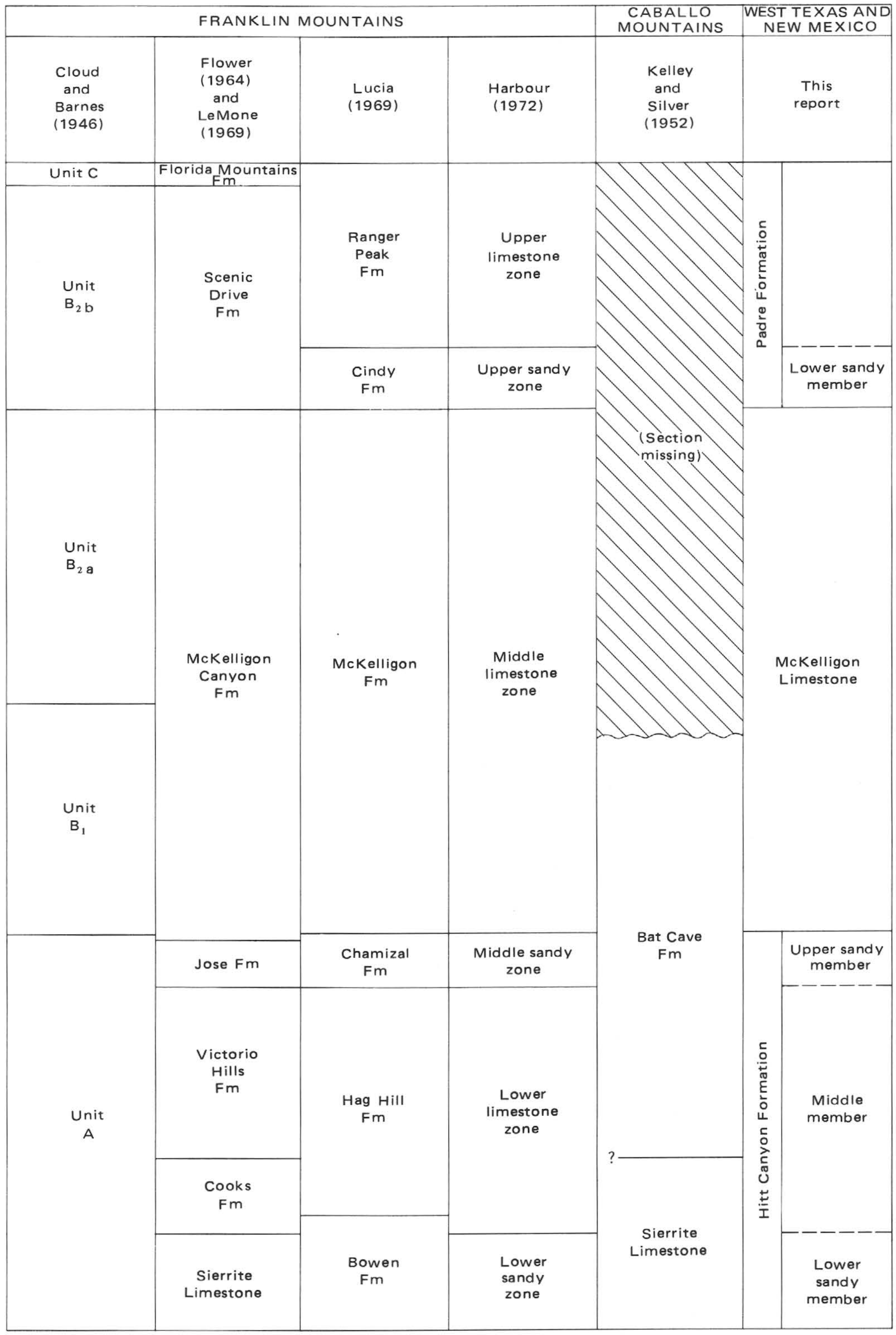


FIGURE 17.— Subdivisions of the El Paso Limestone (or Group) as used by various workers in the region, showing their probable relations to one another. Flower (1964) and LeMone (1969), in some areas other than the Franklin Mountains, recognized the Big Hatchet Formation between the Sierrite and Cooks and, in ascending order, the Mud Spring Mountain and Snake Hills Formations between the Jose and McKelligon Canyon. Where the nomenclatures of Flower (1964) and LeMone (1969) do not coincide, that of LeMone is used—for example, Flower used the terms Victorio, McKelligon, and Florida for the Victorio Hills, McKelligon Canyon, and Florida Mountains.

the Texas localities is indeed disconformable, the hiatus represented by the disconformity must be slight.

EL PASO GROUP

PREVIOUS NOMENCLATURE

The El Paso Limestone was named by Richardson (1904) for exposures near Scenic Drive (fig. 4 and loc. 45, fig. 1) in the Franklin Mountains of Texas. He later restricted the El Paso by removing the upper part as the Montoya Limestone (Richardson, 1908). Gordon and Graton (1907) used the term Mimbres Limestone for the unit in part of southwestern New Mexico; that term was abandoned and was replaced there with the name El Paso by Paige (1916) and Darton (1917b), and since then the name has been extended throughout much of the present report region.

Kelley and Silver (1952), working in the Mud Springs and Caballo Mountains (between locs. 13 and 16), proposed elevating the El Paso to a group composed of two formations, the Sierrite Limestone and the overlying Bat Cave Formation (fig. 17). With varying degrees of success, other workers have attempted to extend these subdivisions to nearby areas in New Mexico.

Flower (1964) and LeMone (1969) also considered the El Paso as a group and proposed as many as 10 formations in the group (fig. 17). The lowest of these was called the Sierrite Limestone although Flower (1964) recognized that his Sierrite represented a shorter time interval of deposition and included a more restricted lithology than the Sierrite of Kelley and Silver (1952).

Lucia (1969) also regarded the El Paso of the type locality as a group, but he divided it into six formations. He accepted Flower's McKelligon Formation in the middle of the El Paso but proposed five new formational names to replace most of those used by Flower (1964) and LeMone (1969), as is shown in figure 17.

Harbour (1972) maintained a formational status for the El Paso but divided it into six informal subdivisions that coincide almost exactly with the formations of Lucia (1969).

All the various subdivisions of the El Paso referred to above, as well as the informal subdivisions used by Cloud and Barnes (1946) in western Texas, are recognizable and useful in the local areas in which they were proposed; and some of the contacts can be recognized with a reasonable degree of certainty over much of the region of the El Paso distribution.

NOMENCLATURE USED IN THIS REPORT

The El Paso is here considered a group throughout the eastern area as outlined in figure 6; west of there it is considered a formation. Three formations of the El Paso Group are recognizable, mappable, and correlatable with a reasonably high degree of certainty throughout the report region (fig. 17). The lowest of these, herein named the Hitt Canyon Formation, coincides with unit A of Cloud and Barnes (1946) and includes as many as seven formations of Flower (1964) and LeMone (1969), three formations of Lucia (1969), and three informal zones of Harbour (1972). The McKelligon Limestone in the middle of the group is an adoption of the McKelligon Formation of Flower (1964); it coincides with units B_1 and B_{2a} of Cloud and Barnes (1946) and with the middle limestone zone of Harbour (1972). The upper formation is the herein-named Padre Formation, which includes units B_{2b} and C of Cloud and Barnes (1946), two formations of Flower (1964) that coincide with Cloud and Barnes' units, two formations of Lucia (1969), and two informal zones of Harbour (1972) that coincide with Lucia's formations.

HITT CANYON FORMATION

NAME AND TYPE SECTION

The Hitt Canyon Formation, here named, comprises the lower 531 feet of the El Paso Limestone (here elevated to El Paso Group) as described by Harbour (1972) in his stratigraphic section 5 (Hitt Canyon, fig. 4 and loc. 44, fig. 1, of this report) measured on a spur on the east side of the Franklin Mountains, El Paso County, Tex., about half a mile south of the drainage course of Hitt Canyon. This section (units 5-13 as described by Harbour) is designated as the type section. As thus defined, the Hitt Canyon Formation comprises the lower sandy, lower limestone, and middle sandy zones of the El Paso as used by Harbour (1972) and is equivalent to unit A of the El Paso as used by Cloud and Barnes (1946) at Beach Mountain (loc. 48 of this report). The section of unit A at Beach Mountain is here designated as the principal reference section of the Hitt Canyon.

In so naming the Hitt Canyon, we recognize that as defined it includes an interval in the Franklin Mountains that was divided into four formations by Flower (1964) and that was divided into three formations by Lucia (1969). All of those formations as defined are so thin, have mutual contacts that are so subtle, and generally occur on such steep slopes that they are not practically mappable units at scales most commonly adopted for mapping in the region. All the units are recognizable, however, in the Franklin Mountains; and many can be recognized with some degree of confidence in some other areas and, thus, would be suitable members of the Hitt Canyon. Unfortunately, none of the names used by Lucia (1969) was taken from properly named geographic features. The Sierrite Limestone of Flower (1964) is not acceptable as a member name because it is a redefinition of the Sierrite of Kelley and Silver (1952). The Jose of Flower (1964) cannot be used because it was not named for a properly recognized geographic feature. Flower's (1964) Cooks and Victorio might be acceptable as local member names, but we believe that the contact between them, being a contact of dolomite and limestone, is not of stratigraphic significance.

General Description

The Hitt Canyon Formation is a generally thinly layered carbonate unit which is notably quartzose in the basal part and which is commonly quartzose and locally oolitic in the uppermost part. It ranges in thickness from slightly more than 200 feet to nearly 600 feet.

Distribution And Stratigraphic Limits

The Hitt Canyon Formation as presently defined is restricted to the eastern area as outlined in figure 6. Its equivalents extend farther to the west but, for the present, are assigned to the El Paso Limestone.

The Hitt Canyon nearly everywhere conformably overlies the Bliss Sandstone except very locally where the Bliss is absent owing to nondeposition and the Hitt Canyon unconformably overlies Precambrian rocks. In the southern part of the region the Hitt Canyon is conformably overlain by the McKelligon Limestone of the El Paso Group. To the north it is disconformably overlain by the Montoya Group of Middle to Late Ordovician age or by younger rocks.

Petrology

The Hitt Canyon Formation is made up almost entirely of rather thinly layered carbonate rocks that in most localities are conspicuously quartzose in the basal 30-100 feet and somewhat quartzose in the top 50-125 feet. The carbonate rocks are dominantly limestone in the vicinity of the Caballo and Hueco Mountains (locs. 13, 15, and 56), dominantly dolomite to the north and east (locs. 1, 7, 9, 18, 27, 28, 35, and 48), and variable in other areas. The following descriptions of the lithologic character of the Hitt Canyon are based on the outcrop examination of the formation at 24 localities and on the examination of 112 thin sections.

Carbonate beds in the lower part of the Hitt Canyon are in general made up of alternating very quartzose laminae and generally thicker slightly quartzose laminae; the relatively quartzose laminae usually weather to pale brown and stand out in relief on the outcrop (fig. 18*A*). The intervening less quartzose laminae are mainly fine-grained lime grainstones or packstones made up of variable ratios of algal(?) and other skeletal grains and lithiclasts (fig. 19*A*); fossil-bearing lime mudstones are relatively sparse. The amount of quartz sand in the lower part of the formation increases from west to east, and at Beach Mountain (loc. 48) a considerable amount of sandstone is included.

Above the basal quartzose part of the formation, limestone fabrics are more diverse but tend to reflect less agitated depositional environments. Skeletal lime wackestone (fig. 19*B*) and fossil-bearing lime mudstone dominate, but fossil-bearing oolite lime packstones and lithiclast lime packstones are also common and become increasingly abundant upward. Some lime mudstones and wackestones display an intricate network of burrows filled with slightly silty lime mudstone (fig. 18*B*). Coarse lithiclast lime wackestones occur both in continuous beds (fig. 18*C*) and, at some localities, in "channels" cut in massive fossil-bearing lime mudstone. Although, in general, the middle part of the Hitt Canyon is free of quartz sand and has a low quartz silt content, it does become somewhat quartzose eastward (as at Agua Chiquita Canyon and Beach Mountain, locs. 1 and 48).

The upper part of the Hitt Canyon, like the lower part, is quartzose at most localities and, even where it is not, can generally be separated from the middle part by the increasing abundance of medium-gray-weathering beds of lithiclast lime packstone to grainstone, oolite packstone to grainstone (fig. 19*C*, *D*), and, in some localities, coarse-grained dolarenite. As with the lower and middle parts of the Hitt Canyon, the upper part is particularly quartzose toward the east and, at Agua Chiquita Canyon and Beach Mountain (locs. 1 and 48), contains beds of dolomitic quartz sandstone.

Secondary chert is irregularly distributed in the Hitt Canyon Formation at most localities. It generally occurs as sparingly distributed irregular nodules of dark- to light-gray porcelaneous chert and sparsely occurs as nearly complete replacement of beds as much as 2 feet thick; it is most abundant in the middle part of the formation.

Sedimentary Structures

A moderate diversity of sedimentary structures indicative of deposition in shallow subtidal and low intertidal environments occurs in the Hitt Canyon Formation. Much more work than was expended on this project would have been necessary to have evolved a detailed environmental analysis. The comments below are sufficient for a general analysis and may be sufficient to stimulate further research by sedimentary petrologists.

Intraformational conglomerates (fig. 18*C*) can be seen in any part of the formation but seem to be more common in the basal and uppermost parts. Most contain small chips, but some have chips of algal-mat dolomite as much as 2 inches across. Algal-mat dolomites from which the chips in some of the conglomerates were derived are present in the formation, particularly toward the base, but are not abundant. Many of the intraformational chip conglomerates may be indicative of subaerial desiccation, but other desiccation features, such as mud cracks and bird's-eye structures, are sparse.

Oncolites and digitate algal stromatolites are commonly seen, especially in the middle part of the formation. Also commonly seen in the middle part of the formation, especially at Mud Springs Mountains, Cable Canyon, San Lorenzo, Capitol Dome, and the Pasotex section (locs. 13, 15, 38, 39, and 56), are elongate mounds of fossil-bearing lime mudstone that were channeled and filled with coarse skeletal-lithiclast lime packstone to wackestone; these are similar to carbonate mounds in the overlying McKelligon Limestone described by Toomey (1970).

Some beds, especially in the middle part of the Hitt Canyon, were intricately burrowed (fig. 18*B*). Burrowed beds as much as 3 feet thick are typically very extensive, and one was used by Harbour (1972) as a marker horizon throughout a large part of the Franklin Mountains. Surface tracks and trails, though less easily seen than burrowed rock, are also common in the middle part of the Hitt Canyon.

The sandstones, sandy dolarenites, and lime grainstones in the lower and upper parts of the Hitt Canyon commonly display small-scale low-angle cross-laminations that are indicative of oscillating currents.

Porosity

Limited studies indicate that the greatest porosities in the Hitt Canyon Formation are in the upper part of the formation and that, in general, porosities in the formation are higher in western Texas than in New Mexico. Because of the effects of near-surface weathering, porosity measurements of rocks from the outcrop probably do not accurately represent the porosities that the same rocks might have if they were deeply buried. Nevertheless, we determined the effective porosities of 13 outcrop samples by the mercury-porosimeter method and the total porosities of an additional 28 samples by the kerosene-displacement method; most of those samples and others were checked in thin section for porosity types.

The highest limestone porosities we measured are in oolite grainstones and coarse lithiclast lime packstones from the upper half of the formation. The highest effective porosity measured for these rock types was 6.1 percent (at Mud Springs Mountains, loc. 13), and the lowest total porosity determined was 2.6 percent. Most of the porosity in these rocks is interparticle porosity, but some is intraparticle porosity.

Medium- and coarse-grained dolomites from the upper half of the formation vary greatly in porosity, but some show total porosities from 4.0 percent to 5.4 percent. The highest measured porosity is a combination of interparticle and fracture porosity.

Except for a few rocks with moldic, vuggy, or fracture porosity, most lime mudstones or wackestones, fine-

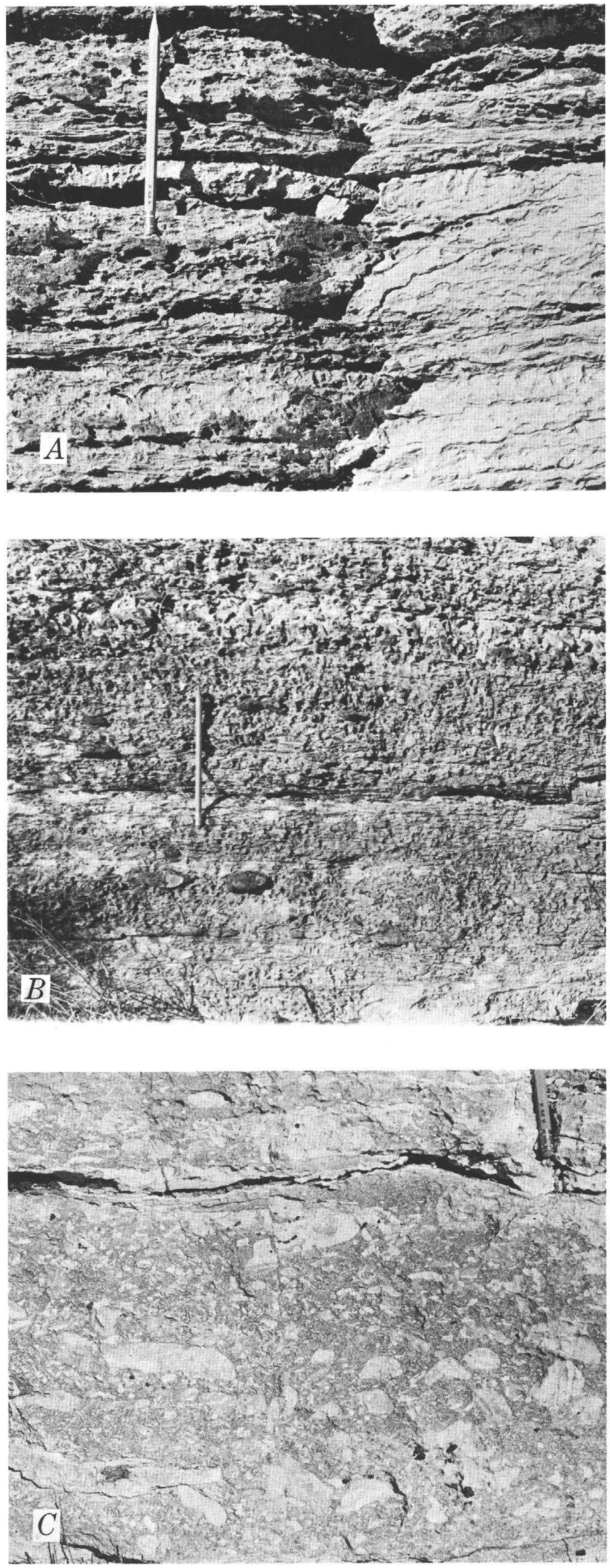
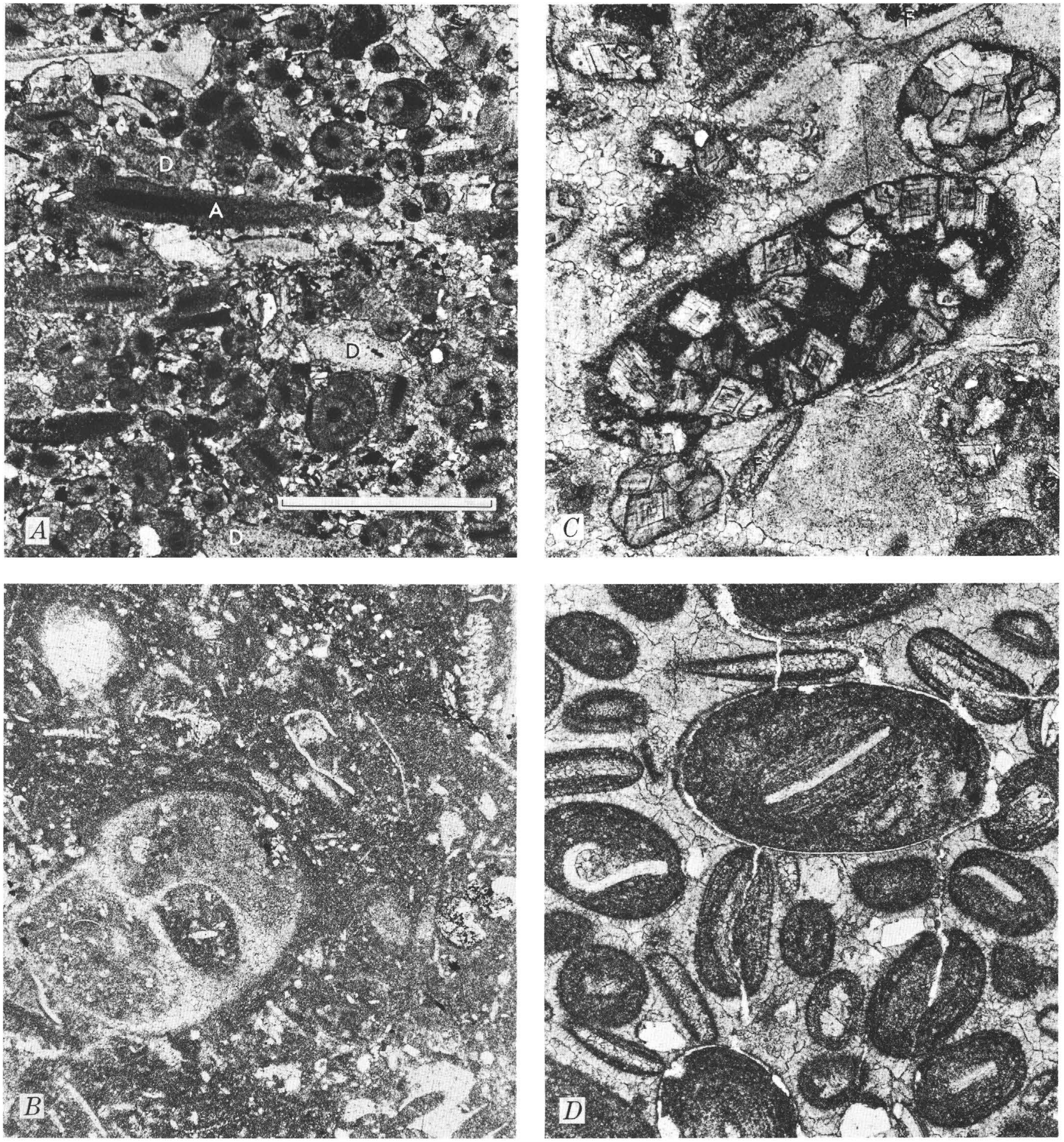


FIGURE 18.—Outcrops of Hitt Canyon Formation. *A*, Thinly layered silty finely oolitic limestone and fossil lime wackestone 70 feet above base of formation at type section, Hitt Canyon (loc. 44). A thin-section photomicrograph of similar rock from a few feet above this outcrop is shown in figure 19*A*. Much of the lower part of the formation has this general appearance. *B*, Burrowed limestone 247 feet above base of formation at Hitt Canyon (loc. 44). Pencil gives scale. Slightly silicified silty burrow fillings stand out in relief. This is the "rusty-weathering band" of Harbour (1972, fig. 4). Similarly burrowed limestones are found in the formation at many localities. *C*, Intraformational conglomerate from a few feet below top of formation of Lone Mountain (loc. 21). Pencil gives scale. In this outcrop dolomite fragments are in a limestone matrix. Rock of similar structure is present in the formation at most localities. A thin-section photomicrograph of generally similar rock from the El Paso Limestone is shown in figure 25*C*.



grained algal(?) lime grainstones, and fine-grained dolomites in the Hitt Canyon have porosities of less than 3 percent. Solution breccias formed beneath the unconformity at the top of the El Paso Group extend downward into the Hitt Canyon Formation at Molinas Canyon (loc. 16) in the Caballo Mountains, and perhaps elsewhere. As noted under the discussion of porosity of the McKelligon Limestone, such breccias could be very porous.

Thickness

The Hitt Canyon Formation ranges in thickness from an erosional wedge edge at the north and around a large Mesozoic highland in western New Mexico to 568 feet at Mescal Canyon (loc. 24) in the Big Hatchet Mountains; at Hitt Canyon, its type section (loc. 44), it is 531 feet thick. Where the formation is conformably overlain by the McKelligon Limestone it thins both northward and east-

FIGURE 19.—Photomicrographs of Hitt Canyon Formation. Bar in *A* is 1 mm; all views are same scale. *A*, Laminated silty glauconitic algal lithiclast lime grainstone from 80 feet above base of formation at type section, Hitt Canyon (loc. 44). This fine-grained but "high-energy" rock type is very common in the lower sandy part of the Hitt Canyon. Silt-sized glauconite grains are not visible in this view but are present in the thin section. Rounded grains of calcite (D) (probably echinodermal) are present but are not as abundant as algal(?) fragments (A) (the small circular alga is *Nuia*). Quartz (white) silt is nearly always present in small quantities in the lower part of the Hitt Canyon. Plain light. *B*, Silty skeletal lime wackestone from 150 feet above base of formation at Werney Hill (loc. 20). This rock type with or without quartz silt is the dominant rock type in the middle part of the Hitt Canyon at most localities. Plain light. *C*, Partly dolomitized coarse fossil-bearing lithiclast lime packstone from 300 feet above base of formation at Capitol Dome (loc. 39). Dolomite in large rhombs has nearly replaced the micrite in the lithiclasts. Dolomite has replaced much of the matrix on the left side. Probable fossil fragments (F) are a minor constituent, as are scattered grains of quartz silt (white). Calcarenite such as this is common in the upper part of the Hitt Canyon at most localities. Plain light. *D*, Sandy oolite lime packstone from about 380 feet above base of formation in Mud Springs Mountains (loc. 13). Micrite matrix is completely dolomitized. Quartz silt and sand in matrix shows as white. This rock type is interbedded with lithiclast lime packstone and is present near the top of the formation at nearly all but easternmost and westernmost localities. Plain light.

ward, and its thinnest known uneroded section is at Agua Chiquita Canyon (loc. 1) in the Sacramento Mountains, where it is 207 feet thick.

Fossils And Age

Although the Hitt Canyon Formation is rarely conspicuously fossiliferous, it has yielded fossils from different horizons at many localities, and its age is thus reasonably well known. The base of the formation is younger from west to east and probably from south to north, whereas the top of the formation is apparently older from west to east. The following comments on the age of the Hitt Canyon are largely based on published faunal information and regional stratigraphic correlations and partly on additional fossil data from collections made during this study.

The lower 100 feet or so of the Hitt Canyon Formation has yielded brachiopods and trilobites from at least five localities (Cooks Range, Lone Mountain, Mescal Canyon, San Lorenzo, and Hitt Canyon, locs. 17, 21, 24, 38, and 44) that indicate correlation with the Early Ordovidian *Symphysurina* zone B of Utah (Hintze and others, 1969) (fig. 5). The fossils from locality 17 in the Cooks Range were reported by Jicha (1954), those from locality 44 in the Franklin Mountains were reported by Harbour (1972), and those from localities 21, 24, and 38 in Grant and Hidalgo Counties were collected during the present study (see "Fossil Lists"). To the east at Beach Mountain (loc. 48), from within 11 feet of the base of the formation, Cloud and Barnes (1946) reported fossils that indicate equivalence with the slightly younger zone C of Utah.

The top of the Hitt Canyon Formation appears to be as old as zone E of Utah at Beach Mountain (loc. 48), where Cloud and Barnes (1946) collected brachiopods similar to *Diaphelasma* within 9 feet of the top, and definite *Diaphelasma* 133 feet below the top. Westward, the top of the Hitt Canyon is as young as zone G of Utah. Zone G trilobites were collected from the upper part of the Hitt Canyon at Mescal Canyon, San Lorenzo, and Capitol Dome (locs. 24, 38, and 39) during this study (see "Fossil Lists"), and at Mescal Canyon they were found 195 feet below the top. Fossils indicative of zone G were also collected from near the base of the overlying McKelligon Limestone at Mescal Canyon.

Fossils indicative of zone D of Utah have been found in the Hitt Canyon Formation at many localities and are most commonly found in the middle part of the formation. Fossils indicative of the Utah zones C and E seem to be missing west of Beach Mountain (loc. 48), and zone F seems to be missing at all localities. I believe that zone E is generally present as a barren zone, that the absence of zone F in the region may be due to a regional depositional hiatus, and that zone C may be represented at some localities by barren rocks and may be truly absent at others.

Contacts

The Hitt Canyon Formation nearly everywhere overlies the Bliss Sandstone with a gradational but generally rather abrupt contact that is described in the text section on the Bliss. Locally, in the Franklin Mountains of western Texas, the Hitt Canyon unconformably overlies Precambrian rocks and is conglomeratic in the lower part, as has been described by Kottlowski, LeMone, and Foster (1969).

In the southern part of the region the Hitt Canyon is conformably overlain by the McKelligon Limestone. In eastern localities the contact is marked by an abrupt change from relatively nonresistant sandy and silty carbonate rocks at the top of the Hitt Canyon to relatively resistant and thick-bedded carbonate rocks at the base of the McKelligon. In western localities, where the upper part of the Hitt Canyon is less sandy and silty and the basal McKelligon is less thickly bedded, the contact is more subtle but is chosen at a horizon where bedding thickness rather abruptly increases. In the northern part of the region, where the McKelligon Limestone is absent, the Hitt Canyon is disconformably overlain by rocks of the Montoya Group or younger strata, and the contact is easily recognizable.

MCKELLIGON LIMESTONE

Name And Type Section

The McKelligon Limestone was named the McKelligon Formation by Flower (1964)[1] for McKelligon Canyon in the southern part of the Franklin Mountains in Texas (fig. 4 and loc. 92, fig. 1). It was assigned a type section by

[1]Sometimes called "McKelligon Canyon Formation" by Flower and other authors.

LeMone (1969), who modified its name to McKelligon Canyon Formation; the type section is approximately along the line of a section measured by Cloud and Barnes (1946) in the Franklin Mountains. Its base is about 2,000 feet southeast of Comanche Peak as shown on the El Paso 7½-minute topographic sheet. As adopted for use in this report as a part of the El Paso Group, the McKelligon Limestone at its type section comprises Cloud and Barnes' units B_1 and B_{2a} and apparently includes a few feet of beds at the base that LeMone (1969) did not include.

General Description

The McKelligon Limestone is made up almost entirely of limestone and (or) dolomite that is relatively free of quartz sand, thick bedded, and resistant as compared with the underlying Hitt Canyon and overlying Padre Formations. It is 350-700 feet thick at most localities where its top is preserved but thins to less than 200 feet at one western locality.

Distribution And Stratigraphic Limits

The McKelligon Limestone is restricted to the eastern area as outlined in figure 6. It is missing, probably owing to erosion, at northern localities in that area but is present at all southern localities.

The McKelligon everywhere overlies the Hitt Canyon Formation with conformable contact. At a few southern localities it is conformably overlain by the Padre Formation, but in most of the area it is disconformably overlain by rocks of the Montoya Group of Middle and Late Ordovician age.

Petrology

The McKelligon Limestone is made up almost entirely of thickly bedded carbonate rocks that at most localities contain scattered irregular nodules of chert. The carbonate rocks are dominantly limestone in much of the central part of the McKelligon distribution area (locs. 13, 15, 17, 39, 44, 45, and 56), dominantly dolomite to the east (locs. 1, 11, 18, 27, and 48) and in one western locality (loc. 21), and variably mixed in most of the remainder of the region. The following descriptions of the lithologic character of the McKelligon are based primarily on the outcrop examination of the formation at 14 localities and on the examination of 28 thin sections.

Most of the McKelligon is characterized by two general carbonate rock types: (1) skeletal lime wackestones (fig. 20*C*) that may grade to skeletal lime packstones or to sparsely fossiliferous lime mudstones and algal boundstones; and (2) lithiclast or skeletal-lithiclast lime packstones (fig. 20*D*) that grade to wackestones (fig. 20*B*) or grainstones. The first general rock type is generally light gray and commonly occurs in broad moundlike bodies or thick beds and is most abundant in the lower part of the formation. The second broad type is generally medium gray and occurs commonly in sharp contact with rock of the first group (figs. 20*A*, 21*A*) and locally as channel fill in rock of the first group (fig. 21*B*); it is the dominant rock type in the upper part of the formation. As described by Klement and Toomey (1967), much of the lime mudstone may have been formed by the destruction of skeletal grains by the blue-green alga *Girvanella*.

Sedimentary Structures

The most abundant and conspicuous sedimentary structures in the McKelligon Limestone are channeled carbonate mounds such as those described in detail by Toomey (1970) in the lower part of the formation near the Scenic Drive section (loc. 45) in the Franklin Mountains. Such mounds were observed in the formation at all localities visited except Beach Mountain (loc. 48), but they are inconspicuous in completely dolomitized sections and are sparse at several localities. The mounds are made up of the first general rock type described above, and the channels cut in the mounds are made up of the second general rock type described above. Nearly all mounds contain digitate algal stromatolites and well-preserved specimens of the sponges *Archaeoscyphia* and *Calathium*. Toomey (1970) believed that the mounds grew in a shallow subtidal environment and that the channels were cut subaerially in an intertidal environment.

Other sedimentary structures common in the McKelligon are burrowed limestones and small mounds built up by *Pulchrilamina* (Toomey and Ham, 1967) or stromatolites (fig. 21). Possible algal-mat dolomite and mud cracks were observed in the upper part of the formation at Agua Chiquita Canyon (loc. 1).

Porosity

Observations on the outcrop, thin-section examinations, and limited laboratory data all indicate that porosities in the McKelligon Limestone are low throughout the report area but seem to be highest in the eastern part. Of nine measurements of the total porosity by the kerosene-displacement method, the two highest were 2.5 percent in dolomites from Agua Chiquita Canyon and Beach Mountain (locs. 1 and 48) in the east. The effective porosities of only two rocks from Little San Nicholas Canyon and San Andres Canyon (locs. 18 and 27) were measured by the mercury porosimeter and found to be 1.4 and 0.7 percent, respectively. The only porosity observed in rocks of the McKelligon on the outcrop was vuggy porosity in dolomites from localities 1 and 48. The chief type of porosity observed in thin sections was cement-filled or cement-reduced microfracture porosity.

As noted by Lucia (1971), solution-collapse features are locally present beneath the unconformity at the top of the El Paso Group and in places extend well into the McKelligon Formation. The porosity characteristics of the solution breccias were not appraised during this study, but Gibson (1965) noted "a zone of porosity and permeability up to several hundred feet in thickness***immediately below the erosion surface" on top of Lower Ordovician rocks in the subsurface of western Texas.

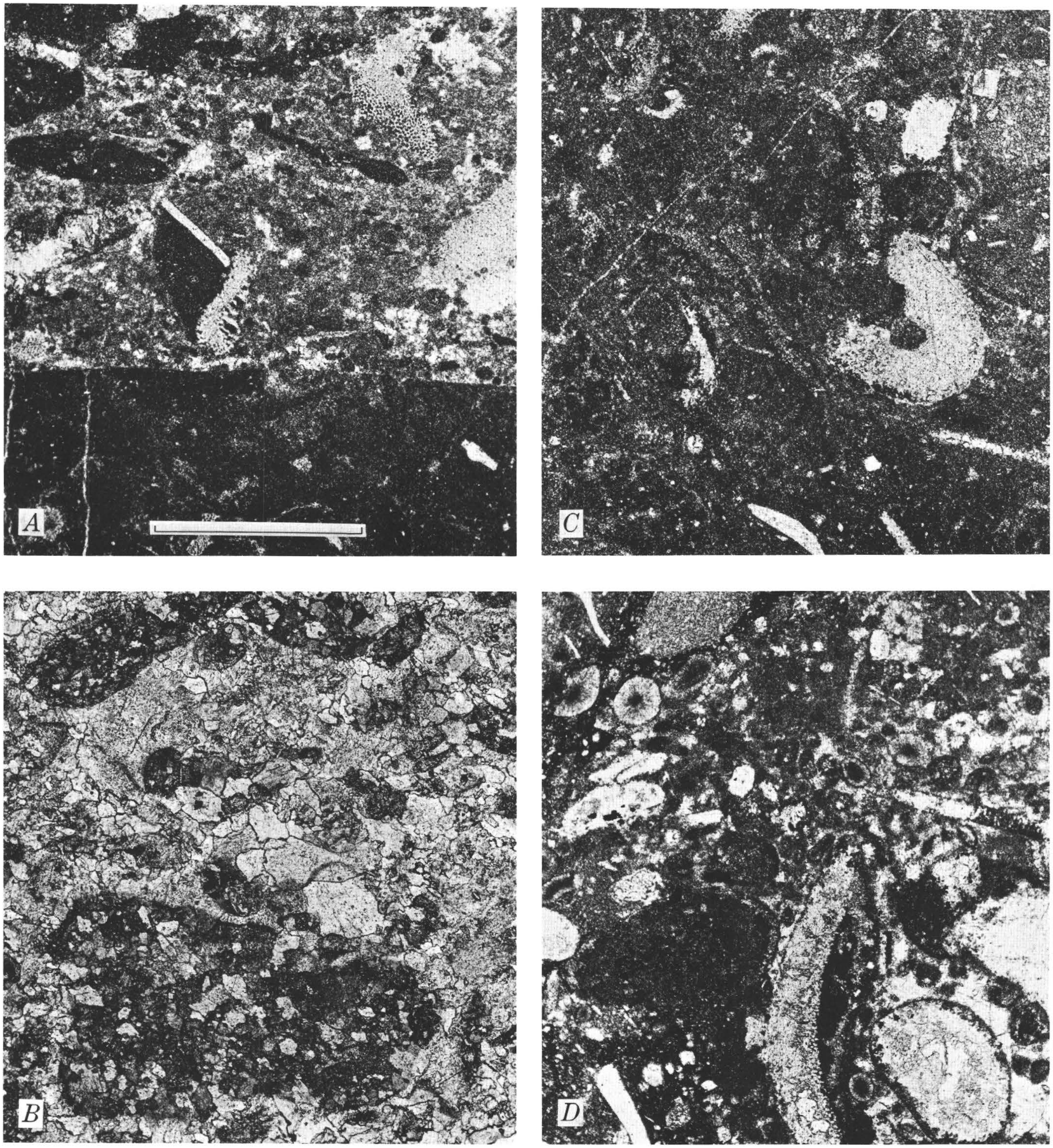


FIGURE 20.—Photomicrographs of McKelligon Limestone. Bar in *A* is 1 mm; all views are same scale. *A*, Fossil-bearing argillaceous lime mudstone sharply overlain by fossil-bearing lithiclast lime wackestone from 220 feet above base of formation at Capitol Dome (loc. 39). Lithiclasts (dark) in upper part appear to have been derived from underlying argillaceous lime mudstone. Both of these rock types are abundant in the McKelligon Limestone. Plain light. *B*, Completely dolomitized coarse lithiclast lime wackestone from 111 feet above base of formation at San Andres Canyon (loc. 27). Except for grain size this rock probably once looked much like the upper part of *A*. Relict structures like this show up in many dolomites in otherwise relatively unaltered rocks. *C*, Skeletal lime wackestone from 8 feet above base of formation in Cooks Range (loc. 17). This is a common rock type of the McKelligon. Plain light. *D*, Skeletal-oolitic-lithiclast lime packstone from 320 feet above base of formation at Hitt Canyon (loc. 44). Much of the upper McKelligon from this area is made up of this rock type. Plain light.

Thickness

The McKelligon Limestone in the southern part of the region, where it is conformably overlain by the Padre Formation and is thus completely preserved, ranges in thickness from 166 to 690 feet. It is thickest at its type section at Scenic Drive (loc. 45) and thinnest about 110 miles to the west at Mescal Canyon (loc. 24). It thins depositionally northward as well as westward and is only 329 feet thick at San Andres Canyon (loc. 27), which is about 65 miles north of the type section. Farther to the north and west the McKelligon thins to an erosional wedge edge.

Fossils And Age

The McKelligon Limestone is not rich in guide fossils but has yielded some fossils, notably cephalopod siphuncles, from most localities. Flower (1969) indicated that the McKelligon is an age equivalent of the Jefferson City Formation of Missouri, and, indeed, the McKelligon has yielded Jefferson City faunal equivalents from the Scenic Drive section in the Franklin Mountains (loc. 45) on the east (Cloud and Barnes, 1946) to Mescal Canyon in the Big Hatchet Mountains (loc. 24) on the west (Zeller, 1965). Because the underlying Hitt Canyon Formation contains beds as young as zone G of Utah (Hintze and others, 1969) in its western exposures and because the overlying Padre Formation is as old as zone G or H at its base, the entire McKelligon throughout the region is probably of zone G age (fig. 5). However, because the top of the underlying Hitt Canyon appears to be younger westward, the zone G equivalents at the base of the McKelligon are probably older in the east than in the west.

Upper Contract

The McKelligon is overlain conformably by the Padre Formation in the southern part of the region. The contact is marked at most localities by the abrupt upward change to notably sandy or silty dolomites or dolomitic sandstones at the base of the Padre. At Capitol Dome in the Florida Mountains (loc. 39), where the Padre is not conspicuously silty or sandy at the base, the contact is marked by an abrupt change from relatively thick bedded limestone in the McKelligon to relatively thin bedded poorly exposed possibly argillaceous limestone at the base of the Padre.

PADRE FORMATION

Name And Type Section

The Padre Formation, the highest formation in the El Paso Group, is here named for Padre Canyon in the Hueco Mountains, Hudspeth County, Tex., shown on the Borrego 15-minute topographic quadrangle. Its type section (Pasotex, fig. 4 and loc. 56, fig. 1) at lat 30°41′20″ N. and long 105°54′20″ W. is on a ridge crest above a small unnamed canyon 2.8 miles due east of Padre Canyon and is described under "Selected Measured Sections" in this report. The Padre Formation in the Scenic Drive section of the Franklin Mountains (loc. 45) coincides with Cloud and Barnes' (1946) units B_{2b} and C of the El Paso measured at that locality, and that section may be regarded as the principal reference section.

As defined, the Padre Formation includes the Scenic

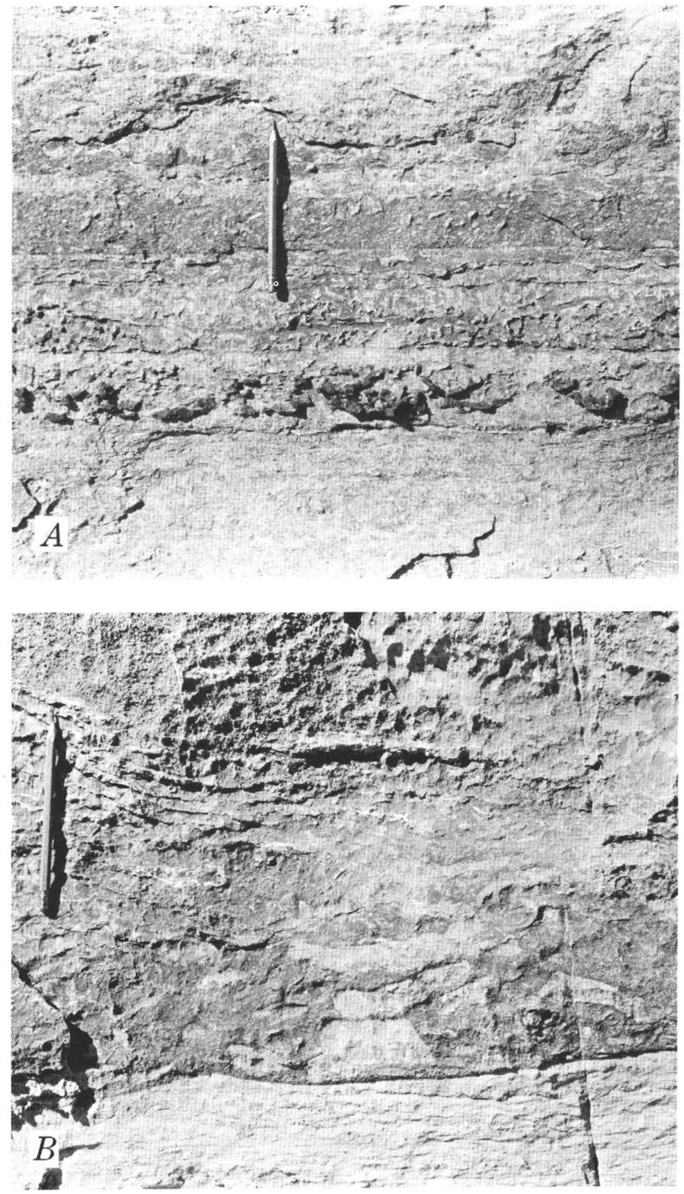


FIGURE 21.—Outcrops of McKelligon Limestone at Hitt Canyon (loc. 44) in the northern Franklin Mountains. *A*, Interlayered lithiclast limestone, skeletal lime packstone, and some burrowed limestone 420 feet above base of formation (loc. 44). The diverse layers indicate alternating subenvironments of deposition. Figure 20*D* is a thin-section photomicrograph of rock like that in the darker bed beneath the pencil. *B*, Scour channel of limestone conglomerate in thinly layered skeletal lime wackestone high in formation. Such channels are commonly associated with carbonate mounds in the McKelligon. Thin layering beneath pencil may be *Pulchrilamina* or may be of stromatolitic origin.

Drive and Florida Mountains Formations of LeMone (1969). The latter is so thin and so local that it is unmappable at standard mapping scales. The name Scenic Drive with minor modification in definition might have been used for the Padre except that the American stratigraphic code discourages the naming of units after ephemeral artificial features.

The Padre also includes the Cindy and Ranger Peak Formations of Lucia (1969). Although distinguishing the two units is possible at some localities, it is not at others. Lucia's units would make useful local members except that the name Cindy was apparently not taken from a recognized geographic feature.

General Description

The Padre Formation is made up of limestones and dolomites that are thinner bedded and less resistant than the underlying McKelligon Limestone and that are notably quartzose at the base at most localities; lithologically it is more similar to the Hitt Canyon Formation than to the intervening McKelligon Limestone. The Padre ranges in thickness from a wedge edge to nearly 400 feet.

Distribution And Stratigraphic Limits

The Padre Formation is limited by definition to the eastern area as outlined in figure 6 and by erosion to the southern edge of that area.

It everywhere overlies the McKelligon Limestone with sharp but conformable contact. In most of the region it is overlain disconformably by rocks of the Montoya Group of Middle and Late Ordovician age; locally, near the extreme southeast corner of the report region it is disconformably overlain by beds of Middle(?) Ordovician age (King, 1965) that have been equated with the Simpson Group of Oklahoma by Jones (1953).

Petrology

Most of the lithologies in the Padre Formation are very similar to lithologies found in the lower formations of the El Paso Group. The basal part of the formation is generally characterized by sandy or silty dolomite or dolomitic sandstone that grades upward into carbonate rocks that are much like those found in the middle part of the Hitt Canyon Formation. Some of these higher carbonate beds at most localities are extremely cherty, and at Capitol Dome in the Florida Mountains (loc. 39) chert makes up about one-third of a 73-foot-thick interval. The following comments on the lithologic character of the Padre Formation are based on the outcrop examination of the formation at eight localities and on the examination of 12 thin sections.

Except at Capitol Dome (loc. 39), the basal 15–80 feet of the Padre Formation consists of quartzose saccharoidal dolomite (figs. 22*A* and 23*A*) or dolomitized lithiclast lime grainstone (fig. 22*B*). At most localities the quartzose dolomite grades upward into silty and generally thinly laminated dolomite (fig. 23*B*). Above these are a variety of fossil-bearing lime mudstones (fig. 22*C*) to skeletal lime wackestones that are commonly interbedded with coarse lithiclast lime packstones or grainstones (fig. 22*D*) much like some of those in the McKelligon Limestone. Oolite lime grainstones (fig. 22*E*) like those in the upper part of the Hitt Canyon Formation are also present. In the Florida and Franklin Mountains (locs. 39, 44, and 45) these upper carbonates are mostly limestones, whereas farther east at Beach Mountain and the Pasotex section (locs. 48 and 56) they are largely dolomitized.

Sedimentary Structures

The basal sandy dolomites of the Padre Formation commonly display conspicuous small-scale cross-laminations that may represent beach deposition (fig. 23*A*).

Most of the very thin laminations in the dolomites above the basal sandy zone are interpreted to represent tidal-flat algal-mat structure. This interpretation is strengthened by the association of thin interbeds of dolomite chip conglomerate, which are especially notable in the Pasotex section in the Hueco Mountains (loc. 56). The intraclasts in these conglomerates are interpreted to be desiccation chips of algal-mat dolomite.

Burrowed limestones are sparse in the upper part of the formation.

Porosity

The highest porosities in the Padre Formation seem to be in some of the very sandy basal beds. Interparticle and vuggy porosity in basal sandy dolomite from the Pasotex section in the Hueco Mountains (loc. 56) showed a total porosity of 6.7 percent when checked by the kerosene-displacement method and an effective porosity of 3.5 percent as checked with the mercury porosimeter. Other samples of basal sandy dolomite showed effective porosities ranging from 0.7 to 2.6 percent.

The carbonate beds higher in the formation seem mostly to be very low in porosity. One thin section of rock from Mescal Canyon in the Big Hatchet Mountains (loc. 24) revealed some microfracture porosity, and other thin sections showed cement-filled fracture, moldic, and channel porosity. Only two limestone samples were checked for total porosity, and each had less than 1 percent.

Like the McKelligon Limestone, the Padre Formation locally contains solution breccias beneath the unconformity at its top which could be zones of high porosity and permeability.

Thickness

The total original thickness of the Padre Formation is not preserved in the region inasmuch as the top contact is everywhere disconformable. The thickest section seen is its type section in the Hueco Mountains (Pasotex, loc. 56), where the formation is 382 feet thick. As shown in figure

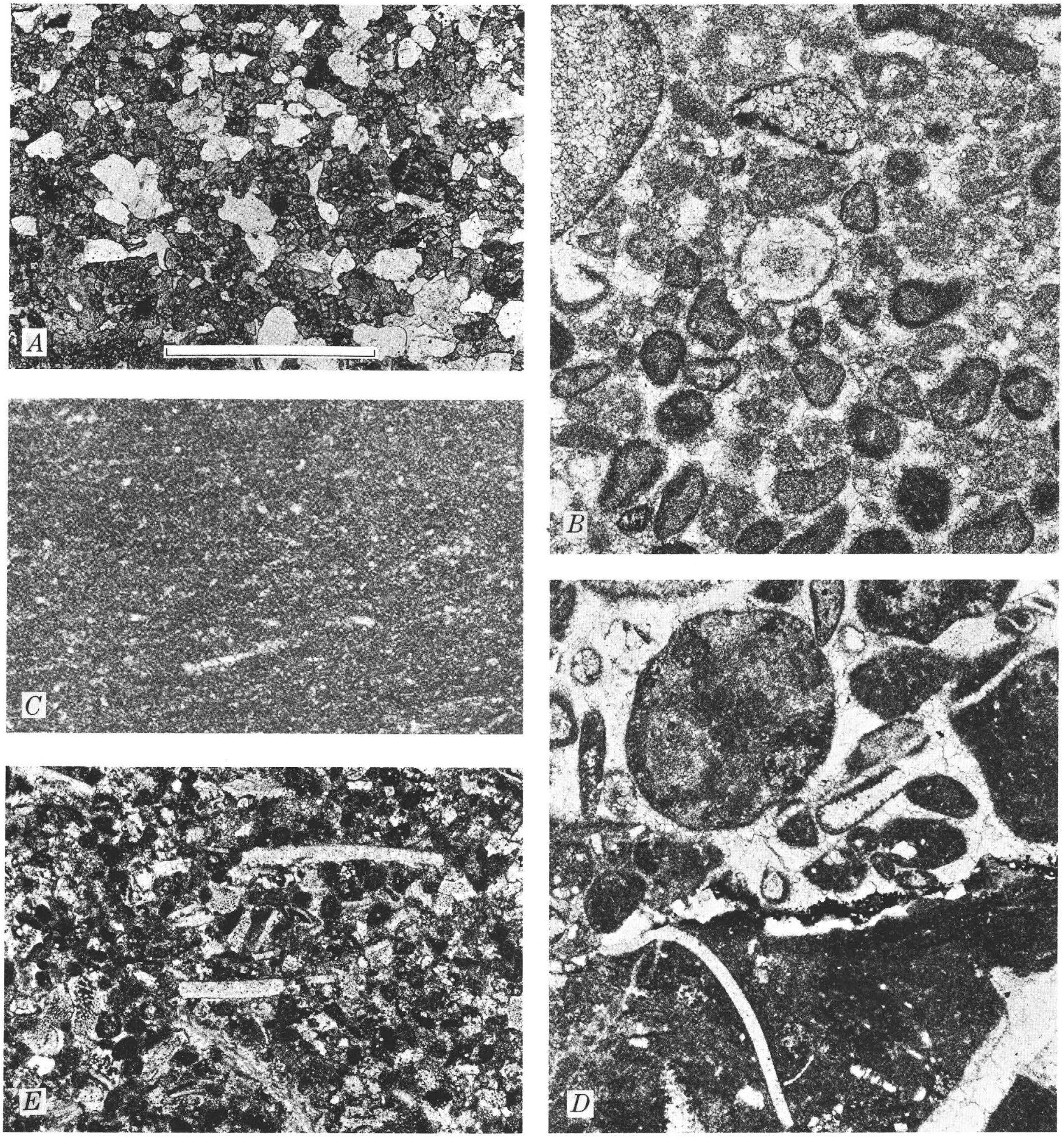


FIGURE 22.—Photomicrographs of Padre Formation. Bar in *A* is 1 mm; all views are same scale. *A,* Very quartzose dolomite from near base of formation at Hitt Canyon (loc. 44). This rock is very similar to some basal rock of the El Paso Group and was probably deposited in a similar environment. Plain light. *B,* Slightly silty lithiclast lime grainstone from low in formation at Beach Mountain (loc. 48). This is another "high-energy" rock from low in the Padre, but it is a type found only at this eastern locality. Plain light. *C,* Lime mudstone from 127 feet above base of formation at Capitol Dome (loc. 39). Rock like this is not dominant but is common well above the base of the Padre. The white flecks are probably minute skeletal grains. Plain light. *D,* Skeletal lime wackestone overlain by coarse lithiclast lime grainstone from about 125 feet above base of formation at Hitt Canyon (loc. 44). The large rounded clasts in the upper part were derived from rock very similar to that below. Similar rocks are found in the McKelligon Limestone. (Compare fig. 20*A*.) Plain light. *E,* Skeletal-oolite lime grainstone from about 200 feet above base of formation at Hitt Canyon (loc. 44). This laminated rock from high in the Padre Formation is similar to rock low in the Hitt Canyon Formation (fig. 19*A*) and probably was deposited in a similar environment. Fossil fragments in the picture are conspicuous; very small oolites are not. Plain light.

48, the formation is more than 200 feet thick at several extreme southern localities but thins to a wedge edge not far to the north and west.

Fossils And Age

The Padre Formation is not richly fossiliferous, but it does contain abundant trilobites and brachiopods in some beds at a few localities, and it has sparse cephalopod siphuncles and gastropods. The Scenic Drive and Florida Formations of Flower (1969), which are included here in the Padre, are the age equivalents of Lower Ordovician zones H through J and possible zone K of Utah (Hintze and others, 1969) (fig. 5). Fossils collected during the present study tend to substantiate that age assignment. Species of the brachiopods *Hesperonomia* and *Diparelasma* collected from the lower part of the formation at Capitol Dome in the Florida Mountains and at Mescal Canyon in the Big Hatchet Mountains (locs. 39 and 24) suggest correlation with Utah zones G or H according to Reuben J. Ross, Jr., of the U.S. Geological Survey. Trilobite and brachiopods collected from the top of the formation at Capitol Dome (loc. 39) are suggestive of zone J to Ross, as are collections from near the top of the formation at Hitt Canyon in the Franklin Mountains (loc. 44) that were reported by Harbour (1972).

Upper Contact

The upper contact of the Padre is everywhere disconformable. Throughout most of the region the Padre is overlain with sharp contact by rocks of the Montoya Group of late Middle and Late Ordovician age; but in a small area in the Baylor Mountains (around loc. 47) at the extreme east edge of the report area, pre-Montoya rocks of Middle Ordovician age disconformably overlie the Padre Formation (King, 1965).

CENTRAL PART OF STUDY REGION

CORONADO SANDSTONE

NAME AND TYPE LOCALITY

The Coronado Quartzite was named by Lindgren (1905) for exposures in the Clifton-Morenci area (near loc. 84, fig. 1). The name was used only in the area of the type locality until recently when I (Hayes, 1972) extended it to include rocks formerly improperly assigned to the Bolsa Quartzite. Because most of the formation in most of the area of its extent is not truly quartzite, the name Coronado Sandstone is preferable for regional use.

GENERAL DESCRIPTION

The Coronado Sandstone consists dominantly of moderately dark weathering sandstone that is variably cemented by quartz and carbonate. In most of its area of occurrence it ranges in thickness from about 200 feet to about 600 feet.

DISTRIBUTION AND STRATIGRAPHIC LIMITS

The Coronado Sandstone occurs only in the central area as outlined in figure 14. Until recently (Hayes, 1972), the name was used only in the vicinity of the type locality.

The Coronado unconformably overlies Precambrian rocks throughout its area of occurrence, and it is conformably overlain by the El Paso Limestone except in some northern areas where the Coronado is disconformably overlain by Devonian or Mississippian rocks. The Coronado is a lateral facies equivalent of the lower three members of the Abrigo Formation and, locally, of the upper part of the Bolsa Quartzite of the western area; the upper part of the Coronado is a lateral equivalent of the Bliss Sandstone of the eastern area. (See fig. 5 and pl. 1.)

PETROLOGY

Virtually all the Coronado is made up of sandstone in the northern part of its distribution area, and at least 70 percent of the formation is sandstone in southern locali-

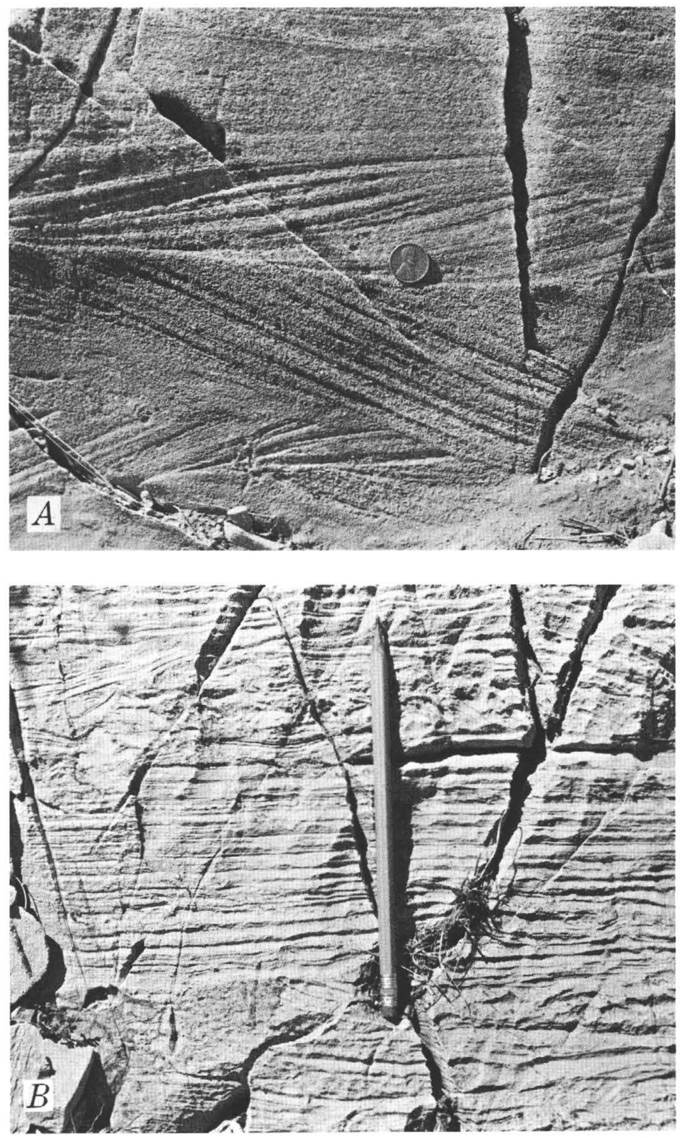


FIGURE 23.—Outcrops of Padre Formation at Hitt Canyon (loc. 44) in the northern Franklin Mountains. *A*, Cross-laminated sandy dolomite about 50 feet above base of formation. Penny gives scale. *B*, Slightly silty laminated dolomite about 100 feet above base of formation.

ties. Most southern sections contain some siltstone and (or) shale, and at Dos Cabezas (loc. 60), near the westward transition of the Coronado into the Abrigo Formation, there is some sandy dolomite in the Coronado. Outcrop colors of the Coronado are mostly reddish brown to pale brown but range from pale red to olive brown. On fresh fracture much of the rock is pinkish gray but ranges to dusky red and dark greenish gray.

Sandstones in the Coronado range from arkose to orthoquartzite; in Dapples' (1972) classification, most are quartz- or dolomite-cemented arenites but a few are subwackes. As with the Bolsa Quartzite and Bliss Sandstone, grain size decreases upward. The following descriptions of sandstones from the Coronado are based on outcrop examination of the formation at seven localities and on the examination of 37 thin sections, of which 29 were point counted.

Quartz is the most abundant cementing material in sandstones from the Coronado (fig. 24*A*, *B*), but dolomite cement is not uncommon in the southern part of the Coronado distribution area, especially in the middle and upper parts of the formation. Hematite cement occurs in a few beds.

Feldspar content of Coronado sandstones decreases upward. True arkoses are present at the base of the section at many localities and make up much of the lower two-thirds of the formation on Nantac Rim (loc. 150). Feldspar rarely makes up more than 5 percent of the rock from the upper one-third of the Coronado and averages less than 2 percent. Rock fragments are present in small amounts in many samples (fig. 24*B*) but do not constitute even 2 percent of any sandstone examined. Glauconite grains are present in many samples and abundant in a few, particularly from southern outcrops (fig. 24*C*). On the whole, glauconite is much more abundant in the Coronado than in the Bolsa Quartzite but not as abundant as in the Bliss Sandstone. Grains of opaque minerals, most commonly hematite, are present in most samples and abundant in some (fig. 24*C*). As with glauconite, hematite is more abundant in the Coronado than in the Bolsa and less abundant than in the Bliss. Sandstones containing clay or sericite in the matrix seem to be more common in the Coronado than in either the Bolsa Quartzite or the Bliss Sandstone and these minerals occur in some beds throughout the distribution area of the Coronado. Several samples examined can be classified as subwackes rather than as arenites. It is suspected, however, that much of the fine matrix in the subwackes results from alteration of feldspars and ferromagnesian minerals.

Siltstones and silty shales from southern localities of the Coronado are mostly dark greenish gray to reddish brown. Most seem to be sericitic or chloritic; some are limonitic or glauconitic; a few are calcareous.

The few beds of dolomite that occur in some Coronado sections are all silty to sandy and irregularly micrograined to coarse grained. They are medium gray to grayish red on fresh fracture and weather to yellowish brown.

SEDIMENTARY STRUCTURES

Small- to medium-scale planar cross-laminations are by far the most conspicuous sedimentary structure seen in the Coronado but certainly do not occur in all beds. Seeland (1968) measured numerous attitudes of cross-laminations in the Coronado at Apache Pass and Morenci (locs. 59 and 84), and I noted many on Nantac Rim (loc. 150). The majority of those at Apache Pass are inclined to the southwest, whereas those at Morenci and Nantac Rim dip mostly a little to the north of west.

Tracks and trails on bedding planes and *Scolithus* tubes are present in a few beds and seem to be more common in northern exposures than in southern ones.

POROSITY

Most samples from the Coronado Sandstone are very low in porosity. Of 26 samples point counted for porosity, 18 showed less than 1 percent, 4 showed between 1 percent and 2 percent, 2 showed about 3 percent each, and 2 showed 11 percent and 15 percent (fig. 24*B*). Only two samples were checked by the mercury porosimeter; these showed 1.4 percent and 3.5 percent porosity. The two fairly porous samples were from near the top of the formation at Morenci and Nantac Rim (locs. 84 and 150), near the northern known limits of occurrence of the Coronado.

THICKNESS

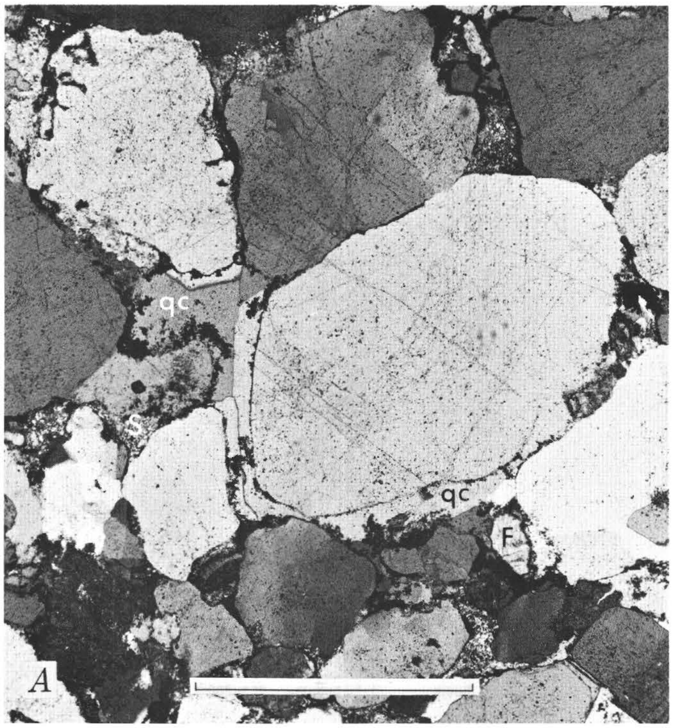
The Coronado Sandstone ranges in thickness from 370 feet to 610 feet in the sections where it is conformably overlain by the El Paso Limestone; there is no known place where the formation is absent because of nondeposition over local relief on the Precambrian, as happens with both the Bolsa Quartzite and the Bliss Sandstone. The Coronado is less than 200 feet thick at Imperial Mountain and Coolidge Dam (locs. 76 and 151), where its top was eroded before Late Devonian or Early Mississippian time, and presumably the formation comes to an erosional wedge edge not far to the north (fig. 14).

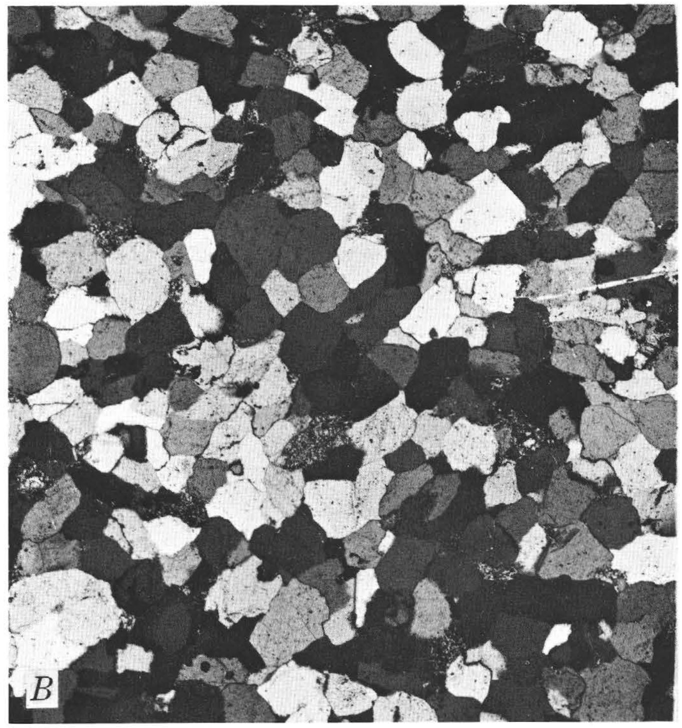
FOSSILS AND AGE

No fossils closely diagnostic of age have been found in the Coronado Sandstone. However, because of the conformable relations of the Coronado with overlying rocks of known Late Cambrian (Franconian) age, at least the upper part of the Coronado is probably no older than early Late Cambrian (Dresbachian) age. This conformity and the distinct lithologic resemblances of the Coronado with sandy facies of the Abrigo Formation indicate that the thick sections of Coronado range in age from Middle Cambrian through early Late Cambrian and that the thinner sections may be entirely of early Late Cambrian age (pl. 1, fig. 5).

CONTACTS

The Coronado Sandstone unconformably overlies Pre-





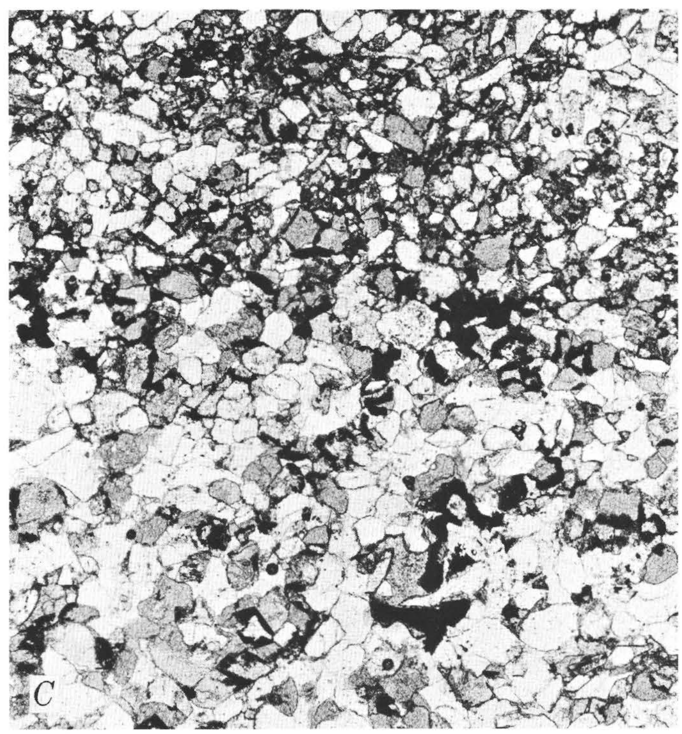


FIGURE 24.—Photomicrographs of Coronado Sandstone. Bar in *A* is 1 mm; all views are same scale. *A*, Poorly sorted coarse arkosic sandstone from basal part of formation near Portal (loc. 57). Feldspar (*F*) is fairly abundant in the basal Coronado, as it is in the basal Bolsa Quartzite. This rock, which is probably an age equivalent of the lower member of the Abrigo of western localities, is less perfectly cemented with quartz (qc) than is most Bolsa. Dusty sericite (S) and hematite (black) is in matrix. Original boundaries of quartz grains show clearly. (Compare fig. 7*B*) Crossed nicols. *B*, Well-sorted sandstone from near top of formation near Morenci (loc. 84). Most grains are quartz but fragments of schist (finely spotted grains) are common. Cement is quartz in optical continuity with grains. Much of the black in the section is open pore space, but some is quartz at extinction. Crossed nicols. *C*, Laminated glauconitic hematitic fine-grained sandstone from 412 feet above base of formation near Portal (loc. 57). This rock is very glauconitic (medium gray) and hematitic (black) and is probably equivalent to the upper sandy member of the Abrigo Formation. (Compare fig. 11.) Plain light.

cambrian rocks at all localities. At most localities the underlying rocks are crystalline rocks, but at and near Imperial Mountain and Coolidge Dam (locs. 76 and 151) the Coronado overlies Precambrian sandstone or quartzite with nearly parallel contact of very low relief. In these two areas it is possible to mislocate the basal contact. Simons (1964), who assigned the beds here called Coronado to the Bolsa Quartzite near Imperial Mountain (loc. 76), conceded that he may have included Precambrian beds in his Bolsa, and I believe that he did. I am not certain that I properly placed the contact at Coolidge Dam (loc. 151); Krieger (1961) has discussed the nature of the Precambrian-Cambrian contact in this area.

The contact of the Coronado Sandstone with the overlying El Paso Limestone is conformable but in most places can be located with little equivocation as sandstone of the Coronado gives way rather abruptly to sandy dolomite at the base of the El Paso.

EL PASO LIMESTONE

NAME AND TYPE LOCALITY

The name and type locality of the El Paso Limestone were discussed earlier in this report in the section on the El Paso Group in the eastern part of the study area.

GENERAL DESCRIPTION

In the central area the El Paso Limestone is divided into lower and upper members. The lower member consists mostly of sandy or silty dolomite that has interbeds of dolomitic sandstone in the upper part, and the upper member is made up of relatively pure carbonate beds that locally contain some rather cherty intervals.

DISTRIBUTION AND STRATIGRAPHIC LIMITS

The El Paso Limestone crops out in several extended outcrop bands in the southern part of the central area (fig. 6) and occurs sporadically in the northern part east of long 110° W.

Wherever the El Paso occurs in the central area, it conformably overlies the Coronado Sandstone. It is disconformably overlain at most localities by Devonian rocks and at Morenci (fig. 4 and loc. 84, fig. 1) by upper Middle Ordovician rock assigned to the Second Value Dolomite.

PETROLOGY

The lower member of the El Paso Limestone in the central area is made up almost entirely of dolomite, quartzose dolomite, and dolomitic sandstone. The upper member is largely dolomite at most localities but contains considerable limestone at Preacher Mountain (loc. 23) and at Apache Pass (loc. 59). The following descriptions of these rocks are based on outcrop examination of the formation at eight localities in the central area and on the examination of 61 thin sections.

Nearly all the dolomite in the lower member appears to be dolarenite (fig. 25*A*). There is minor intraformational dolomite conglomerate at most southern localities and, in some instances, dolomitized calcerenite. Most of the dolomite in the member is at least slightly sandy or silty, and some of it is very sandy (fig. 25*A*, *B*). Most is faintly to distinctly grain-size laminated. Most of the sandy dolomites from northern localities (locs. 84, 150, and 162) are glauconitic; in these, the glauconite grains are rounded particles of the same general grain size as the accompanying quartz sand.

Sandstone in the lower member is generally well sorted fine- to coarse-grained orthoquartzite with dolomite cement. Some is glauconitic.

Carbonates in the upper member are more varied than those in the lower member and include lime mudstones to grainstones and dolomite boundstones. Lithiclast lime packstones and grainstones (fig. 25*C*), some fossil bearing, may be most abundant and are similar to the dolarenites of the lower member except that they are rarely sandy. Lime mudstone, fossil-bearing lime mudstone, and skeletal lime wackestone (fig. 25*C*) are also found in the member. The lime mudstones are commonly slightly silty and argillaceous (fig. 25*D*). Algal-mat dolomites (dolomite boundstones) are present in most sections. The limestones have been largely dolomitized in most areas, but considerable undolomitized limestone remains at Preacher Mountain and Apache Pass (locs. 23 and 59).

SEDIMENTARY STRUCTURES

Many of the dolarenites and dolomitic sandstone beds in the lower member display conspicuous small- and medium-scale planar cross-laminations. Some cross-laminated dolomite occurs in the upper member near Morenci (loc. 84).

Intraformational chip conglomerates are present in the lower member at most localities and in the upper member at a few localities (fig. 26*A*). Mud cracks were observed in the upper member near Morenci and to the northwest (locs. 84, 150, and 162).

Algal-mat dolomite is present in the upper member at several localities, and at Morenci (loc. 84) it displays bird's-eye structures (fig. 26*B*).

Burrowed limestone or dolomite is present in the upper member at nearly all localities and in the lower member near Portal (loc. 57). Tracks and trails were observed on bedding planes in the lower member at Nantac Rim and Barlow Pass (locs. 150 and 162).

POROSITY

Some dolomitic sandstone and sandy dolomite from the lower member of the El Paso Limestone has moderate porosity, but most outcrop samples of the formation in the central area are low in porosity. Eight samples from the lower member were checked for effective porosity with the mercury porosimeter, and the porosities determined ranged from 0.5 to 6.4 percent and averaged 3.1 percent; the highest porosities were from Morenci and Nantac Rim (locs. 84 and 150), and the lowest were from Preacher Mountain and Portal (locs. 23 and 57). The rocks with the greatest porosities had dominantly between-particle porosity but some vuggy and fracture porosity.

Six samples of carbonate rocks from the upper member were checked by the mercury porosimeter and showed effective porosities from 0.7 to 3.8 percent and averaged 1.9 percent. A wide variety of porosity types, largely cement reduced or cement filled, was noted in these rocks. Between-particle, fracture, and vuggy porosities are most common, but moldic, fenestral, and burrow porosities were also noted.

THICKNESS

In the central area the thickness of the El Paso Limestone ranges from a measured maximum of 887 feet in the Portal section (loc. 57) to an erosional wedge edge on the west and presumably on the north. Even the maximum thickness does not represent an original thickness inasmuch as the top of the El Paso is disconformable throughout the area. The thickness of the lower member, which is conformable at both base and top, ranges from 86 feet at Preacher Mountain (loc. 23) to 181 feet at Portal (loc. 57).

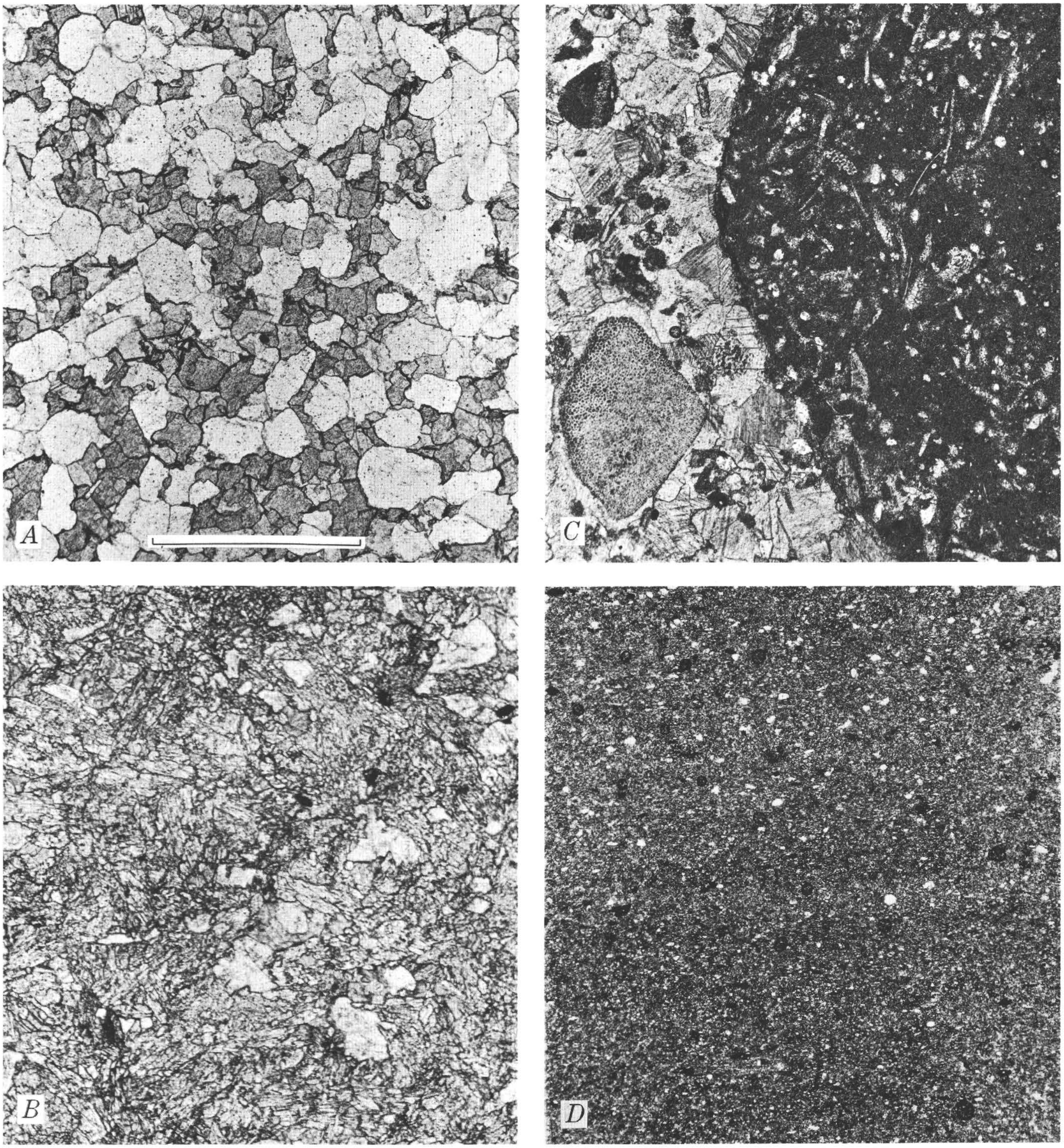


FIGURE 25.—Photomicrographs of El Paso Limestone. Bar in *A* is 1 mm; all views are same scale. *A*, Well-sorted quartzose dolarenite from lower part of formation near Dos Cabezas (loc. 60). Note similarity to figure 13*B*, which is of a very nearly coeval rock. Plain light. *B*, Metamorphosed sandy dolomite from lower part of formation at Apache Pass (loc. 59). Before metamorphic recrystallization of the dolomite this rock probably looked much like that in *A* or in figure 13*B*. (Compare fig. 33*D*.) Plain light. *C*, Large clast of silty skeletal lime wackestone (right) in recrystallized matrix from 220 feet above base of formation near Dos Cabezas (loc. 60). Clast at lower left is rounded calcite crystal of echinodermal origin. A few quartz silt grains show as white. Intraformational limestone conglomerates (very coarse lithiclast lime wackestones to grain stones) like this are found in the lower part of the El Paso and in the Hitt Canyon Formation at most localities, especially toward the south. (See fig. 18*C*.) Plain light. *D*, Laminated silty and argillaceous lime mudstone from 454 feet above base of formation at Apache Pass (loc. 59). Rock such as this is common in the upper member of the El Paso Limestone in Arizona and is present but uncommon in the Hitt Canyon Formation. Plain light.

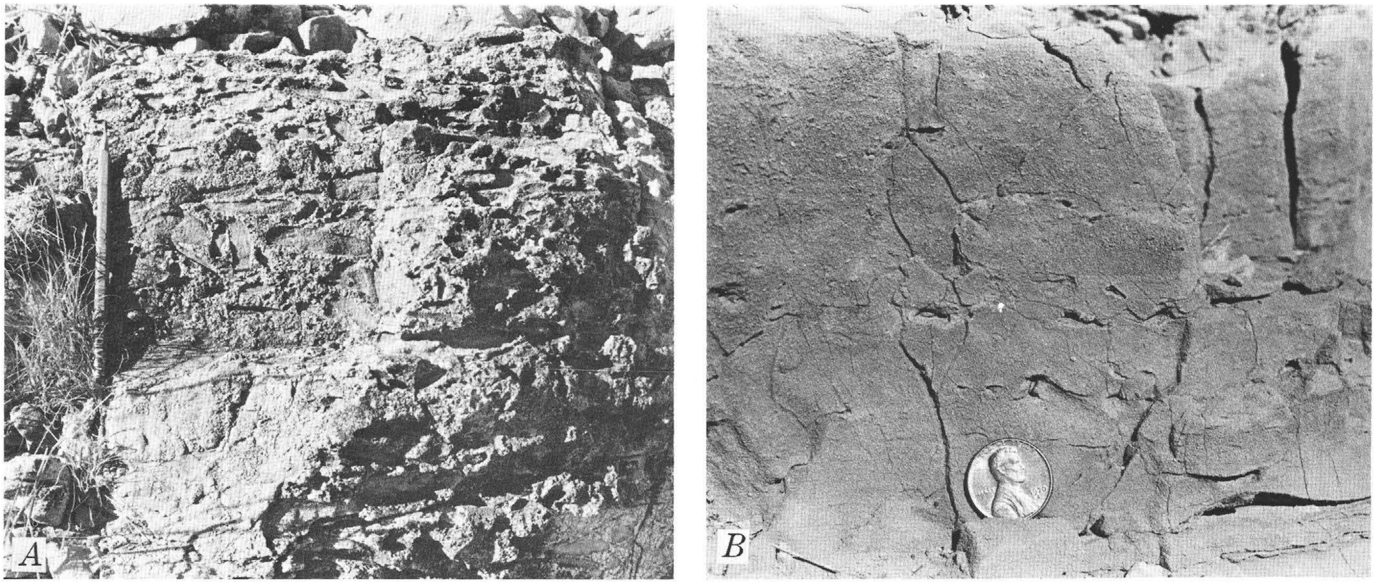


FIGURE 26.—Outcrops of El Paso Limestone. *A*, Intraformational conglomerate 80 feet above base of formation at Preacher Mountain (loc. 23). Flat dolomite clasts are in a sandy dolomite matrix. This part of the El Paso at this locality is probably of latest Cambrian age. Similar intraformational conglomerates can be found in various parts of the Abrigo Formation at various localities and in the Bliss Sandstone. (See fig. 16*B*) *B*, Bird's-eye structures in dolomite about 200 feet above base of formation near Morenci (loc. 84).

FOSSILS AND AGE

The El Paso Limestone of the central area includes beds of Late Cambrian and Early Ordovician age. The lower member has yielded only Cambrian fossils, and the upper member has yielded only Ordovician fossils; presumably the systemic boundary lies near the contact between the lower and upper members.

Lindgren (1905) collected fossils from 20 feet above the base of rocks now assigned to the El Paso near Morenci (loc. 84) that Charles D. Walcott thought were probably uppermost Cambrian. Sabins (1957) reported *Billingsella* sp., which is indicative of a Franconian (Late Cambrian) age, from the basal beds of the El Paso on Blue Mountain (near loc. 58). We found brachiopods identified by M. E. Taylor of the U.S. Geological Survey (written commun., Aug. 16, 1971) as *Billingsella* cf. *B. coloradoensis* from 52 feet above the base of the lower member on Nantac Rim (loc. 150). From 98 feet above the base (and 83 feet below the top) of the lower member near Portal (loc. 57) we collected the brachiopod *Plectotrophia* sp., identified by Reuben J. Ross, Jr., of the U.S. Geological Survey (written commun., Oct. 9, 1970), and possible *Matthevia,* as determined by Ellis L. Yochelson of the U.S. Geological Survey (written commun., Dec. 6, 1971). These forms indicate a Late Cambrian age. Unfortunately, age-diagnostic fossils have not been found in the upper part of the lower member.

The upper part of the El Paso of the central area has yielded cephalopods and sparse gastropods of Early Ordovician age from Preacher Mountain (loc. 23) (Gillerman, 1958), Apache Pass (loc. 59) (Sabins, 1957), Dos Cabezas (loc. 60) (Gilbert, 1875; Darton, 1925), and Morenci (loc. 84) (Lindgren, 1905). Gastropods collected by Gillerman (1958) from near Preacher Mountain (loc. 23) were believed by R. H. Flower (cited in Gillerman, 1958) to represent his first endoceroid zone, which, according to Flower (1969), is equivalent to Early Ordovican zone D of Utah (Hintze and others, 1969). We collected generically unidentified endoceroid siphuncles from 102 to 117 feet above the base of the upper member of the El Paso at Preacher Mountain (loc. 23), and I presume that these represent Flower's first endoceroid zone. According to Flower (cited in Sabins, 1957) a nautiloid siphuncle from about 150 feet above the base of the El Paso (very low in the upper member) at Apache Pass (loc. 59) probably represents the lower of the two cephalopod zones of the Gorman Formation of Texas and thus also would probably represent zone D of Utah. The cephalopods from Dos Cabezas (loc. 60) were thought by Flower (cited in Sabins, 1957) to be of middle Canadian age. The fossils from Morenci (loc. 84) were regarded by Walcott (quoted in Lindgren, 1905) to be of Early Ordovician age.

On the basis of the fossil evidence from the central area and lithologic correlation with fossil-bearing beds in the eastern and western areas, the lower member of the El Paso Limestone in the central area is assumed to be of Franconian and Trempealeauan (late Late Cambrian) age. It is, thus, equivalent to the Copper Queen Member of the Abrigo Formation to the west and to the lower part of the Bliss Sandstone to the east (pl. 1). The upper member of the El Paso in the central area is assumed to be of Early Ordovician age and may contain beds at the top of the thickest sections as young as Early Ordovician zone G of

Utah. It is, thus, equivalent to the upper part of the Bliss Sandstone, all or most of the Hitt Canyon Formation, and possibly, at its thickest sections, the basal part of the McKelligon Limestone of the eastern area (fig. 5).

UPPER CONTACT

The upper contact of the El Paso is disconformable throughout the central area. At Morenci (loc. 84) the El Paso is overlain by a thin remnant of the Second Value Dolomite, and at that locality both the El Paso and the Second Value were included in the Longfellow Limestone until the Longfellow was abandoned by Hayes (1972). Elsewhere the El Paso is sharply overlain by shaly strata of Middle or Late Devonian age.

MIDDLE ORDOVICIAN UNCONFORMITY

Throughout the report region the rocks of the Sauk sequence of Sloss, Krumbein, and Dapples (1949) and Sloss (1963) are separated from the overlying Middle Ordovician or younger rocks by a disconformity. In general, the amount of geologic time represented by the disconformity increases from east to west and from south to north. This is due both to a general westward and northward increase in age of the top of the Sauk sequence (fig. 27; pl. 1) and to a general but irregular westward and northward slight decrease in age of the rocks immediately overlying the Sauk sequence (fig. 28).

In Culberson County, Tex., at and near locality 47 (fig. 1) in the southeast, pre-Montoya Group rocks that have been correlated with the Middle Ordovician Simpson Group of Oklahoma overlie the Padre Formation of late late Canadian age, and the disconformity represents only latest Early Ordovician and early Middle Ordovician time. In most of westernmost Texas and southern New Mexico the Montoya Group overlies the El Paso Group; the El Paso becomes increasingly older at the top northward and westward, so at places such as Morenci, Winston, and Eaton Ranch (locs. 84, 41, and 35) the disconformity represents much of Early Ordovician and most of Middle Ordovician time.

Still farther west and north, beyond the erosional edge of the Montoya Group, the pre-Montoya and one or more post-Montoya disconformities have coalesced, and so in much of southern Arizona Devonian rocks overlie Sauk sequence rocks that become older at the top westward. Thus, in western Pima and Pinal Counties (locs. 80–82), the disconformity at the top of the Sauk sequence represents all of Late Cambrian, Ordovician, Silurian, and Early and Middle Devonian time.

In areas where later erosion has removed the rocks of the Sauk sequence the effects of the Middle Ordovician unconformity are, of course, lost. Thus, in the Diablo region of western Texas, Permian rocks overlie the Precambrian; on the Burro uplift of western New Mexico and in a large area in southern Arizona, Cretaceous rocks overlie the Precambrian; and along the entire north edge of the region, Devonian to Pennsylvanian rocks overlie the Precambrian (figs. 27, 28).

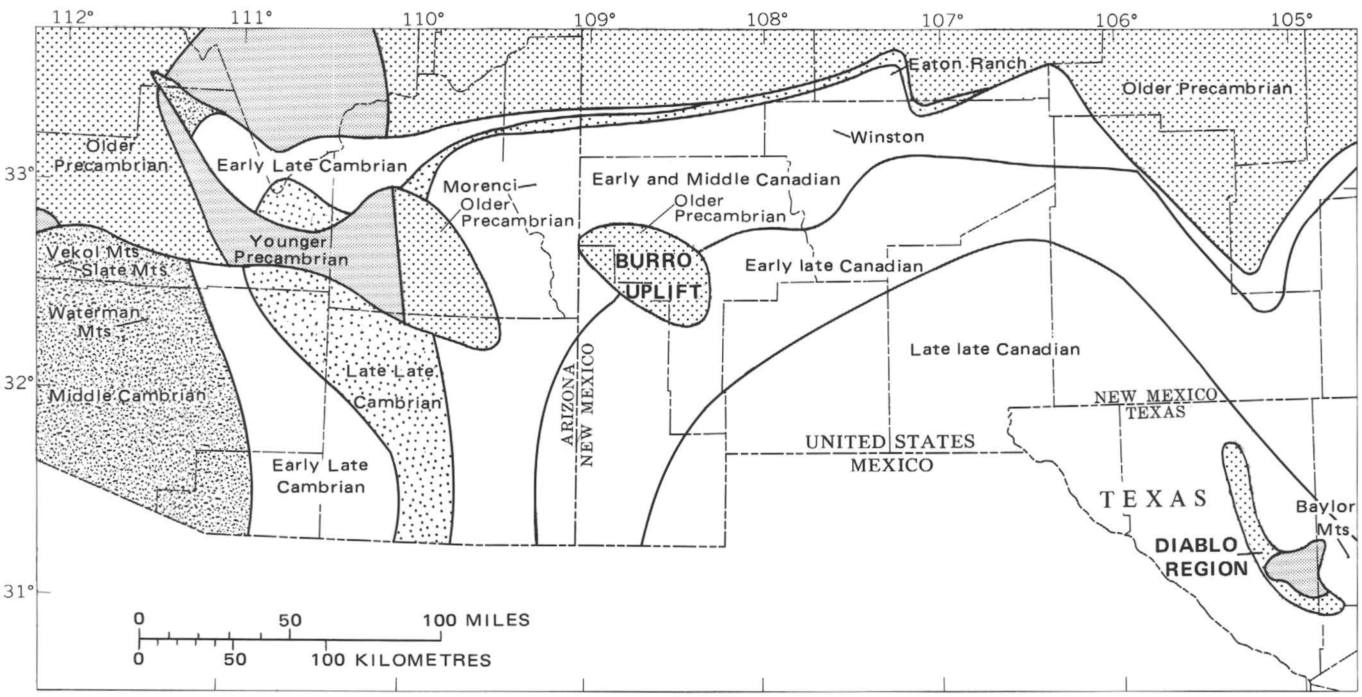


FIGURE 27.—Generalized map showing distribution of rocks of the Sauk sequence before the end of Cretaceous time and the age of rocks at the top of the sequence. Ages of pre-Sauk rocks are shown where rocks of the Sauk sequence are missing.

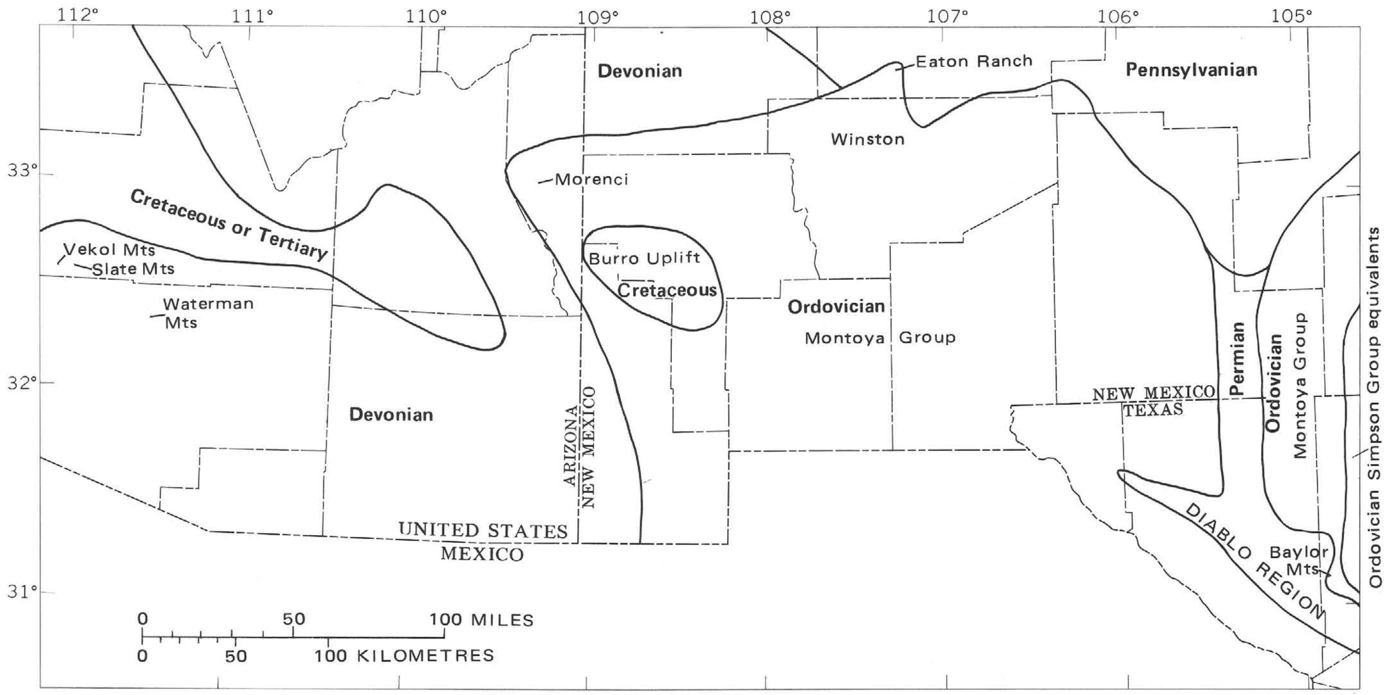


FIGURE 28.—Generalized map showing rocks overlying the Sauk sequence and older rocks.

MIDDLE AND UPPER ORDOVICIAN ROCK UNITS

MONTOYA GROUP

The Montoya Limestone was named by Richardson (1908) for exposures near the Scenic Drive (fig. 29 and loc. 45, fig. 1) in the Franklin Mountains, Tex. Richardson (1914) extended the name eastward to the Baylor Mountains and Beach Mountain (locs. 47, 52, and 50), and Darton (1917a) extended the name throughout much of southern New Mexico. Entwistle (1944) subdivided the Montoya at Boston Hill in the Silver City area, New Mexico (loc. 91), into three members that were previously described as informal members by Darton (1917a); Entwistle's Montoya consisted in ascending order of the Second Value, Par Value, and Raven Members. Kelley and Silver (1952) recognized the same subdivisions in the Caballo and Mud Springs Mountains (locs. 13–16) of New Mexico and elevated the Montoya to group rank. They believed that Entwistle's type sections were inadequate because of faulting and mineralization[2] and renamed the Par Value and Raven Members the Aleman and Cutter Formations, respectively. The Second Value Member was not used, and rocks formerly assigned to it were divided into the Cable Canyon Sandstone and overlying Upham Dolomite. Pray (1953), working in the Sacramento Mountains, N. Mex. (around locs. 1–3), used the term Montoya Formation for the lower part of the Montoya of other workers and applied the name Valmont Dolomite to the beds referred to the Raven Member by Entwistle (1944) and the Cutter Dolomite by Kelley and Silver (1952). Although Entwistle's (1944) names had priority, the subdivisions of Kelley and Silver (1952) have since been used either as formational names in the Montoya Group or as member names in the Montoya Dolomite at most localities where the Montoya occurs in the report region. Pratt (1967), in his mapping near Silver City (around Lone Mountain, loc. 22), considered the Montoya as a group but found that he was unable to map the Cable Canyon separately from the Upham at his 1:24,000 mapping scale. He considered the Cable Canyon Sandstone and Upham Dolomite as members of the Second Value Dolomite, which was overlain by the Aleman Formation and Cutter Dolomite. In his discussions of regional stratigraphy, Flower (1965, 1969) considered the Montoya as a group comprising in ascending order the "Second Value Formation, Par Value-Aleman Formation, and the Raven-Cutter-Valmont Formation."

Although I believe that Entwistle's (1944) type section of his subdivisions of the Montoya is adequate and that his older names unfortunately were neglected in favor of newer names, the units of Kelley and Silver (1952) are obviously rather firmly established. In this report, following the example of Pratt (1967), the Montoya is considered as a group made up in ascending order of the Second Value Dolomite, the Aleman Formation, and the Cutter Dolomite. In most areas, where a basal sandstone unit is recognizable in the Second Value, the Second Value is further divided into the Cable Canyon Sandstone Member and the overlying Upham Dolomite Member (fig. 5).

[2]I do not agree. In my examination of Entwistle's (1944) Boston Hill section (loc. 91) I had no difficulty in identifying units across the minor faults.

The Montoya Group as a whole is restricted mostly to southern New Mexico and western Texas but extends a few miles into Arizona at one locality. The thickness of the group exceeds 500 feet locally but thins to erosional wedge edges to the north and west and locally elsewhere (fig. 29).

SECOND VALUE DOLOMITE

NAME AND TYPE LOCALITY

The Second Value Dolomite was named by Entwistle (1944) as a member of the Montoya Dolomite for exposures at Boston Hill (fig. 30 and loc. 91, fig. 1) near Silver City, N. Mex. Pratt (1967) recognized the Second Value as a formation made up of the Cable Canyon Sandstone Member at the base and the Upham Dolomite Member at the top. The Cable Canyon and Upham were named as formations by Kelley and Silver (1952) for exposures in Cable Canyon (loc. 15) in the Caballo Mountains, N. Mex. The terminology used by Pratt (1967) is used here except in areas where the Cable Canyon is missing and the Upham Dolomite Member is synonymous with the Second Value Dolomite.

GENERAL DESCRIPTION

The Second Value Dolomite, 35-145 feet thick, in general occurs as a conspicuous dark-weathering cliff. The Cable Canyon Sandstone Member is present at the base at a majority of localities and ranges in thickness from less than 1 foot to slightly more than half the thickness of the entire formation. It is made up of poorly sorted medium-grained dolomitic sandstone that may be either sharply or gradationally overlain by the Upham Dolomite Member. The Upham is dolomite at most localities but limestone at a few. It is somewhat variable in detail but is generally fine grained and is everywhere either apparently unbedded or indistinctly bedded.

DISTRIBUTION AND STRATIGRAPHIC LIMITS

As shown in figure 30 the Second Value Dolomite is present in most of western Texas and southern New Mexico but extends into only a very small part of easternmost southern Arizona. Rocks characteristic of the Upham Dolomite Member occur over the entire Second Value distribution area, but the Cable Canyon Sandstone Member is absent from the south-central part of the region between Bishop Cap, Capitol Dome, and Long Canyon (locs. 4, 39, and 46), in the north-central part of the region around Johnson Park Canyon, Capitol Peak, and the south Sierra Oscura (locs. 7, 9, and 28), and at the extreme west edge of the Second Value distribution area near Morenci (loc. 84).

The Second Value Dolomite disconformably overlies progressively older rocks from southeast to northwest. Along the southeastern edge of the region it overlies Middle Ordovician rocks that have been correlated with the Simpson Group of Oklahoma (fig. 28). Over most of the region, however, it overlies Lower Ordovician formations of the El Paso Group that become progressively older northwestward, as shown in fugures 27 and 28.

The Second Value is overlain with generally abrupt but apparently conformable contact by the Aleman Formation throughout all but the extreme north and west edges of its distribution area. Near those edges, where post-Montoya erosion removed the Aleman but not all of the Second Value, the Second Value is unconformably overlain by Devonian or younger rocks.

PETROLOGY

Cable Canyon Sandstone Member

The Cable Canyon Sandstone Member is made up almost entirely of poorly sorted dolomitic orthoquartzite that is light to medium gray on fresh fracture but is moderate brown to dark brownish gray on weathered surfaces. At some localities, particularly toward the west, very sandy detrital dolomite is present or dominant. At a few localities the sandstones have dominantly siliceous rather than dolomitic cement. The following comments on the petrology of the member are based on outcrop examination of the member at 25 localities and on the examination of 23 thin sections, of which 21 were point counted.

Grain-size sorting in the sandstones seems to be poor to very poor (fig. 31*A*, *B*) in most areas, but on the basis of sieve analyses of sands from Lead Canyon in the Sacramento Mountains (loc. 3) and from Jose (loc. 6) in the Cooks Range, Howe (1959) reported an average Trask coefficient of sorting of 1.67, which would indicate well-sorted sand. Grains in most samples range in size from coarse silt or very fine sand to coarse sand or granules. The coarser grains are generally well rounded. The sand grains are dominantly quartz, but rock fragments of chert, siltstone, mudstone, or dolomite are locally common (fig. *31A*, *C*). Feldspar grains and grains of opaque minerals are commonly present in trace amounts but are never abundant.

Fine- to medium-grained dolomite cements most sandstone of the Cable Canyon and generally makes up one-fourth to one-half of the rock. Calcite cement is occasionally present. Near Lake Valley (loc. 19), the Cable Canyon has been pervasively silicified, and quartz cement has patchily replaced about half of the dolomite cement. Virtually all the cement is quartz in an elongate northern area in western Socorro and Sierra Counties including Eaton Ranch, Winston, and South Percha Creek (locs. 35, 41, and 43) (fig. 31*B*).

Dolomite included in the Cable Canyon is typically fine to medium grained and is very sandy. At some western localities it is slightly silty and fine grained and contains abundant irregular pockets or connected borings of dolomitic sandstone (fig. 31*D*).

Flower (1961) mentioned "saccharoidal" sandstones at the base of the Cable Canyon at a few localities that he believed are unlike the remainder of the unit. He proposed that they are remnants of an older unit which he correlated with the Harding Sandstone of Colorado. Although we visited those localities, we were not convinced of the distinction.

Upham Dolomite Member

The Upham Dolomite Member is nearly everywhere made up of medium- to dark-gray massively bedded resistant fine to very finely crystalline dolomite that generally weathers to olive gray or brownish gray but also to a distinctive mottled yellow gray and olive gray (fig. 32*A*). It commonly displays a very rough weathered surface (fig. 32*B*). At a few localities the dolomite is slightly calcareous, and at a few others much or all of the member is made up of limestone. The basal few feet is commonly slightly sandy. Small quantities of nodular chert occur locally in the member. The following descriptions of the rock are based on the outcrop examination of the member at 33 localities and on the examination of 47 thin sections.

Most thin sections of dolomite from the Upham show only irregularly microcrystalline to finely crystalline dolomite and display no relict limestone fabric (fig. 33*B*). A few, however, display relict images of fossil-bearing lime mudstone, skeletal lime wackestone to packstone (fig. 33*A*), or fossil-bearing lithiclast lime wackestone to packstone; the skeletal lime wackestone to packstone is probably the most abundant. Thin sections of pelmatozoan(?) limestone from the Cooks Range and Morenci (locs. 17 and 84) (fig. 33*E*) showed little that was not evident in hand specimen.

Some dolomites from mineralized areas display a fibrous fabric (fig. 33*D*) that may be characteristic of hydrothermal dolomite. These offer no clue as to their original depositional fabric. Finely crystalline dolomites from throughout the region commonly display vug fillings of coarsely crystalline dolomite (fig. 33*C*). On the outcrop these vug fillings appear as conspicuous white spots on a dark background.

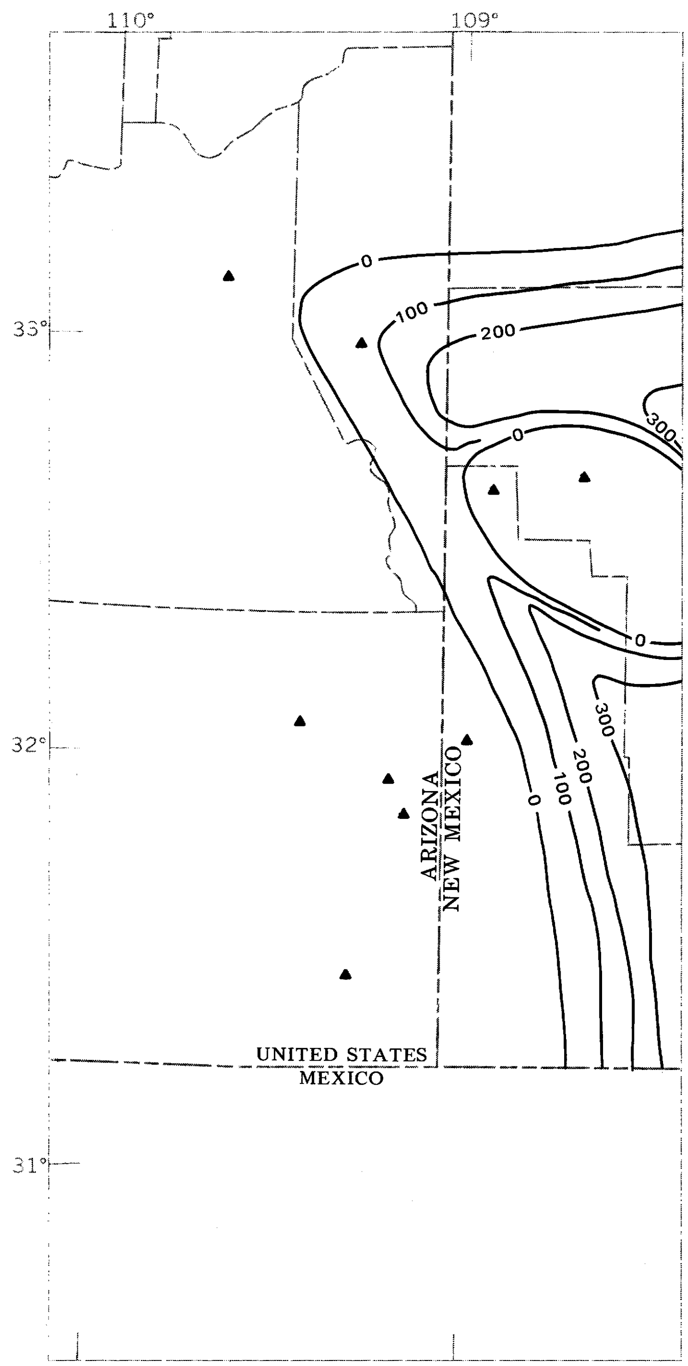
Quartz sand grains in dolomites from the lower part of the Upham are similar to those in the Cable Canyon Sandstone Member but are in general finer.

SEDIMENTARY STRUCTURES

Notable sedimentary structures are rare in the Second Value Dolomite. Indistinct cross-laminations were observed in the Cable Canyon Sandstone Member at a few localities but seem to be absent from most areas. Irregular burrow fillings and pockets of dolomitic sandstone in sandy dolomite are present in the upper part of the Cable Canyon at several localities in the western part of the region (fig. 34). Faint indications of thin beds of intraformational conglomerate were noted in the Upham Dolomite Member at two localities.

POROSITY

The poor grain-size sorting of the Cable Canyon Sandstone Member allows for very little intergranular porosity in the unit, but many samples show considerable cement-reduced or cement-filled vuggy, channel, or fracture porosity. The total porosities of seven samples were checked by the kerosene-displacement method; these ranged from 3.2 to 7.6 percent and averaged 4.8 percent. The sample that showed 7.6 percent total porosity had an effective porosity of 6.4 percent, as checked by the mercury porosimeter, which indicates that most of the pore spaces were effectively interconnected. However, three other effective porosity determinations showed only 1.6, 1.9, and 2.8 percent.



Vuggy porosity was observed in a large proportion of thin sections of samples from the Upham Dolomite Member, but most of the vugs are cement reduced or cement filled. Moldic porosity is also common in the member, and microfracture porosity is not unusual. The total porosities of 11 samples checked ranged from 0 to 8.8 percent and averaged 3.0 percent. The effective porosities of 12 samples checked ranged from 0.7 to 5.1 percent and averaged 2.0 percent. Two samples were checked by both methods and showed 5.1 and 8.8 percent total porosity but only 1.1 and 2.2 percent effective porosity, respectively. These large differences are explained by the nature of the porosity observed in the thin sections of the two samples—moldic in one and vuggy in the other.

THICKNESS

The Second Value Dolomite ranges from a maximum measured thickness of 144 feet at Point of Mountains in Culberson County, Tex. (loc. 50), on the east to erosional

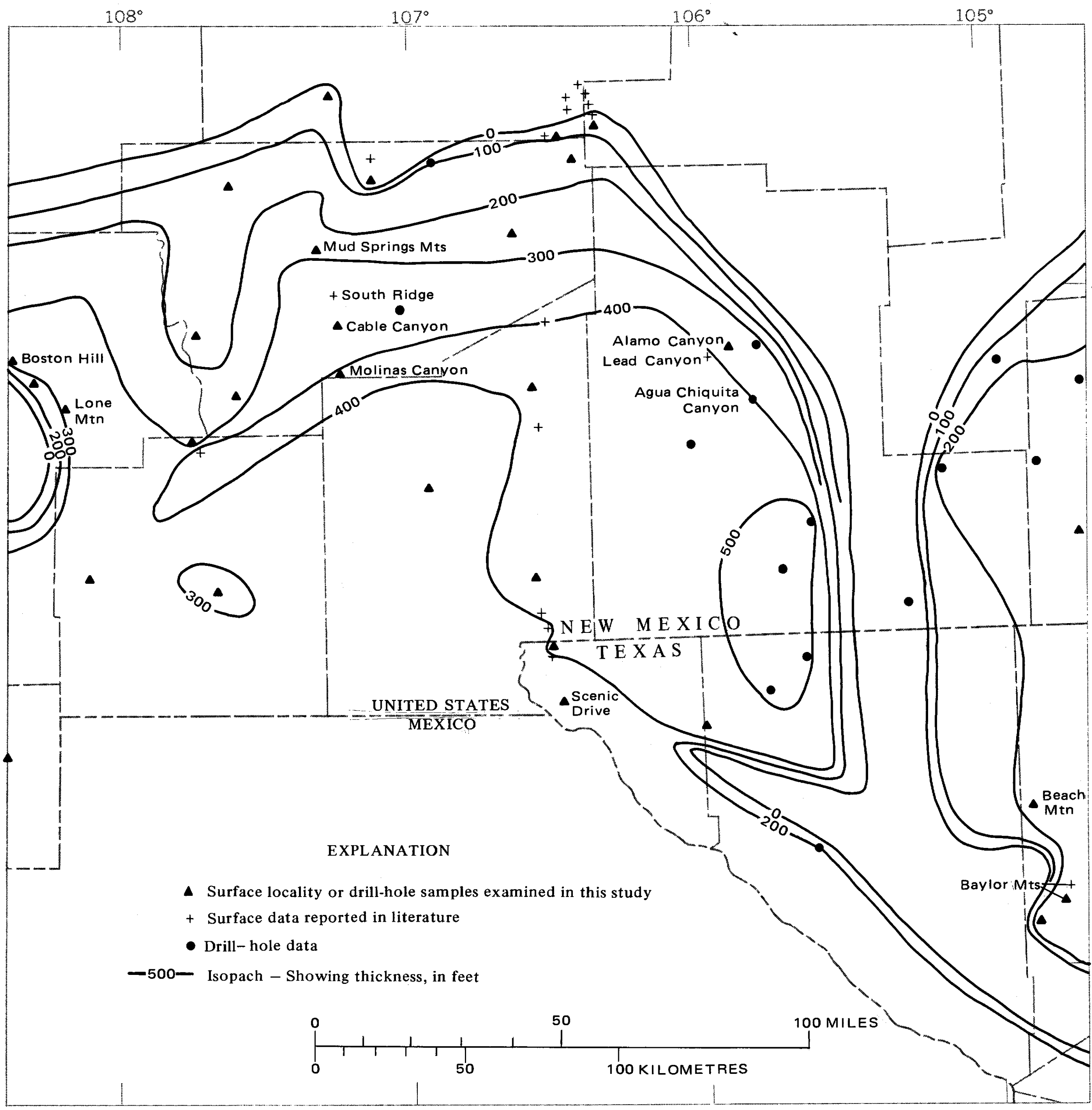


FIGURE 29.—Distribution and preserved thickness of Montoya Group.

wedge edges on the north and west and around some post-Ordovician high areas (fig. 30); it is 80 feet thick at its type locality at Boston Hill (loc. 91). Its minimum measured thickness is 35 feet at San Lorenzo (loc. 38), where the formation is conformably overlain by the Alemen Formation and thus is not thinned by erosion. Although the Second Value does vary irregularly in thickness, it is generally thickest toward the southeast and thinnest toward the northwest.

The thickness of the Cable Canyon Sandstone Member is highly irregular in the region. It is absent, owing to nondeposition, or only inches thick in the triangular area in south-central New Mexico and extreme western Texas defined by Bishop Cap, Capitol Dome, and Long Canyon (locs. 4, 39, and 46) and at Johnson Park Canyon, Capitol Peak, and south Sierra Oscura (locs. 7, 9, and 28) in central New Mexico. At its type locality at Cable Canyon (loc. 15) in the Caballo Mountains it has a reported thickness of 35 feet (Kelley and Silver, 1952) and is nearly as thick at several other nearby localities. The greatest known thickness is 55 feet at Point of Mountains (loc. 50) in the Sierra Diablo, but only about 20 miles away in the southern Baylor Mountains (loc. 52) the thickness is only 2 feet.

The thickness of the Upham Dolomite Member where completely preserved ranges from 16 feet at San Lorenzo (loc. 38) to 115 feet at Rhodes Canyon (loc. 10) in the San Andres Mountains. The Upham is reported to be 78 feet thick at its type section at Cable Canyon (loc. 15) (Kelley and Silver, 1952).

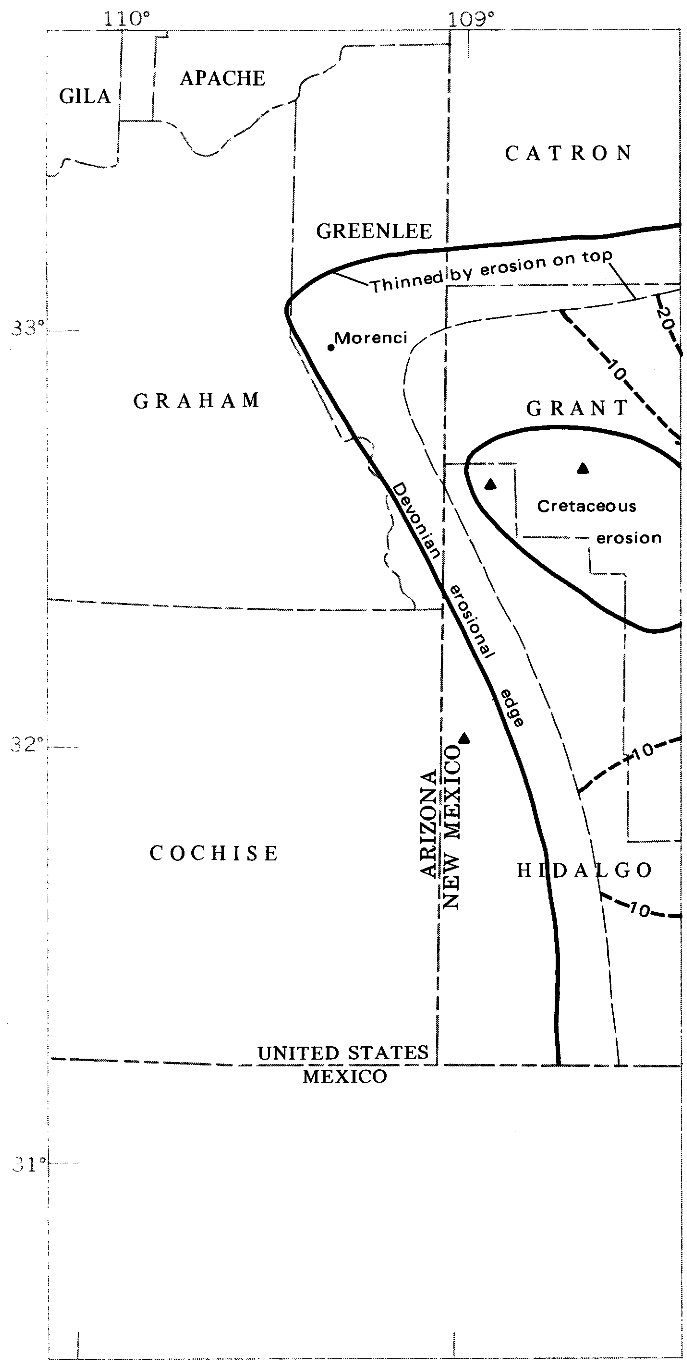
FOSSILS AND AGE

Marine invertebrate fossils occur in the Second Value Dolomite at nearly all localities. Corals are most conspicuous but brachiopods, mollusks, and pelmatozoan remains are common; trilobites and bryozoans are sparse. No forms that had not previously been found in the formation were collected during this study. As discussed by Howe (1959), Hill (1959), and Flower (1961, 1969), different faunal elements suggest ages ranging from Black River (late Middle Ordovician) to Red River (Late Ordovician). For the present it seems safest to say that the Second Value is roughly of late Middle Ordovician (Trenton) age. It may also be of early Late Ordovician age and correlative with the Bighorn Dolomite of Wyoming.

CONTACTS

The base of the Second Value Dolomite lies disconformably on earlier Ordovician rocks throughout the report region, and the contact is everywhere abrupt. The Second Value is conformably overlain by the Aleman Formation, but the contact in most places is rather abrupt inasmuch as the massive chert-free carbonates of the Second Value generally give way rather abruptly to more distinctly bedded finer grained and very cherty carbonates of the Aleman. In this study the contact was selected at the lowest appearance of abundant chert regardless of the nature of the carbonates.

The contact between the Cable Canyon Sandstone Member and the Upham Dolomite Member apparently is conformable at all localities. Generally, however, the contact can be picked within very narrow limits because the dolomitic sandstone or conspicuously sandy dolomite at the top of the Cable Canyon gives way rather abruptly to only slightly sandy dolomite at the base of the Upham. At most localities a distinct bedding plane separates the two members.



ALEMAN FORMATION

NAME AND TYPICAL LOCALITY

The Aleman Formation was named by Kelley and Silver (1952) for exposures in the Caballo Mountains, N. Mex., at Cable Canyon (fig. 36 and loc. 15, fig. 1).

GENERAL DESCRIPTION

The Aleman Formation, 47–238 feet thick, is made up of fine-grained generally thinly laminated bedded carbonate that is characterized by an abundance of chert, much of which is distinctively layered (fig. 35).

DISTRIBUTION AND STRATIGRAPHIC LIMITS

The Aleman Formation is distributed throughout most of western Texas and southern New Mexico, except on some large post-Ordovician high areas (fig. 36); it is not known to extend into southern Arizona. It conformably overlies the Second Value Dolomite throughout its distri-

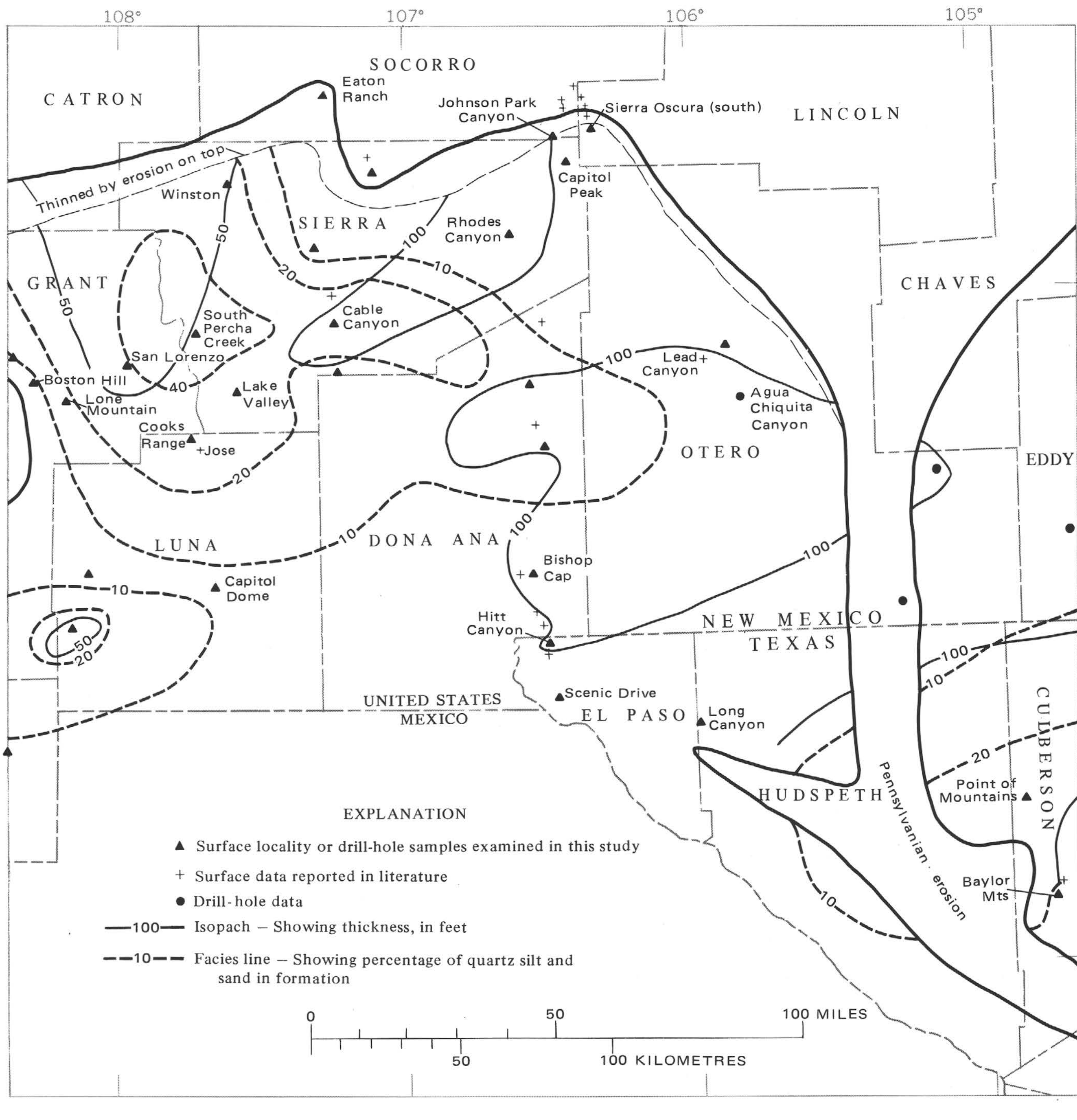


FIGURE 30.—Distribution, thickness, and facies of Second Value Dolomite.

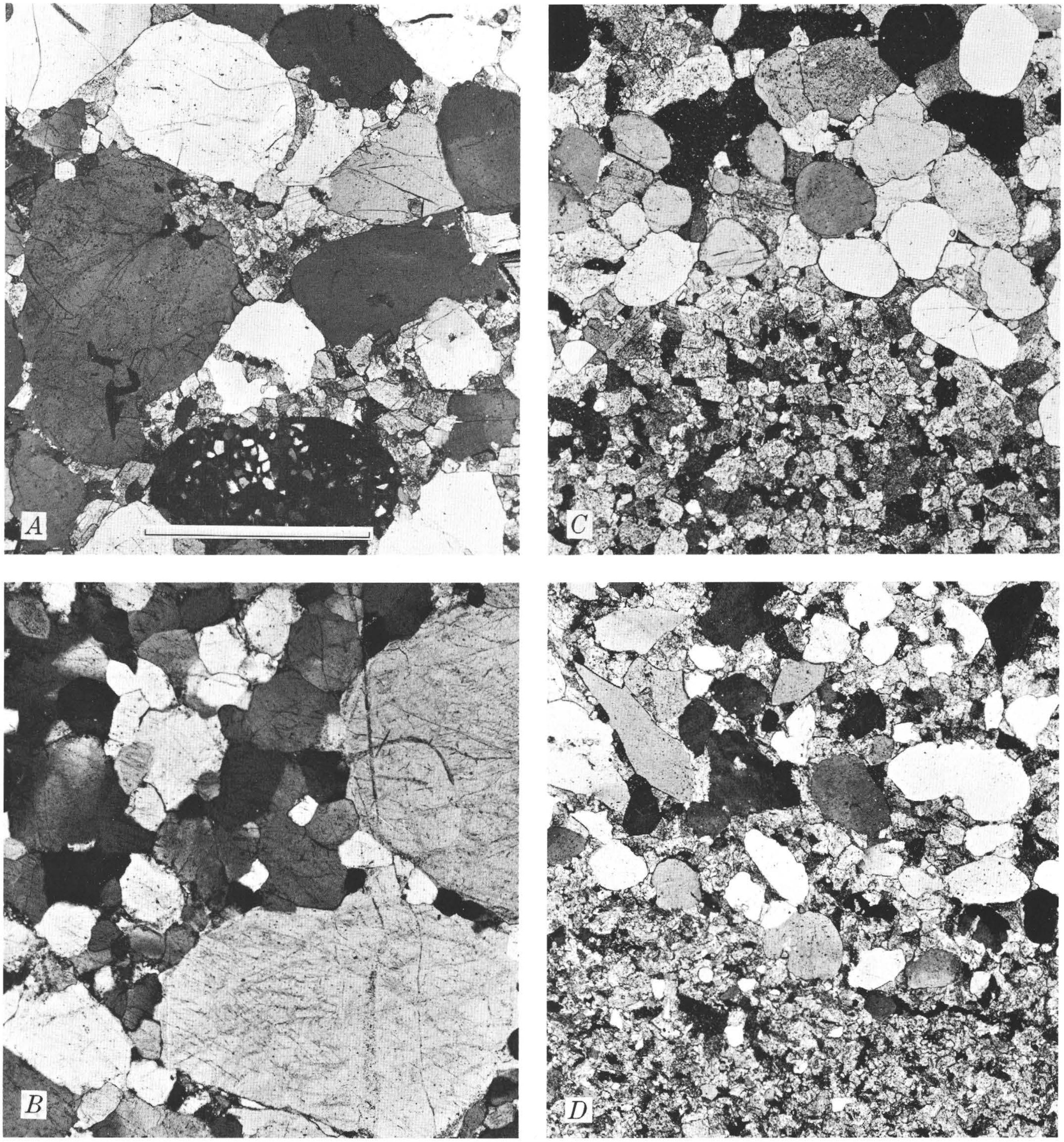


FIGURE 31.—Photomicrographs of Cable Canyon Sandstone Member of Second Value Dolomite. Bar in *A* is 1 mm; all views are same scale. *A*, Coarse-grained dolomitic sandstone from 6 feet above base of member at Lone Mountain (loc. 22). Most grains are quartz, but near base of picture is large dark fragment of silty mudstone whose source is unknown. Cement is dolomite, some of which has replaced margins of quartz grains. Crossed nicols. *B*, Poorly sorted orthoquartzite from member on South Percha Creek (loc. 43). Sandstone such as this, without dolomite cement, is unusual in the Cable Canyon and may result from replacement of dolomite by quartz in this sample. Crossed nicols. *C*, Dolomitic sandstone from 4 feet above base of member at Point of Mountains (loc. 50). Grains are mostly quartz and cement is mostly dolomite, but large area of dolomite at base is part of a large detrital fragment of dolomite—not an uncommon feature of the Cable Canyon. Crossed nicols. *D*, Bottom edge of dolomitic sandstone fill in burrowed silty dolomite from 3 feet above base of member at Boston Hill (loc. 91). Sand-filled burrows and pockets in dolomite are common in the Cable Canyon at several western localities. Crossed nicols.

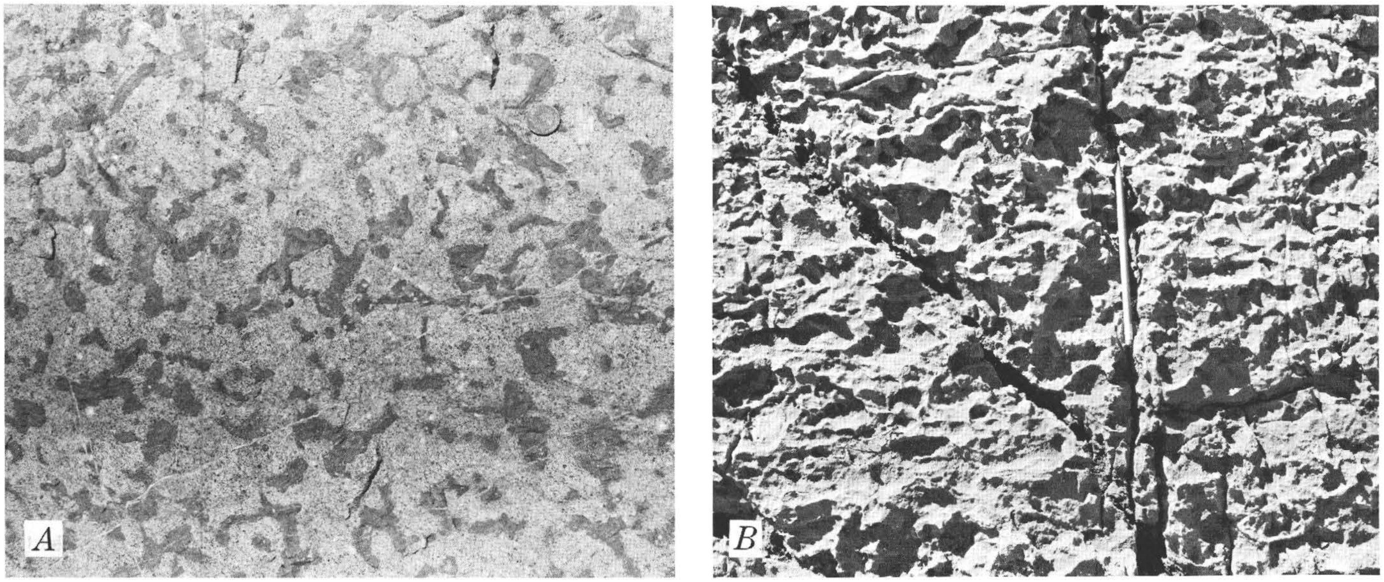


FIGURE 32.—Outcrops of Upham Dolomite Member of Second Value Dolomite. *A*, Mottled dolomite near base of member near Scenic Drive section in southern Franklin Mountains (loc. 45). The origin of this mottling is unclear, but such mottling is common in the Upham in and near extreme western Texas and is seen sporadically elsewhere. Penny gives scale. *B*, Very rough weathering calcareous dolomite about 40 feet above base of member at Hitt Canyon in northern Franklin Mountains (loc. 44). Such rough weathered surfaces are characteristic of the Upham at many localities. Pencil gives scale.

bution area. The Aleman is conformably overlain by the Cutter Dolomite except near the margins of its distribution area, where it is unconformably overlain by post-Ordovician rocks.

PETROLOGY

The Aleman Formation is made up dominantly of generally thinly laminated microcrystalline cherty dolomite at most sections, but considerable limestone is present at several southern localities extending from the Florida Mountains to the Sierra Diablo (locs. 39, 44, 46, and 50), and the carbonate is all limestone in the Cooks Range (loc. 17). The carbonate rocks are mostly distinctly bedded and average medium gray on fresh fracture and light medium gray to light olive gray on weathered surfaces. Nearly white to very dark gray chert that occurs in extensive horizontal lentils as much as several inches thick and in elongate nodules makes up 10–45 percent of the formation, and it probably averages 25 percent over the region. A thin bed of sandstone was seen near Winston in the Sierra Cuchillo (loc. 41). The following comments on the lithology of the Aleman are based on outcrop examination of the formation at 27 localities and on the examination of 43 thin sections.

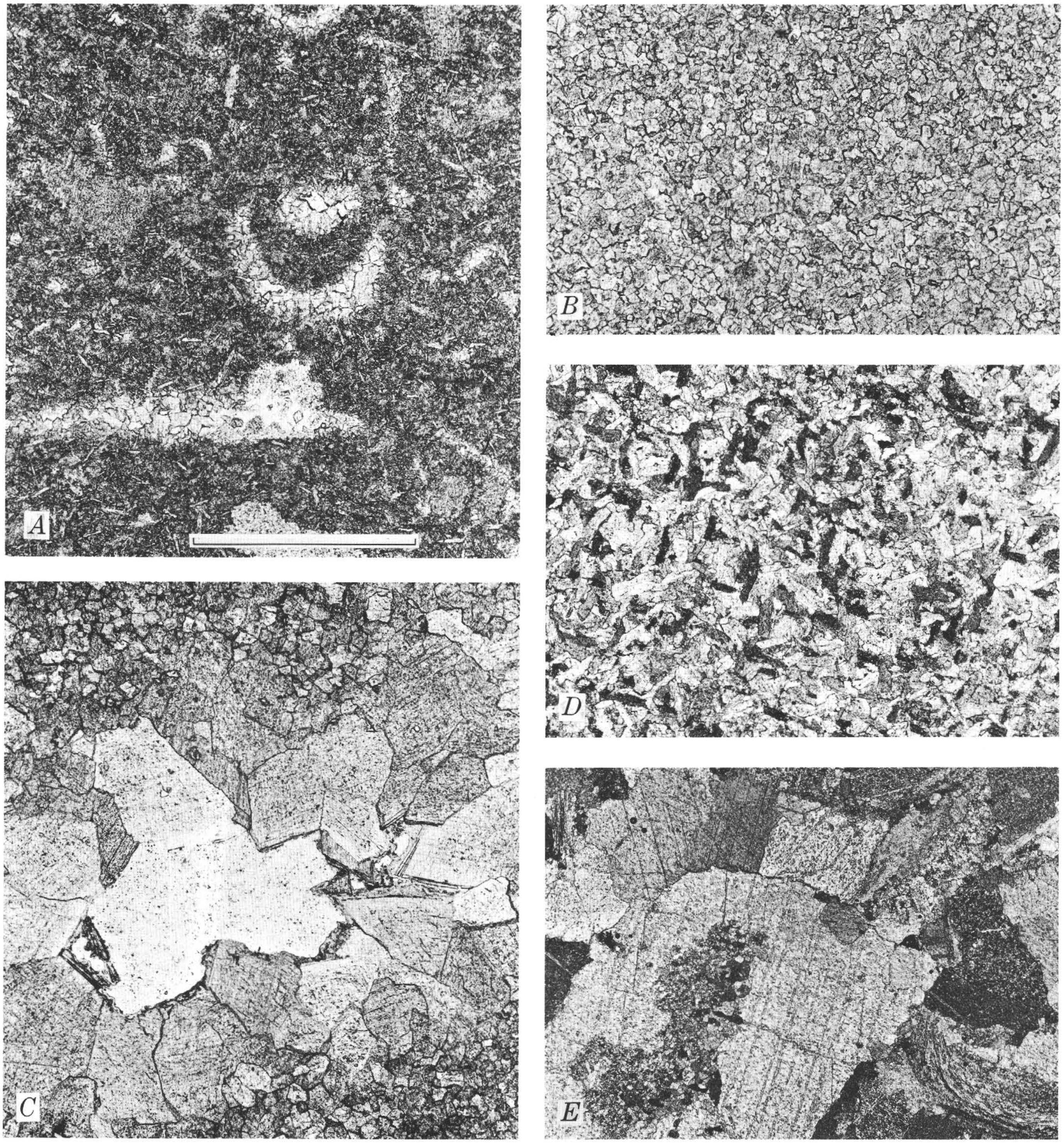
Because the Aleman is largely or completely dolomitized at most localities, relatively few thin sections of limestone were examined, but many of the dolomites display a rather distinct relict texture. Most of the carbonate is (or was) lime mudstone or fossil-bearing lime mudstone; much is thinly laminated and on occasion shows oncolite structures (fig. 37*F*). Skeletal lime wackestone (fig. 37*A*) and skeletal lime packstone are sparsely represented. Siliceous spicules can be seen in many lime mudstones whether or not they have been dolomitized (fig. 37*D*).

Most dolomite in the formation is microcrystalline (fig. 37*B*), but some laminae or irregular areas are very finely crystalline to medium-crystalline dolomite (fig. 37*E*).

Many of the chert bands and nodules in the Aleman are sharply bounded (fig. 37*B*), but others have gradational boundaries with the dolomite (fig. 37*B*, *E*). In addition, most carbonate in the formation contains considerable silica in the form of siliceous spicules (fig. 37*D*), intergranular chert (fig. 37*B*, *F*), chert veinlets, and incipient chert nodules (fig. 37*D*). In most thin sections the formation of chert nodules or lentils postdated dolomitization, but in some thin sections later dolomite can be seen as veins in chert (fig. 37*E*). Much of the chert in the formation may have been derived from the abundant siliceous spicules in the carbonate.

SEDIMENTARY STRUCTURES

Megascopic sedimentary structures that might be of use in interpreting depositional environments are not common in the Aleman Formation. The thinly laminated dolomites common to much of the formation might be interpreted as algal-mat dolomites, but, other than scattered oncolites (fig. 37*F*), sedimentary structures that are usually associated with supertidal and intertidal algal mats are lacking. Evidence for aerated shallow marine waters occurs in the Franklin Mountains area (Hitt Canyon and Sugarloaf, locs. 44 and 93), where colonial coral colonies in apparent growth position are found at one horizon (fig. 38).



POROSITY

Porosities in the Aleman Formation are low. The total porosity of five samples was checked by the kerosene-displacement method; the porosities ranged from 0.7 to 2.7 percent and averaged 1.5 percent. The effective porosity of 10 different samples was checked by the mercury porosimeter; the porosities ranged from 0.5 to 4.4 percent and averaged 1.5 percent. In thin section the most commonly observed types of pore space were microfractures, minute vugs, and fossil molds. Possible fenestral porosity was noted in one sample.

THICKNESS

The Aleman Formation has a maximum measured thickness of 238 feet in the northern Baylor Mountains (loc. 47) and thins to an erosional wedge edge on the west and north and around some post-Ordovician high areas

FIGURE 33.—Photomicrographs of Upham Dolomite Member of Second Value Dolomite. Bar in *A* is 1 mm; all views are same scale. *A*, Completely dolomitized skeletal lime wackestone from about 100 feet above base of member in Rhodes Canyon (loc. 10). Few dolomitized samples of the Upham show such distinct relict structure. Here the lime mud matrix has recrystallized into a matte of fibrous dolomite, whereas the fossil fragments are mostly replaced by more coarsely crystalline dolomite. Plain light. *B*, Very finely crystalline dolomite from near base of member in Agua Chiquita Canyon (loc. 1). Many Upham samples look like this in thin section and offer little clue as to the original sedimentary structure. It may have been lime mudstone. Plain light. *C*, Coarsely crystalline dolomite filling in vug in very finely crystalline dolomite from 95 feet above base of Second Value Dolomite at Bishop Cap (loc. 4). Such vugs are common in the Upham but are, as in this instance, generally filled. Even where only partially filled, the pore spaces, though abundant in places, do not appear to be interconnected. Plain light. *D*, Finely crystalline fibrous dolomite from about 20 feet above base of member at Boston Hill (loc. 91). This dolomite, which is from a mineralized area, appears to have been metamorphosed and may once have looked like *A* or *B*. There is virtually no suggestion of the original sedimentary fabric. (Compare fig. 25*B*.) Crossed nicols. *E*, Coarsely recrystallized pelmatozoan(?) limestone from 7 feet above base of member in Cooks Range (loc. 17). This is from one of the very few localities where the Upham is limestone. Crossed nicols.

(fig. 36). Its minimum measured thickness in areas where conformably overlain by the Cutter Dolomite and thus presumably completely preserved is 47 feet at Mescal Canyon in the Big Hatchet Mountains (loc. 24). In its typical locality at Cable Canyon (loc. 15) in the Caballo Mountains the Aleman has a reported thickness of 107 feet (Kelley and Silver, 1952). In general, the formation is less than 100 feet thick in the western part of the region and more than 150 feet thick in much of the central and southeastern part of the region (fig. 36).

FOSSILS AND AGE

The Aleman Formation is not conspicuously fossiliferous, but at most localities there are a few abundantly fossiliferous beds and other scattered fossils. Brachiopods and corals are most common, but bryozoans, mollusks, trilobites, conodonts, and other forms have been found. Previously unreported bryozoans and conodonts collected during this study are listed under "Fossil Lists."

Because of difficulties of correlating the fossil zones of the Aleman with Ordovician zones of the central United States, the precise age of the Aleman is still in doubt. However, both Howe (1959) and Flower (1969) agreed that it belongs to the Late Ordovician. Howe (1959) believed that there is no faunal hiatus between the Aleman and the underlying Second Value Dolomite, but Flower (1969) believed that part of the lowest Upper Ordovician is missing between the formations. Because the two formations seem to be lithologically gradational, I believe that no real hiatus exists and that the Second Value Dolomite of late Middle Ordovician age is conformably overlain by the Aleman of Late Ordovician age.

UPPER CONTACT

The contact of the Aleman Formation with the overlying Cutter Dolomite is gradational and arbitrary. At most localities it can be picked fairly closely as the horizon at which very cherty beds of the Aleman give way upward to virtually chert-free beds of otherwise similar lithology in the Cutter. Because the boundary is arbitrary, different workers might choose the contact differently at some localities. A general decrease in thickness of the Aleman westward and a concomitant increase in thickness of the Cutter westward might indicate that the contact is generally in progressively older beds westward.

CUTTER DOLOMITE

NAME AND TYPE LOCALITY

The Cutter Dolomite was named by Kelley and Silver (1952) for exposures in the Caballo Mountains, N. Mex., at Cable Canyon (fig. 39 and loc. 15, fig. 1).

GENERAL DESCRIPTION

The Cutter Dolomite, which has a maximum thickness of 300 feet but is generally less than 200 feet thick, is made up almost entirely of yellowish-gray-weathering medium- to light-gray microcrystalline dolomite that typically crops out in steep slopes.

DISTRIBUTION AND STRATIGRAPHIC LIMITS

The Cutter Dolomite underlies much of westernmost Texas and southern New Mexico, except in two large and many small post-Ordovician high areas, but it does not extend into Arizona (fig. 39). It conformably overlies the Aleman Formation and is disconformably or unconformably overlain by post-Ordovician rocks.

PETROLOGY

The Cutter Dolomite consists almost entirely of obscurely to distinctly bedded medium- to light-gray

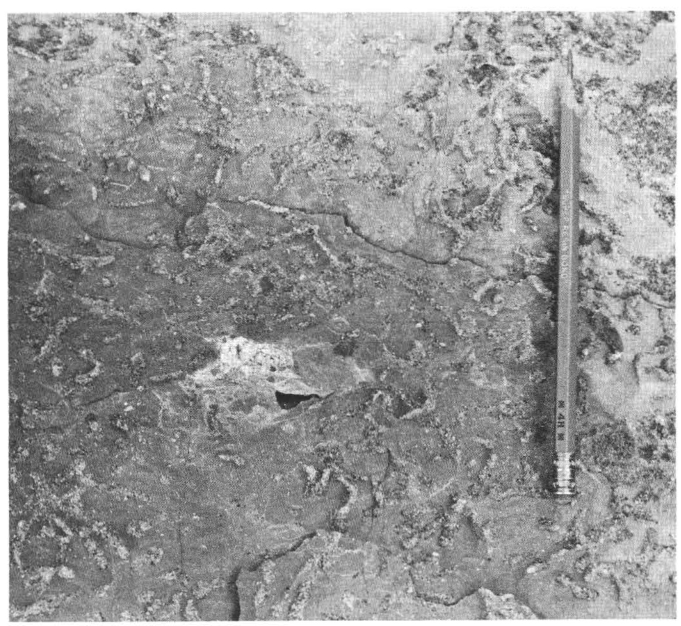


FIGURE 34.—Sandy dolomite with burrow fillings of dolomitic sandstone 12 feet above base of Cable Canyon Sandstone Member of Second Value Dolomite at Lone Mountain (loc. 22). Rock such as this is present at several localities. (See photomicrograph of similar rock in fig. 31*D*.)

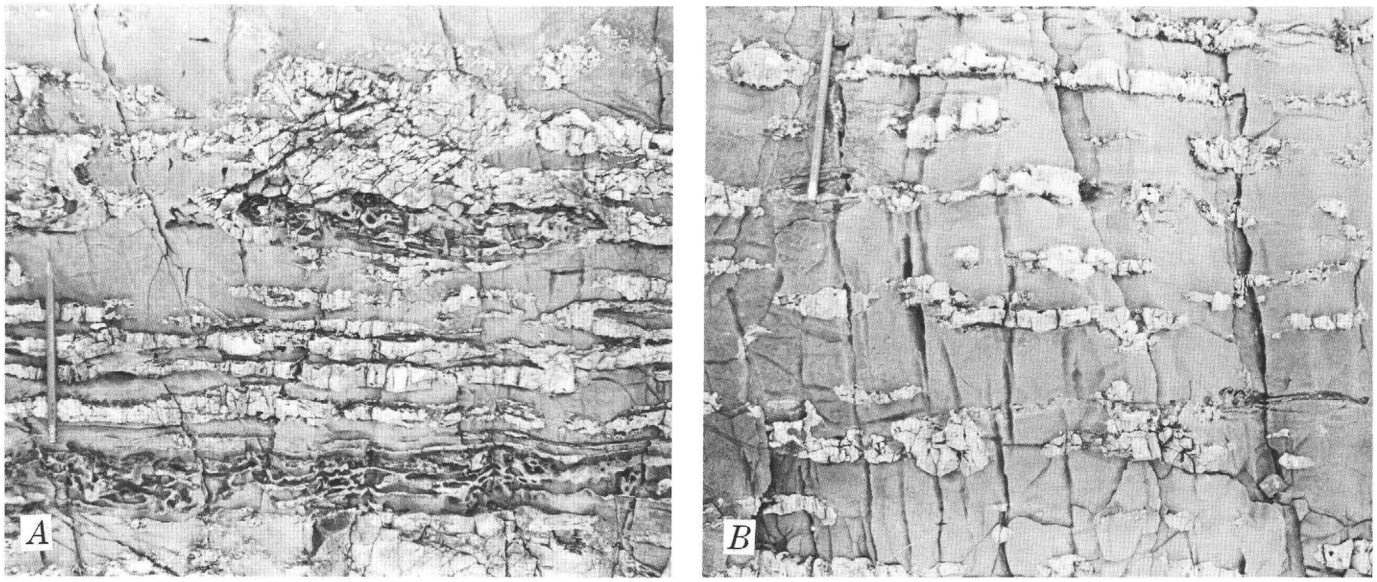


FIGURE 35.—Cherty fine-grained dolomite, 26–32 feet above base of Aleman Formation at Hitt Canyon in the Franklin Mountains (loc. 44). Pencil gives scale. Several habits of chert occurrence are shown in *A* and another in *B*. The bedded chert under the pencil in *A* and the elongate lenticular chert in *B* are most characteristic of the Aleman at most localities.

microcrystalline dolomite that in general weathers to a pale yellowish gray; in some areas similarly colored limestone is present in the formation. The basal few feet of the formation is commonly marked by an argillaceous or slightly silty interval. Some nodular chert is present at most localities. The following comments on the petrology of the Cutter are based on the outcrop examination of the formation at 21 localities and on the examination of 40 thin sections.

Although the Cutter is now largely dolomite, thin sections commonly display indistinct to conspicuous relict textures of the original limestone. Most of the rock in the formation seems to have been lime mudstone or fossil-bearing lime mudstone (fig. 40*B*), but beds of dolomitized skeletal wackestone to packstone are also present (figs. 40*A*, 41*A*). More than half of the dolomitized lime mudstone is conspicuously laminated (figs. 40*C*, 41*B*).

Most of the dolomites are largely microcrystalline, but laminae or patches of very fine to medium-crystalline dolomite are commonly present (fig. 40*B*, *C*). The two limestone samples examined show scattered dolomite rhombs or dolomitized patches (fig. 40*A*).

A few samples of dolomite from the Cutter contain siliceous spicules or chert replacement of fossil debris, but silica in any form is much scarcer in the Cutter than in the underlying Aleman Formation, where carbonates are otherwise very similar to those in the Cutter.

Minor argillaceous material and traces of quartz silt were noted in a sample from near the base of the Cutter at Long Canyon (loc. 46) in the Hueco Mountains. Specks of probable carbonaceous or bituminous material were seen in several samples.

SEDIMENTARY STRUCTURES

Sedimentary structures useful for paleoenvironmental interpretation seem to be virtually nonexistent in the Cutter Dolomite. The common very thin laminations might be interpreted to be of algal-mat origin, but no features were noted that are suggestive of subaerial desiccation of tidal-flat algal mats. The only evidence of current action noted was in a thin lenticular bed of cross-laminated saccharoidal dolomite 40 feet above the base of the Cutter at Lone Mountain (loc. 22).

POROSITY

Most of the Cutter Dolomite is very low in effective porosity, but some of it has moderate total porosity in the form of small vugs and fossil molds. Only three samples were checked for total porosity by the kerosene-displacement method, and these had 2.1, 3.6, and 4.2 percent porosity. Several other samples viewed in thin section had visible porosities estimated at 5-10 percent. The effective porosities of nine samples checked by the mercury porosimeter ranged from 0.2 to 2.3 percent and averaged only 0.8 percent. The sample whose measured total porosity was 4.2 percent showed an effective porosity of only 0.3 percent. This disparity is not surprising, considering that vuggy and moldic porosity is not interconnected. Although microfractures were noted in many samples in thin section, these were nearly all filled by cement.

THICKNESS

Because the Cutter Dolomite has a disconformable or unconformable upper contact throughout the report region, its total original thickness is probably nowhere preserved. Its greatest thicknesses are near the west edge of its distribution area, but it thins suddenly to an erosional wedge edge farther westward as well as northward. The maximum measured thickness is 293 feet at Mescal Canyon in the Big Hatchet Mountains (loc. 24), and the reported (Kelley and Silver, 1952) thickness at the Cutter type locality at Cable Canyon (loc. 15) in the Caballo Mountains is 129 feet.

FOSSILS AND AGE

Fossils are sparse to absent in much of the Cutter Dolomite, but at nearly all localities there are a few beds rich in corals or brachiopods. Mollusks and conodonts may be recovered from some beds. As summarized by Howe (1959) and Flower (1961, 1969), the Cutter is of Richmond (Late Ordovician) Age. Howe (1959) believed that deposition was continuous from Aleman into Cutter time, but Flower (1969) suggested that a minor erosion interval separated deposition of the two formations over most of the region. On the basis of lithology and the seeming westward increase in age of the contact between the formations, I am strongly inclined to agree with Howe (1959) that deposition was virtually continuous.

UPPER CONTACT

The Cutter is disconformably overlain by the Fusselman Dolomite of Silurian age over much of the region, but near the north and west erosional edges and along some post-Ordovician high areas, rocks of Devonian, Pennsylvanian, Permian, or Cretaceous age may unconformably overlie the Cutter. Distinguishing the Cutter from post-Silurian rocks is no problem, but the dolomite-dolomite contact between the Cutter and the Fusselman, though knife sharp, can seem subtle to those unfamiliar with it. With a little experience, however, one can readily detect the slight change in color and texture between the two dolomites. The Fusselman weathers to a brownish gray or olive gray or to a yellowish gray that is darker than that of the Cutter. It is nearly everywhere more coarsely grained than the Cutter and is almost everywhere more massively bedded.

ROCKS DIRECTLY OVERLYING CAMBRIAN AND ORDOVICIAN STRATA

Silurian strata overlie Ordovician rocks over much of southern New Mexico and western Texas, Devonian rocks overlie Cambrian or Ordovician rocks over most of southern Arizona and part of southern New Mexico, and various rocks younger than Devonian overlie the Cambrian or Ordovician in small local areas in various parts of the region. Because the character of overlying rocks can be of major significance in evaluating the oil and gas potential of the underlying rocks, brief descriptions of the rocks that overlie the Cambrian or Ordovician are presented.

SILURIAN ROCKS

Silurian strata assigned to the Fusselman Dolomite disconformably overlie the Middle and Upper Ordovician Montoya Group over much of southern New Mexico and western Texas (fig. 42). The formation is many hundreds of feet thick in part of southern New Mexico and in western Texas but thins to an erosional wedge edge to the west and north.

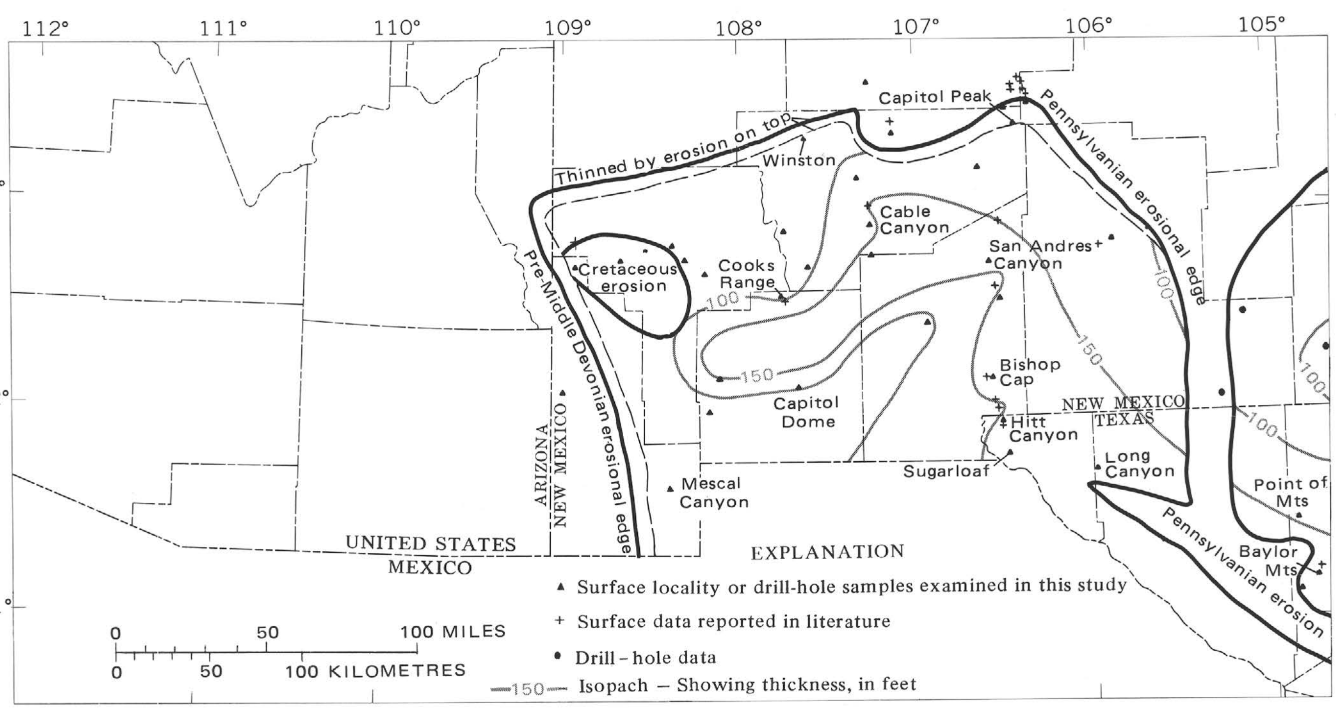


FIGURE 36.—Distribution and thickness of Aleman Formation.

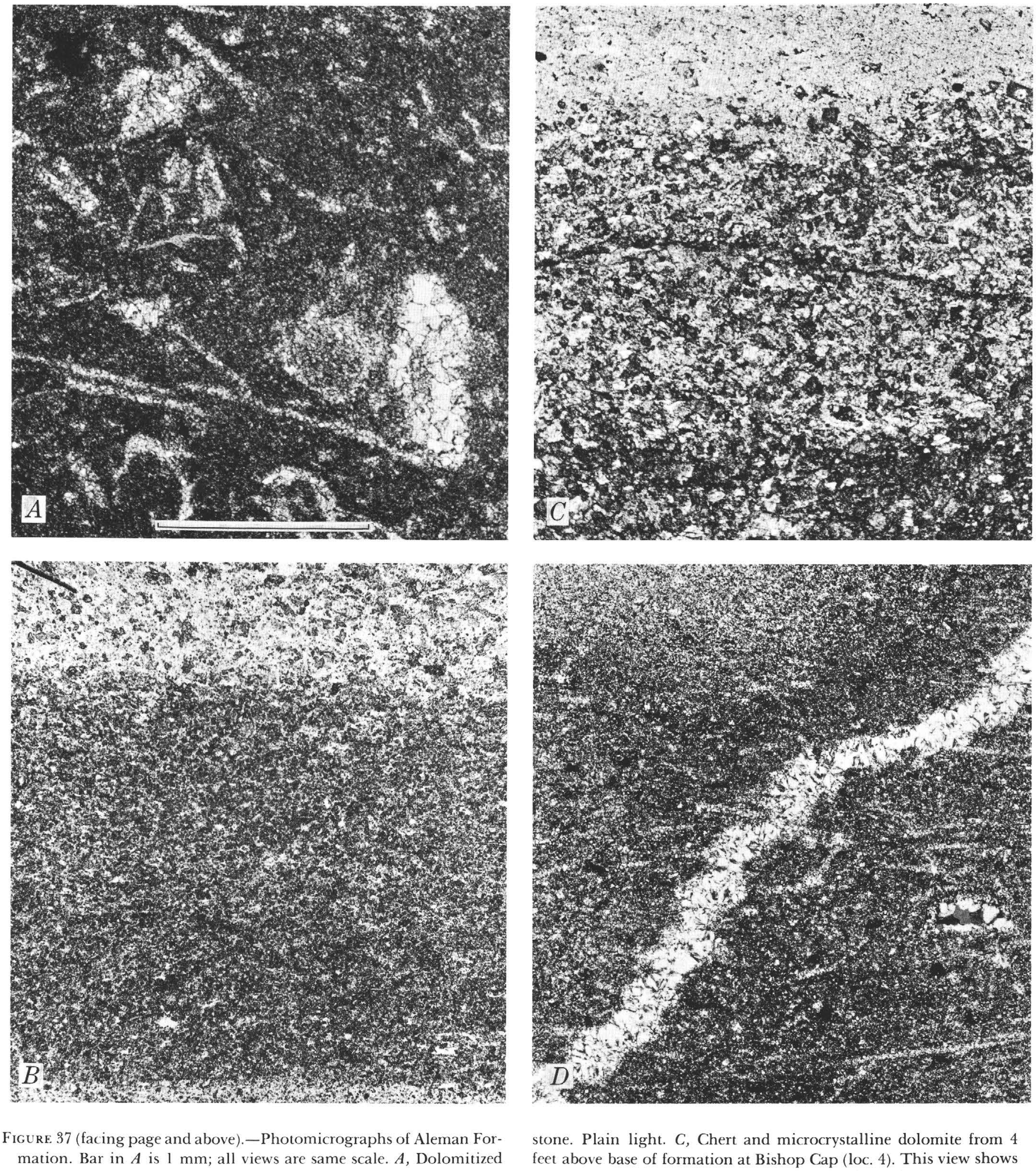
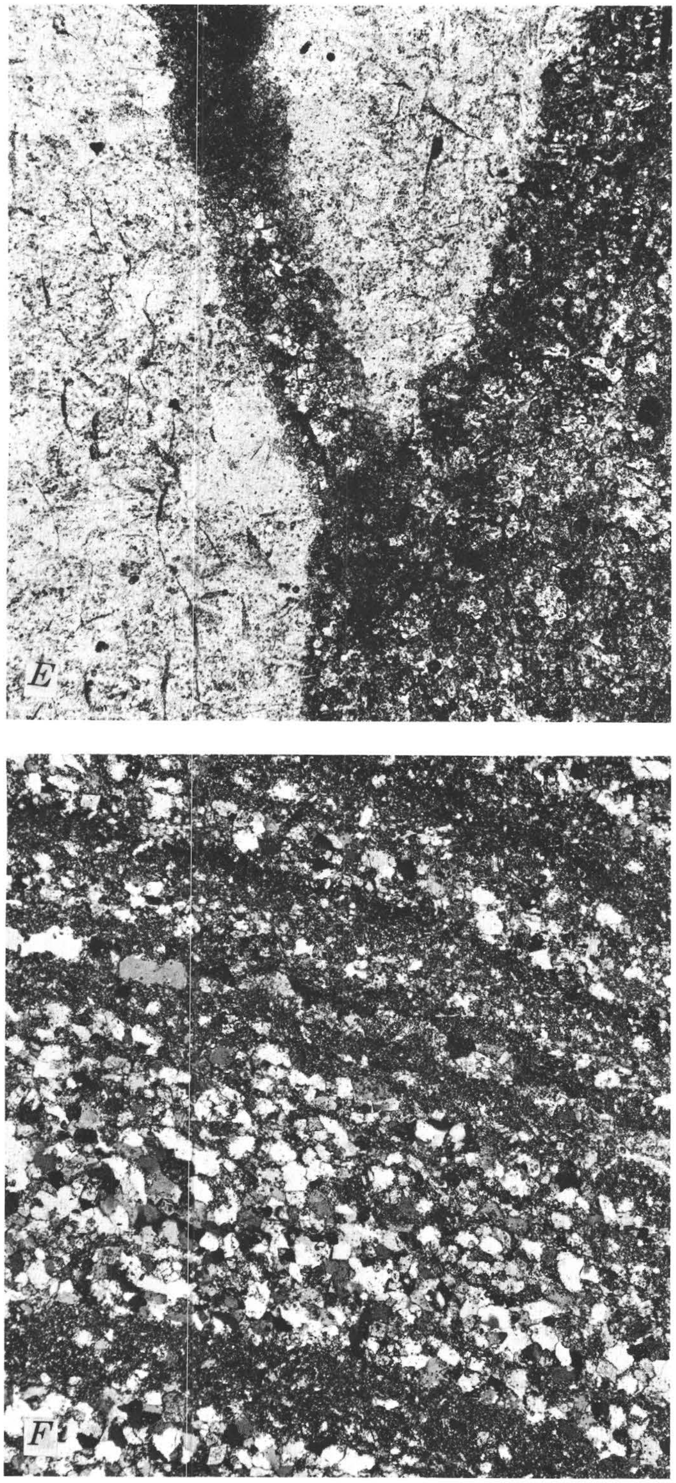


FIGURE 37 (facing page and above).—Photomicrographs of Aleman Formation. Bar in *A* is 1 mm; all views are same scale. *A*, Dolomitized skeletal wackestone from about 75 feet above base of formation in San Andres Canyon (loc. 27). Rock such as this is common but not predominant in the Aleman. Plain light. *B*, Chert-banded microcrystalline dolomite from about 25 feet above base of formation at Capitol Dome (loc. 39). The lower very thin chert lamina is fairly sharply bounded, whereas the upper one has diffused boundaries. Flecks of silica (white) occur in the dolomite, and dolomite flecks remain in the chert. The dolomite may be dolomitized lime mudstone. Plain light. *C*, Chert and microcrystalline dolomite from 4 feet above base of formation at Bishop Cap (loc. 4). This view shows a zone more than 1 mm thick of incompletely silicified dolomite between chert at top and slightly siliceous dolomite on bottom. Boundaries between chert and dolomite are diffuse like this in most thin-section views although on the outcrop or in hand specimen the boundaries appear to be very sharp. Plain light. *D*, Siliceous microcrystalline dolomite with chert veinlet from 5 feet above base of formation at Hitt Canyon (loc. 44). The dolomite contains numerous siliceous sponge spicules. These may be the source of the silica



in the chert veinlet and in the diffused area of "incipient" chert at upper left. Plain light. *E*, Chert with veinlets of microcrystalline dolomite from near top of formation at Long Canyon (loc. 46). Here the process of silicification appears to have been reversed — chert at left is veined with microcrystalline dolomite (dark areas). Plain light. *F*, Partly silicified section of part of a dolomitized oncolite from top of formation at Capitol Peak (loc. 9). The microcrystalline dolomite in the curved laminae of this oncolite are about one-half replaced by granular chert. Crossed nicols.

The Fusselman consists almost entirely of coarsely microcrystalline to medium-crystalline massively bedded dolomite throughout most of its distribution area; limestone occurs very locally. Most of the dolomite is medium gray on fresh fracture and weathers to yellowish gray or light olive gray. Large irregular chert nodules are abundant in some areas and absent from others. Dolomitization of the Fusselman is generally so complete that original limestone fabrics are lost, but faint relict textures in a few of 14 thin sections cut from rock collected from the basal part of the formation suggest that much of the rock may have ranged from lime mudstone to skeletal lime wackestone.

The determined total porosities of six samples of Fusselman Dolomite ranged from 0.7 to 4.8 percent and averaged 3.0 percent. One sample that had 4.3 percent total porosity proved to have an effective porosity of only 0.7 percent, indicating that the pore spaces were not effectively interconnected. The effective porosities of three other samples were 1.4, 2.2, and 2.6 percent. The low effective porosities were probably due to the vuggy nature of the porosity noted in most thin sections.

The Fusselman is nearly everywhere overlain by dark shaly Devonian strata except locally near the Plymouth 1 Federal well (loc. 108), Cable Canyon (loc. 15), Baylor Mountains (loc. 52), and Victorio Mountains (loc. 90); at these four localities the Devonian was removed and the Fusselman is overlain, respectively, by Mississippian, Pennsylvanian, Permian, and Cretaceous rocks.

DEVONIAN ROCKS

Devonian strata up to a few hundred feet thick disconformably overlie Cambrian, Ordovician, or Silurian strata over much of the report region, as indicated in figure 51. Dark-gray marine shales and siltstones assigned to several widespread or local stratigraphic units make up a significant part of the Devonian in western Texas, New Mexico, and easternmost Arizona; but farther west in Arizona, carbonates of shallow marine origin assigned to the Martin Formation are the dominant lithology of the Devonian (Poole and others, 1967). The Devonian rocks, particularly those to the east, offer excellent potential as petroleum source beds.

POST-DEVONIAN ROCKS

Pennsylvanian strata of marine origin made up of fine to coarse terrigenous clastics and carbonates directly overlie Ordovician rocks in a wedge-shaped area near the north edge of the Ordovician distribution area in central New Mexico. These Pennsylvanian rocks, which contain possible petroleum source beds, have been described by Kottlowski (1960b) and Bachman (1968).

Permian strata of marine origin overlie Ordovician rocks in the subsurface of eastern New Mexico and western Texas along the margins of areas uplifted in Pennsylvanian time, but unless already penetrated by drill holes the precise locations of such areas is speculative. A hole

FIGURE 38.—Silicified colonial coral 131 feet above base of Aleman Formation at Hitt Canyon in the Franklin Mountains (loc. 44). Pencil points up. These colonies are most commonly found in the formation in extreme western Texas and nearby areas.

(Turner 1 State) drilled at locality 105 (fig. 1) penetrated Permian strata that directly overlie Lower Ordovician rocks. The nature of the Permian rocks in the region was reviewed by McKee, Oriel, and others (1967).

Cretaceous strata overlie Ordovician rocks at Capitol Dome (loc. 39, fig. 1) and probably overlie Cambrian and (or) Ordovician rocks elsewhere in the subsurface along the margins of areas in western New Mexico and Arizona that were uplifted in Mesozoic time. The nature and distribution of the Cretaceous rocks of the region, which toward the north might offer some potential as petroleum reservoir rocks, were summarized by Hayes (1970).

TIME-STRATIGRAPHIC UNITS

CAMBRIAN

MIDDLE CAMBRIAN

DEFINITION AND DISTRIBUTION

Middle Cambrian rocks as interpreted in this report include the Bolsa Quartzite and overlying lower member of the Abrigo Formation in the western part of the region and the lower part of the Coronado Sandstone in the central part of the region (fig. 5); Middle Cambrian rocks are absent, probably owing to nondeposition, in the eastern part of the region. Middle Cambrian rocks are thus present in most of southern Arizona except in a broad area where they were presumably removed by erosion during Cretaceous time (fig. 43).

THICKNESS

Middle Cambrian rocks of the region, which unconformably overlie Precambrian rocks on a surface of variable relief, thin irregularly northeastward from 800 or 1,000 feet in the southwestern part of the region to a depositional wedge edge in the vicinity of the Arizona–New Mexico State line (fig. 43). In the Caborca area of Sonora, about 110 miles southwest of American Peak (loc. 83), apparently near the margins of the early Paleozoic Cordilleran geosyncline (Poole and Hayes, 1971), Middle Cambrian rocks are more than 2,600 feet thick (Cooper and Arellano, 1952).

LITHOLOGY

In the southwestern part of the region, the basal part of the Middle Cambrian is represented by the dominant sandstones of the Bolsa Quartzite, and the upper part, by the shales and limestones of the lower member of the Abrigo Formation. Northward and eastward from there the basal part of the Bolsa laps out irregularly on a Precambrian paleoslope; the basal part of the lower member of the Abrigo apparently grades into sandstones at the top of the Bolsa; and the upper part of the lower member of the Abrigo changes irregularly in facies from dominant shales and limestones to siltstones and fine-grained sandstones. Still farther eastward the siltstones and fine-grained sandstones of the lower member of the Abrigo grade into coarser sandstones of the basal part of the Coronado Sandstone. As a result, in the southwesternmost part of the region the Middle Cambrian rocks are only about one-half sandstone and about two-thirds total terrigenous clastic rocks, whereas near the eastern edge of its occurrence the Middle Cambrian is mostly sandstone (fig. 43). Concomitant with the northeastward lapping out of the lower beds and coarsening of the upper beds, there is a northeastward increase in feldspar content of sandstones at given horizons and an apparent increase in glauconite in the same direction.

CONDITIONS OF DEPOSITION

The thickness variations, gross lithofacies trends, and broad regional considerations all rather strongly suggest that the Middle Cambrian strata of the report region were deposited on a surface of modest relief near the margins of a shelf sea that transgressed northeastward perhaps 120 miles during the roughly 20 million years of Middle Cambrian time.

Whereas reasonable confidence can be maintained for the broad concept of sedimentation near the margins of a northeastward-transgressing sea, less certainty can be claimed for interpretations of the subenvironments in which various Middle Cambrian lithotypes were deposited. Generally, the sandstone of the Bolsa Quartzite and basal Coronado Sandstone can be called transgressive sandstone, but whether the sands were deposited in a high-energy beach environment as interpreted by Lochman-Balk (1971) or on offshore bars affected by strong ebbtide currents as interpreted by Seeland (1968) is unsettled. Considering the regional stratigraphy, lithologies, and sedimentary structures as a whole, I tend to favor the beach-sand interpretation. The rare scattered small phosphatic brachiopods as well as the occasional glauconite could have been washed landward onto a beach and are no proof of a subtidal marine depositional site; also, the surface tracks and trails and the *Scolithus* tubes common in the Bolsa, especially in the upper part, are common enough in modern beach sands. I also concur with Lochman-Balk (1971) that both the sandy and the shaly facies of the lower member of the Abrigo Formation were probably deposited in an intertidal environment. The mud cracks and mud-chip conglomerates (fig. 8*B*) common in the member are evidence of probable periods of subaerial desiccation. Paleoenvironmental interpretations by Kepper (1972), based on detailed studies in Nevada and Utah, suggest that the westward transition from intertidal to subtidal conditions in Middle Cambrian time may have been in eastern Nevada.

DRESBACHIAN AGE

DEFINITION AND DISTRIBUTION

As interpreted in this report, rocks of Dresbachian age (of Howell and others, 1944) include the middle and upper sandy members of the Abrigo Formation in much of southern Arizona, much of the Coronado Sandstone in the Arizona–New Mexico boundary region, and some beds near the base of the Bliss Sandstone in far western New Mexico (fig. 5).

Rocks of Dresbachian age occur in much of southern Arizona and extend to a depositional wedge edge in western New Mexico (fig. 44). Their present distribution is limited northward and southwestward by pre-Middle Devonian erosional edges and in another broad area by an Early Cretaceous erosional edge (fig. 44).

THICKNESS

Rocks of Dresbachian age seem to be completely represented in the central part of their distribution area, where they maintain a fairly constant thickness of between 275 and 375 feet but tend to be somewhat thicker toward the west (fig. 44). Farther west the rocks of Dresbachian age are thinner because of pre-Middle Devonian erosion on top, and toward the east they are thinner where they rest unconformably on the Precambrian; they thin to a depositional wedge edge in western New Mexico.

LITHOLOGY

Rocks of early Dresbachian age, as represented by the middle member of the Abrigo Formation, change completely in facies from nearly all partly silty laminated limestone in the southwest to fine- to medium-grained orthoquartzite in the northeast. An imtermediate facies contains both sandstone and dolomite, with the sandstone dominant at the base and the dolomite dominant above. The orthoquartzite of northeastern exposures of

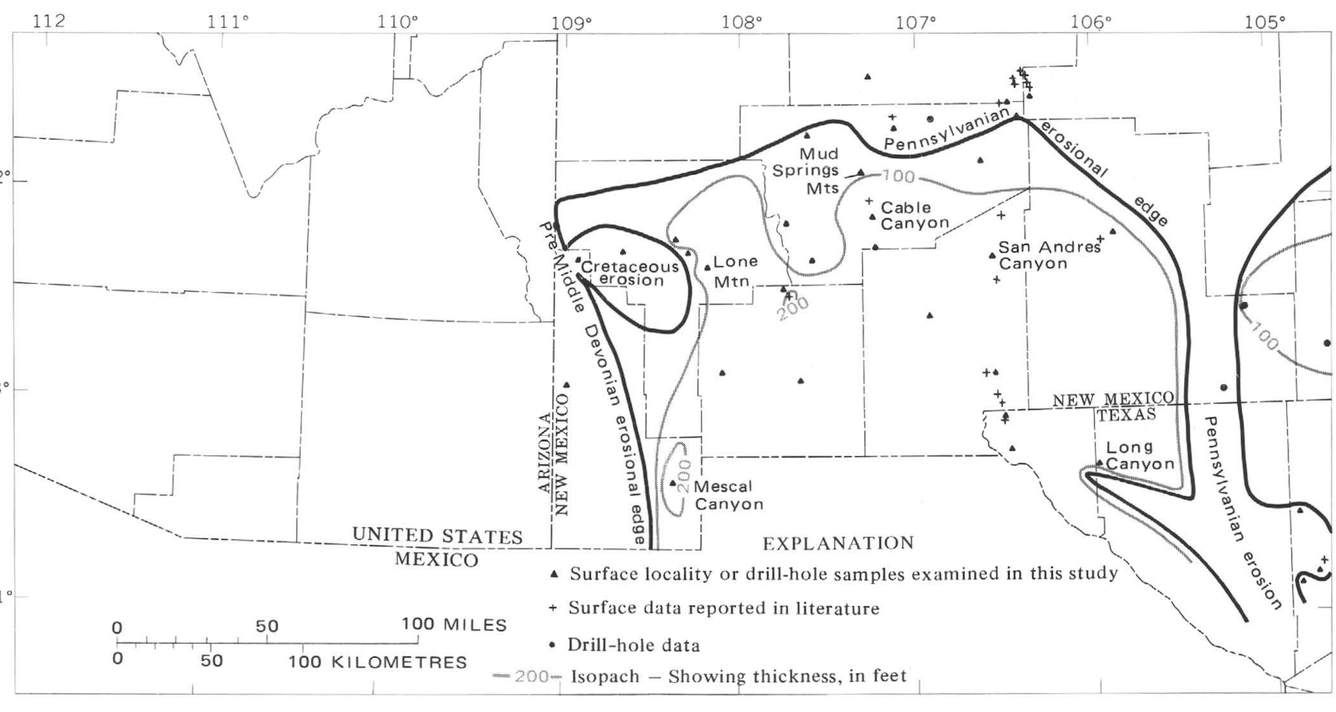


FIGURE 39.—Distribution and thickness of Cutter Dolomite.

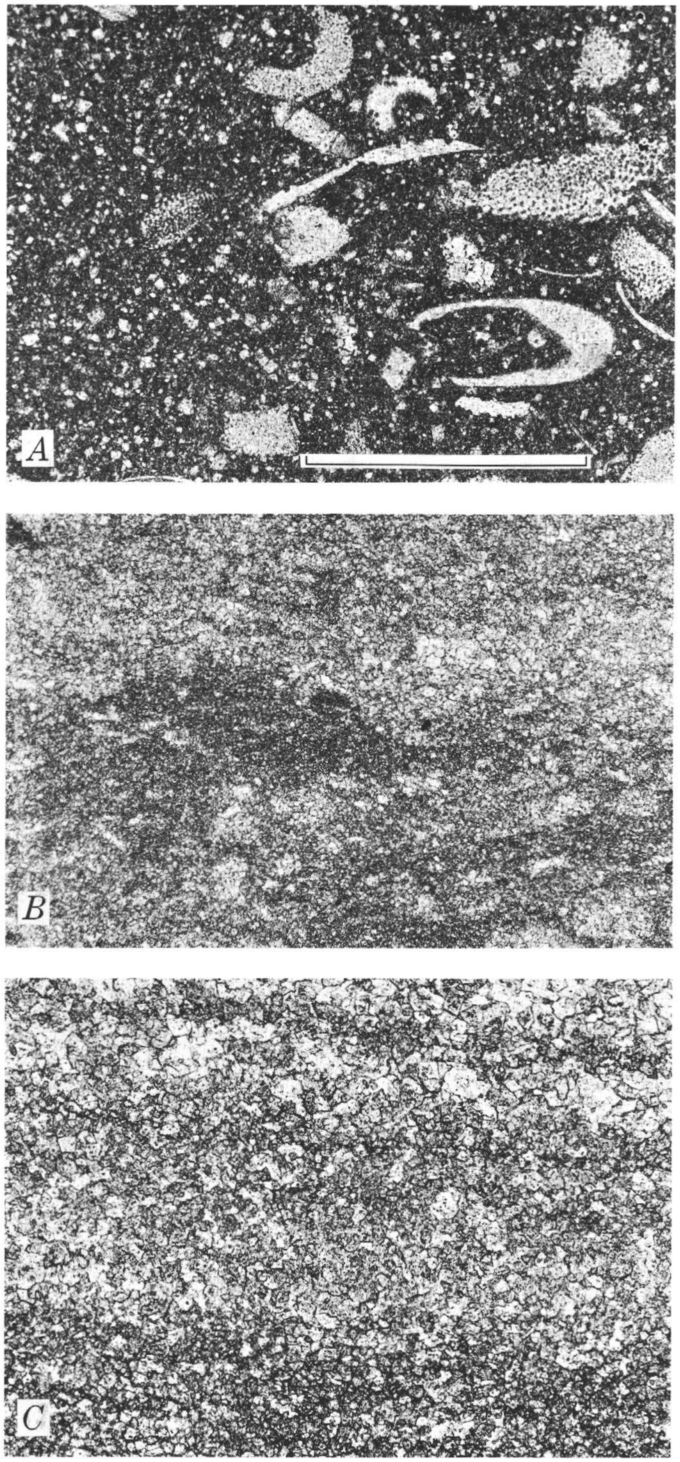


FIGURE 40.—Photomicrographs of Cutter Dolomite. Bar in *A* is 1 mm; all views are same scale. *A*, Slightly dolomitic skeletal lime wackestone from 28 feet above base of formation in Mud Springs Mountains (loc. 13). Scattered dolomite rhombs show up as light flecks over most of view. Skeletal wackestone to packstone like this is a common but minor rock type in the Cutter at most localities. At most localities, however, it is completely dolomitized. Plain light. *B*, Microcrystalline dolomite from near base of formation at San Andres Canyon (loc. 27). Relict clastic texture is visible in lower part of picture. Before dolomitization the lower part of this sample may have been similar to *A*. Plain light. *C*, Crystal-size laminated dolomite from about 85 feet above base of formation at Long Canyon (loc. 46). Such rock is predominant in the Cutter at most localities. Before dolomitization it was probably laminated lime mudstone. Plain light.

the middle member of the Abrigo grades laterally farther northeastward and eastward into arkosic and generally somewhat glauconitic sandstones of the Coronado Sandstone. Still farther eastward and northeastward, beds of presumed early Dresbachian age lap onto Precambrian rocks.

Rocks of late Dresbachian age, as represented by the upper sandy member of the Abrigo Formation, are much more persistent in character across the region but do change from dominantly sandy dolomite interbedded with dolomitic sandstone in the southwest to almost entirely dolomitic sandstone in the northeast. Farther northeastward and eastward the upper member of the Abrigo grades laterally into even less dolomitic sandstone of the Coronado Sandstone and still farther eastward into the basal part of the Bliss Sandstone, which in turn laps eastward onto Precambrian rocks.

The total effect of the lithologic changes in rocks of both early and late Dresbachian age is to change the carbonate-sandstone ratio from about 10:1 at the southwest to much less than 1:10 in the east and northeast (fig. 44).

CONDITIONS OF DEPOSITION

Like the Middle Cambrian rocks, the strata of Dresbachian age were deposited near the margins of a shallow-shelf sea. From the beginning of Dresbachian time to the end, a period of roughly 10 million years, the sea apparently transgressed eastward perhaps 10–20 miles, a much slower rate of transgression than that of Middle Cambrian time; the transgression may have been interrupted by minor regressions in earliest and latest Dresbachian times.

The southwestern carbonate facies of the lower Dresbachian middle member of the Abrigo Formation with its laminated lime mudstones, skeletal lime wackestones, algal(?) and oolitic lime packstone, and limestone and dolomite chip conglomerates is interpreted to have been deposited chiefly in a limy intertidal environment and partly in a shallow subtidal environment. The well-sorted cross-laminated sandstones of the member to the north and northeast are interpreted to represent sandy beach deposition. Such sand was deposited farther southwestward in earliest Dresbachian time, as exemplified by the local Southern Belle Member (Creasey, 1967a), and probably represents a minor southwestward regression of the shoreline[3].

The upper sandy member of the Abrigo Formation of late Dresbachian age with its dolomitic and commonly

[3]The Southern Belle Member is almost arbitrarily assigned a Dresbachian age. It may be of latest Middle Cambrian age, and the regression represented by the unit may correlate with a regressive facies noted by Kepper (1972) in the Highland Peak Formation of Nevada.

glauconitic cross-laminated sandstones, sandy dolarenites, and dolomite chip conglomerates is interpreted to have been deposited in a storm-tossed intertidal environment during a period of increased influx of sand from the northeast.

Those parts of the Coronado Sandstone and Bliss Sandstone that are of Dresbachian age probably represent sandy-beach deposition.

FRANCONIAN AND TREMPEALEAUAN AGES

DEFINITION AND DISTRIBUTION

As interpreted in this report, the Franconian and Trempealeauan ages (of Howell and others, 1944) of the Late Cambrian are represented by the Copper Queen Member of the Abrigo Limestone in much of southeastern Arizona, by the lower member of the El Paso Limestone in easternmost Arizona, by the highest beds of the Coronado

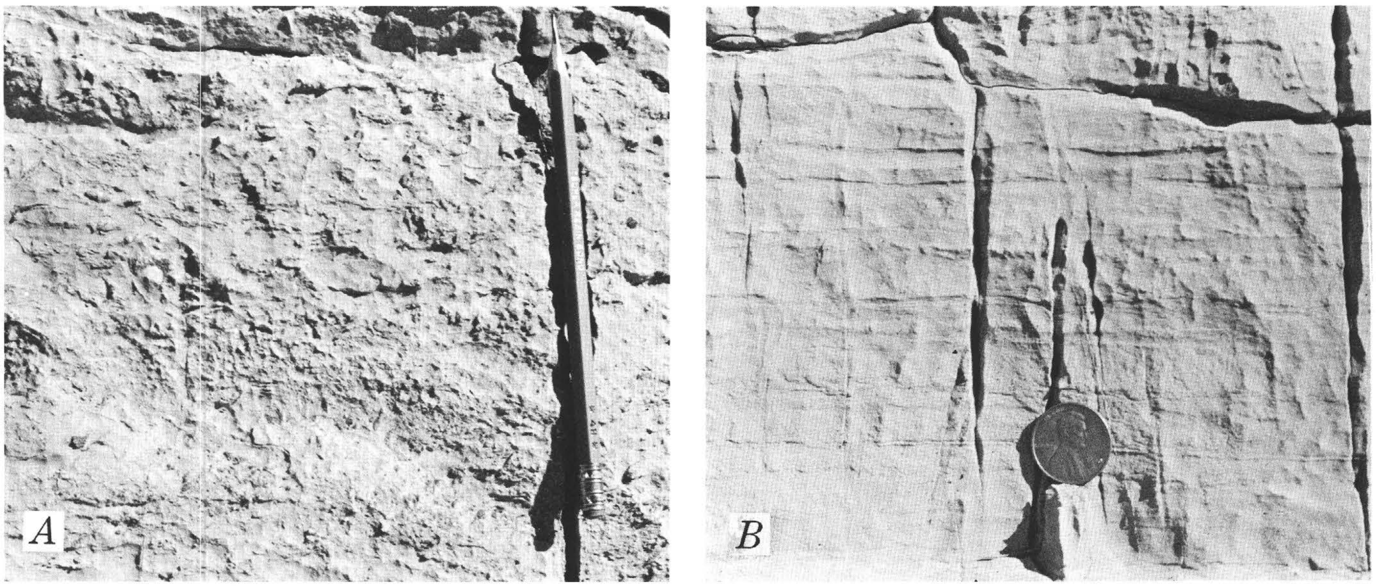


FIGURE 41.—Outcrops of Cutter Dolomite at Lone Mountain (loc. 22). *A*, Finely crystalline dolomite containing abundant silicified brachiopod debris 24 feet above base of formation. A photomicrograph of undolomitized rock of this type is shown in figure 40*A*. *B*, Finely crystalline thinly laminated dolomite 86 feet above base of formation. This is the most characteristic lithology of the Cutter.

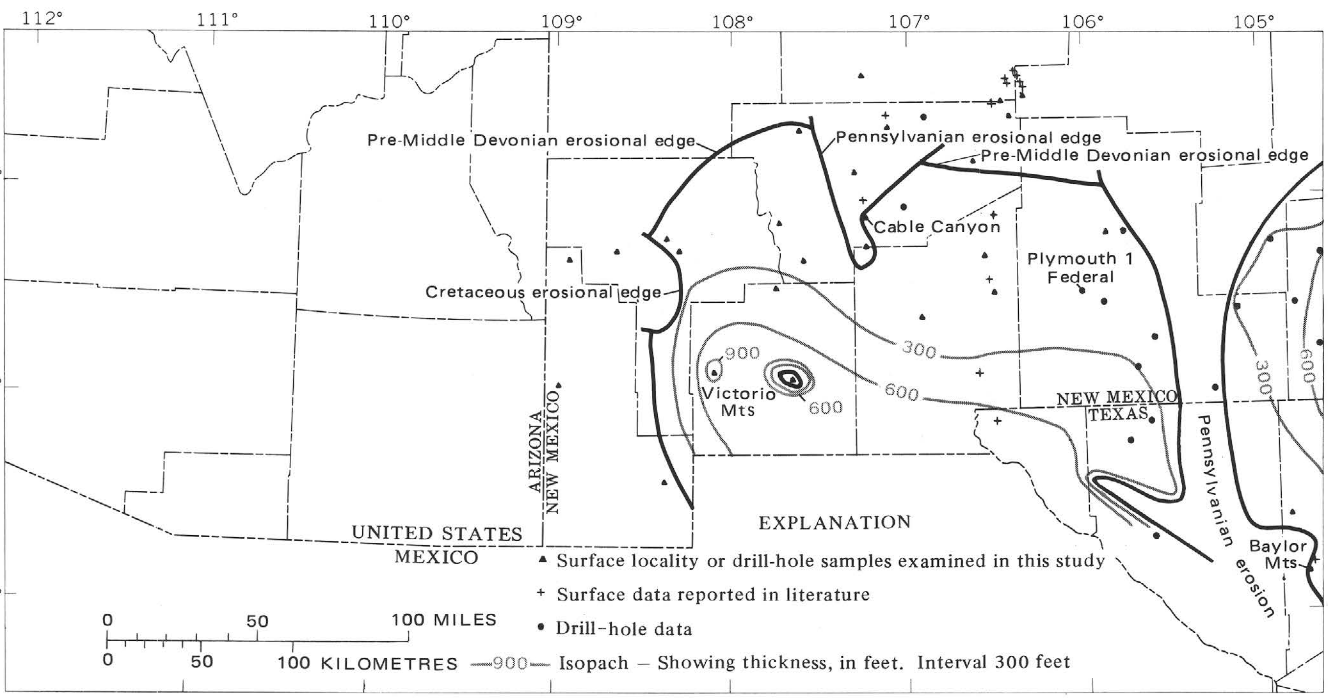


FIGURE 42.—Distribution and thickness of Fusselman Dolomite.

Sandstone and the lower member of the El Paso Limestone in westernmost New Mexico, and by the lower part of the Bliss Sandstone in southwestern New Mexico and extreme western Texas (fig. 5). Rocks of Franconian and Trempealeauan ages were removed by pre-Middle Devonian erosion in the western and northern parts of southeastern Arizona and by Early Cretaceous erosion in other areas in southeastern Arizona and southwestern New Mexico (fig. 45). They are absent because of nondeposition in the eastern part of the report region.

THICKNESS

In easternmost Arizona and westernmost New Mexico, where rocks of Franconian and Trempealeauan age conformably overlie strata of Dresbachian age and are conformably overlain by Ordovician strata, the Franconian and Trempealeauan strata range in thickness from about 115 to about 250 feet. To the east, where these strata rest unconformably on Precambrian rocks, they thin irregularly to an erosional wedge edge and are everywhere less than 200 feet thick and generally less than 100 feet thick (fig. 45). In the western part of the region, where these uppermost strata are disconformably overlain by Devonian beds, they are generally less than 100 feet thick and thin to an erosional wedge edge to the west.

LITHOLOGY

In the southwestern part of the region, rocks of Franconian and Trempealeauan age in the Copper Queen

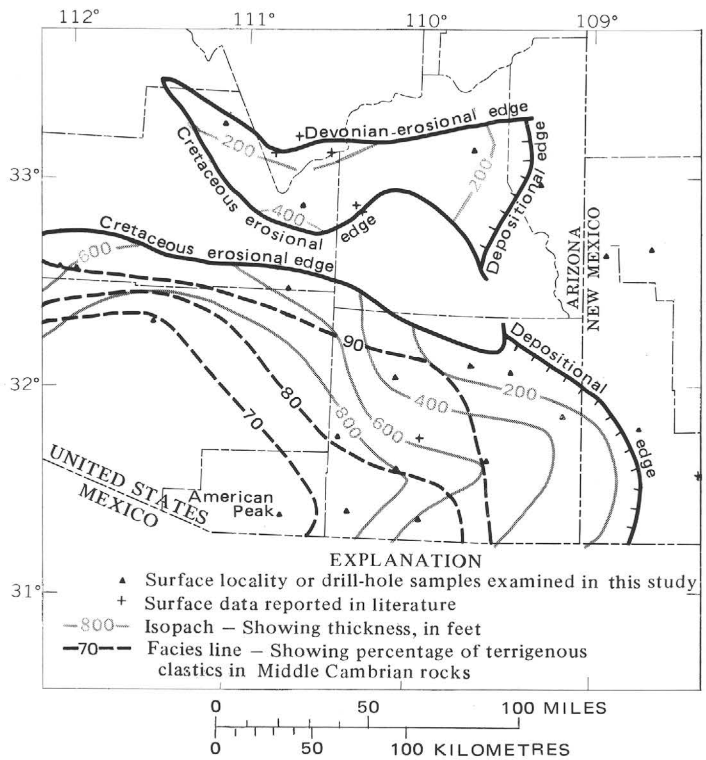


FIGURE 43.—Distribution, thickness, and facies of Middle Cambrian rocks.

Member of the Abrigo Formation are made up mostly of lithiclast lime grainstone or dolarenite and a few interbeds of oolite lime grainstone and well-sorted cross-laminated dolomitic sandstone. Age-equivalent beds in easternmost Arizona and westernmost New Mexico in the lower member of the El Paso Limestone are similar but are sandier, somewhat glauconitic, and more cross-laminated and contain beds of limestone chip conglomerate at most localities. Age-equivalent beds in the Bliss Sandstone farther east in New Mexico and western Texas are made up almost entirely of sandstone, much of which is cross-laminated; some lithiclast lime grainstones, oolite lime grainstones, or dolarenites are present toward the west. Beds of very hematitic sandstone occur in the Bliss in northern areas.

CONDITIONS OF DEPOSITION

Strata of Franconian and Trempealeauan ages were deposited along or near the margins of a shelf sea that advanced eastward very roughly 150 miles during the approximately 15 million years of Franconian and Trempealeauan time—a rate of transgression that was much greater than that of Dresbachian time and somewhat greater than that of Middle Cambrian time. This transgression covered much of southern New Mexico and western Texas, but local hills of Precambrian rock such as one described by Kottlowski, LeMone, and Foster (1969) stood up as islands in the sea or mendips on a coastal plain.

Rocks in the Copper Queen Limestone Member of the Abrigo Formation are interpreted to represent deposition in fairly agitated shallow subtidal waters. Rocks in the lower member of the El Paso Limestone in eastern Arizona and westernmost New Mexico are interpreted to represent deposition in an alternation of similar shallow subtidal waters and intertidal carbonate flats. Rocks in the Bliss Sandstone of New Mexico are interpreted to represent beach sand deposition for the most part, but some intertidal-flat deposition took place intermittently in western New Mexico. As interpreted by Lochman-Balk (1971), the hematitic beds of the Bliss may have accumulated in isolated pools on a coastal plain.

ORDOVICIAN

EARLY AND MIDDLE CANADIAN

DEFINITION AND DISTRIBUTION

As used in this report, early and middle Canadian time represents all of Ordovician time up to the time of deposition of the basal part of the McKelligon Limestone. It thus coincides roughly with Ordovician time before the time of deposition of the Jefferson City Dolomite of Missouri, probably with most of the combined Gasconadian and Demingian Stages of Flower (1964), and roughly with the time of deposition of Ordovician fossil zones A through F of Utah (Hintze and others, 1969).

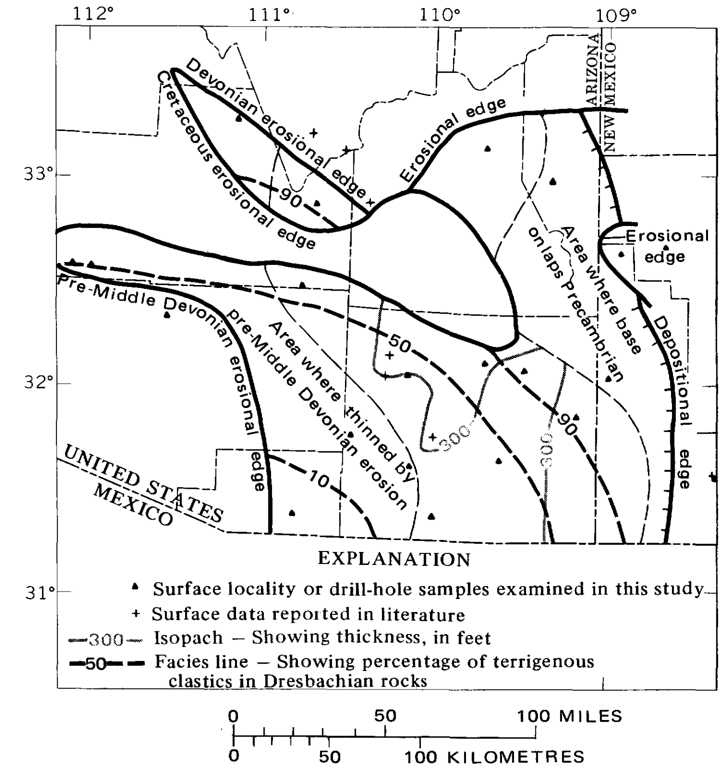


FIGURE 44.—Distribution, thickness, and facies of rocks of Dresbachian age.

Rocks interpreted to be of early and middle Canadian age in the report region consist of the El Paso Limestone as it is used in the western area (figs. 5, 6), most of the upper member of the El Paso Limestone of the central area, and part or all of the Bliss Sandstone and all of the Hitt Canyon Formation of the eastern area.

Strata of early and middle Canadian age may once have extended across the entire report region but are now missing in most of Arizona, along the entire north edge of the region, and locally elsewhere owing to several episodes of post-Ordovician erosion (fig. 46).

THICKNESS

In areas where strata of early and middle Canadian age are conformably overlain by beds of late Canadian age and thus have not been thinned by erosion, they range in thickness from about 260 feet at Lone Mountain near Silver City (fig. 46 and loc. 21, fig. 1) to about 685 feet at Hitt Canyon in the Franklin Mountains (loc. 44). They seem to thin fairly regularly to the west, north, and east of extreme western Texas (fig. 46). Farther to the north and west they are thinned by erosion on top and eventually thin to a wedge edge.

LITHOLOGY

Near the west edge of the distribution area of strata of early and middle Canadian age the strata are made up almost entirely of relatively pure limestone and (or) dolomite, and the estimated content of terrigenous clastics is less than 5 percent. Eastward from there, as the Bliss Sandstone at the base makes up an increasing proportion of the interval and as the carbonates become sandier, content of quartz silt and sand increases to about 50 percent at Beach Mountain (loc. 48) near the southeast corner of the report region (fig. 46). Some shale and siltstone is present in the Ordovician part of the Bliss Sandstone, particularly toward the north.

A highly generalized summary of the diversities of composition, texture, and sedimentary structures found in the lower and middle Canadian rocks follows. In general, the Bliss Sandstone, which lies at the base of the sequence in all but the western part of the region and whose top becomes younger eastward, can be described as consisting dominantly of quartz- or carbonate-cemented grain-supported quartz arenites that commonly display planar cross-laminations; hematite cement and grains of hematite ooids are locally common, especially toward the north and west. In general, the carbonates of early and middle Canadian age that occur just above the basal sandstone in the central part of the region are dominantly quartzose algal and lithiclast lime packstones to grainstones that are commonly cross-laminated and that in places contain beds interpreted to be algal-mat dolomite and beds of limestone or dolomite chip conglomerate. Above these beds in the central part of the region, nonsandy fossil-bearing lime mudstones and skeletal lime wackestones are dominant; locally some of the lime mudstones contain channels of skeletal-lithiclast lime packstone. Burrows, tracks, and trails are common in these rocks and oncolites and digitate algal stromatolites are locally found. Carbonates in the upper part of the lower and middle Canadian sequence in the central part of the region tend to be quartzose and are made up largely of dolarenite, lithiclast lime packstone and oolite packstone, all of which may be cross-laminated. Limestone or dolomite chip conglomerates are also locally present in these upper beds. In the western part of the region the carbonates are basically similar to those just described in the central part but are not sandy in either the lower or the upper parts. In the southeastern part of the region the carbonates are generally similar to those in the lower and upper parts of the sequence in the central part of the region; nonsandy carbonates are relatively scarce even in the middle part of the sequence.

CONDITIONS OF DEPOSITION

Strata of early and middle Canadian age in the region were deposited near the margins and in shallow waters of the sea that had transgressed northeastward and eastward across most of the region during Middle and Late Cambrian time. During earliest Canadian time the sea migrated farther eastward and covered the entire region.

The Bliss Sandstone at the base of the lower and middle Canadian sequence is inferred to have been deposited primarily in a beach environment. Most of the overlying carbonates in the region are interpreted to have been deposited in a limy intertidal environment, but some carbonates in the middle part of the Hitt Canyon Formation in all but the easternmost part of the region and some of the carbonates in the El Paso Limestone in extreme western New Mexico and eastern Arizona probably were deposited in a shallow subtidal environment. Apparently very slight changes in sea level caused repeated alternations from intertidal to shallow subtidal conditions over much of the region during much of early and middle Canadian time.

The isopachs (fig. 46) of lower and middle Canadian rocks show that, although transgression took place primarily eastward, there was a pronounced depositional thinning northward from the western tip of Texas. Although the present northern limit of lower and middle Canadian rocks is a post-Early Ordovician erosional edge, a depositional edge probably existed within about 100 miles to the north of the present erosional edge.

EARLY LATE CANADIAN

DEFINITION AND DISTRIBUTION

As used in this report, early late Canadian time is the time during which the McKelligon Limestone was deposited. It corresponds approximately to the time of deposition of the Jefferson City Dolomite of Missouri, to the Jeffersonian Stage of Flower (1964) of New Mexico, or to the time of deposition of most of the strata that contain Early Ordovician fossil zone G of Utah (Hintze and others, 1969).

In the report region rocks of early late Canadian age include the McKelligon Limestone of the El Paso Group in most of southern New Mexico and western Texas and the upper part of the upper member of the El Paso Limestone in southwesternmost New Mexico and southeasternmost Arizona (fig. 5).

THICKNESS

Rocks of early late Canadian age in the report region are thickest at the Scenic Drive section (loc. 45, fig. 1) in the Franklin Mountains in extreme western Texas, where they are 715 feet thick. They thin depositionally from there to the west, north, and northeast, and farther in those directions they are further thinned by erosion on top until they reach an erosional wedge edge (fig. 47). The thinnest completely preserved section of lower upper Canadian rocks, where they are believed to be conformably overlain by upper upper Canadian rocks, is 329 feet at San Andres Canyon (loc. 27), about 67 miles north of the Scenic Drive section.

LITHOLOGY

Strata of early late Canadian age in the region consist almost exclusively of limestone and dolomite that is locally cherty. Details of the lithologic character and sedimentary structures of these strata are given under the descriptions of the McKelligon Limestone in the eastern part of the study region and the upper member of the El Paso Limestone in the central part. In general, the strata are similar throughout the report region, but sedimentary structures and limestone textures interpreted to be indicative of deposition in subtidal waters are more abundant in

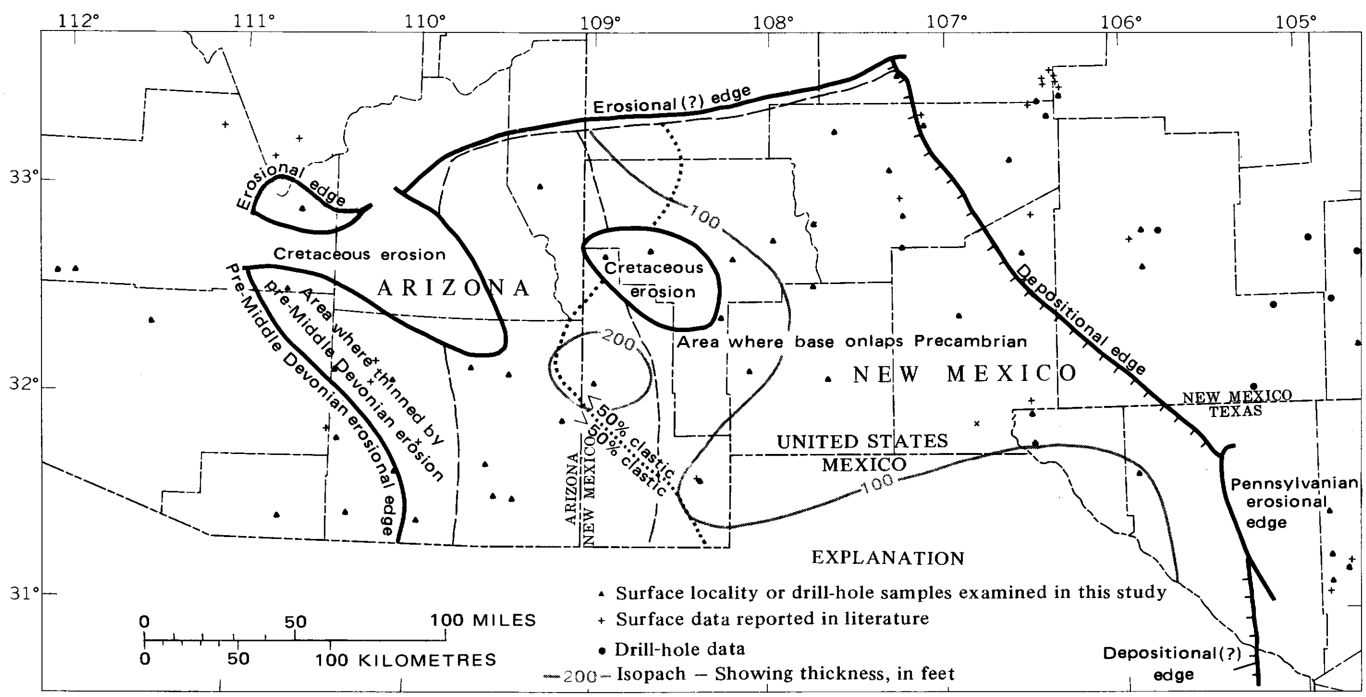


FIGURE 45.—Distribution, thickness, and facies of rocks of Franconian and Trempealeauan ages.

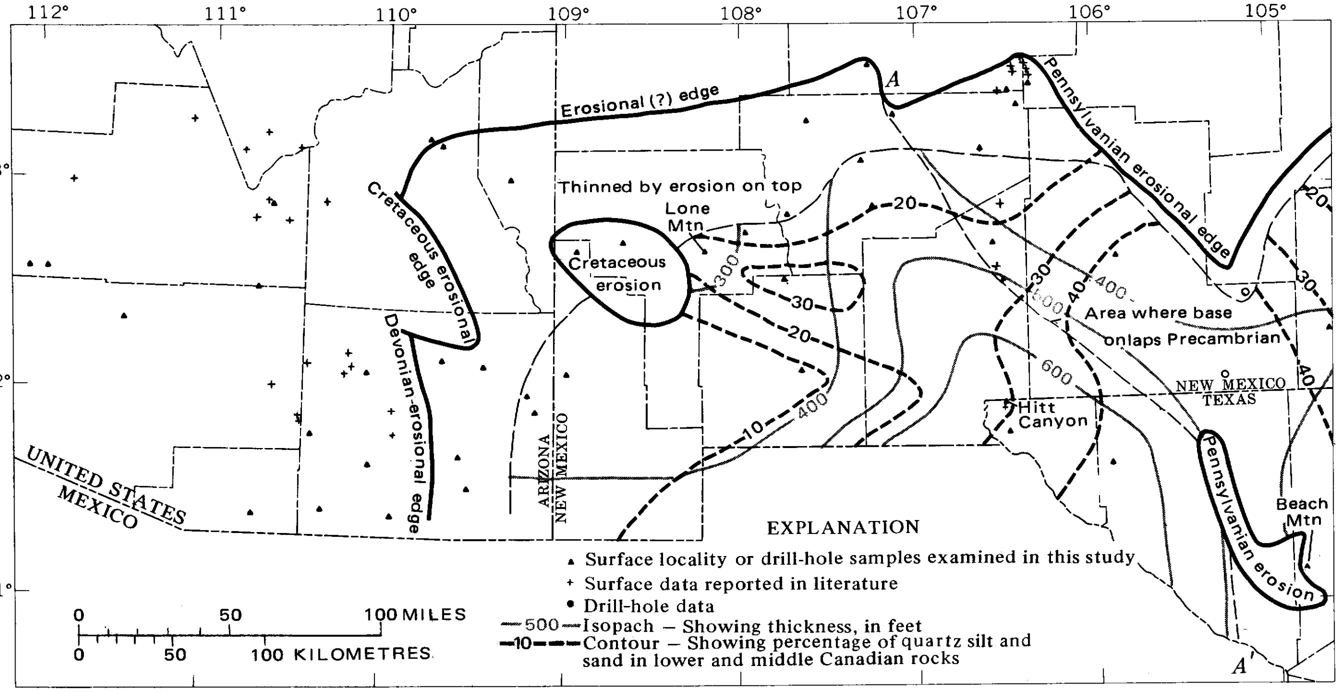


FIGURE 46.—Distribution, thickness, and facies of rocks of early and middle Canadian age. East of dashed-line *A-A'* the entire Bliss Sandstone is presumed to be of this age.

the south-central part of the area and in the lower part of the sequence. Conversely, sedimentary structures that are interpreted to be indicative of deposition in an intertidal environment greatly dominate in the vicinity of Beach Mountain and Agua Chiquita Canyon (locs. 48 and 1) to the southeast and northeast and in some extreme western localities.

CONDITIONS OF DEPOSITION

All the rocks of early late Canadian age in the report region are interpreted to have been deposited in intertidal or shallow subtidal environments of a sea that had transgressed across the region during Cambrian and earlier Ordovician time. Limy subtidal conditions probably predominated in the south-central part of the region in earliest late Canadian time, but as time progressed the sea apparently began a slow intermittent southward regression, and limy intertidal conditions become of increasing importance. Intertidal conditions were probably predominant throughout early late Canadian time in areas to the west, north, and east of the south-central part of the region. During this entire time the margins of the sea probably were near the north edge of the report region not far beyond the present erosional wedge edge of the McKelligon Limestone and equivalents (fig. 47). Lithofacies and thickness trends indicate that deeper marine waters probably lay to the south of the report region.

LATE LATE CANADIAN

DEFINITION AND DISTRIBUTION

Late late Canadian time as used here refers to the time of deposition of the Padre Formation of the El Paso Group (fig. 5). It thus corresponds closely to the Cassinnian Stage of Flower (1964) and to the time of deposition of the strata that contain Early Ordovician fossil zones H through J of Utah (Hintze and others, 1969).

Rocks of late late Canadian age (the Padre Formation) in the report region are restricted to a part of southern New Mexico and western Texas as shown in figure 48. Their distribution is limited to the west, north, and east by a Middle Ordovician erosional edge.

THICKNESS AND LITHOLOGY

The thickness and lithology of the Padre Formation, and thus of upper upper Canadian rocks, were described earlier in this report under a discussion of the eastern part of the study region.

CONDITIONS OF DEPOSITION

Strata of late late Canadian age in the report region were deposited on or near the margins of the same sea in which lower and middle Canadian rocks were deposited. The crossbedded sandy saccharoidal dolomites at the base of the Padre are interpreted to represent beach deposition following a slight regression of the sea during late middle or early late Canadian time. This regression was followed by slight northward transgression and a return to the type of limy intertidal environment that apparently dominated middle Canadian time.

EARLY MIDDLE ORDOVICIAN

DEFINITION AND DISTRIBUTION

As used here, early Middle Ordovician time was all the time between the end of deposition of the Padre Formation of the El Paso Group and the beginning of deposition of the Second Value Dolomite of the Montoya Group. Rocks of early Middle Ordovician age occur only in the extreme southeast corner of the report region in and near the Baylor Mountains (loc. 47, fig. 1). The rocks are unnamed but have been correlated by Jones (1953) with the Simpson Group of Oklahoma.

DESCRIPTION

The unnamed rocks of early Middle Ordovician age in and near the Baylor Mountains (loc. 47) were not studied in detail during this investigation but have been described by King (1965). The strata are not more than 80 feet thick. According to King (1965),

> The strata include two layers of medium-grainded brown calcareous sandstone, between which are beds of shaly or silty limestone and marl, some of which are green. Sedimentary analyses of the sandstone indicate a textural resemblance to the St. Peter Sandstone of the northern interior region (Howe, 1959, p. 2289–2291) * * *

GEOLOGIC HISTORY

On the basis of the character and distribution of the rocks of early Middle Ordovician age at the southeast edge of the report region, of the age and nature of Lower Ordovician rocks beneath the early Middle Ordovician unconformity over most of the region, and of the character of upper Middle Ordovician rocks overlying the unconformity, reasonable speculations on early Middle Ordovician history can be made. The entire region was elevated slightly above sea level at about the beginning of early Middle Ordovician time, and the resulting land surface sloped gently southward to southeastward. The Lower Ordovician rocks on that surface were then eroded slightly, with erosion being somewhat greater in the north and west than in the south and east. The products of erosion were carried southeastward to a sea which was transgressing toward the report area from the southeast and which reached the southeast corner of the region to leave marginal marine sediments there.

Probable minor local upwarping in parts of southwestern New Mexico and possibly in western Texas during early Middle Ordovician time allowed the local erosional exposure of Precambrian rocks. Evidence for this is not direct but is deduced from the nature of rocks in the lower part of the Montoya Group.

LATE MIDDLE ORDOVICIAN

DEFINITION

As used herein, late Middle Ordovician time coincides with the time of deposition of the Second Value Dolomite of the Montoya Group (fig. 5).

DISTRIBUTION, THICKNESS, AND LITHOLOGY

The distribution, thickness, and lithology of rocks of late Middle Ordovician age are described in detail under the description of the Second Value Dolomite and are graphically summarized in figure 30.

CONDITIONS OF DEPOSITION

The lithologic characteristics, sedimentary structures, and fossil types found in the Second Value Dolomite in the region all suggest that these strata of late Middle Ordovician age were deposited in a rather agitated subtidal ma-

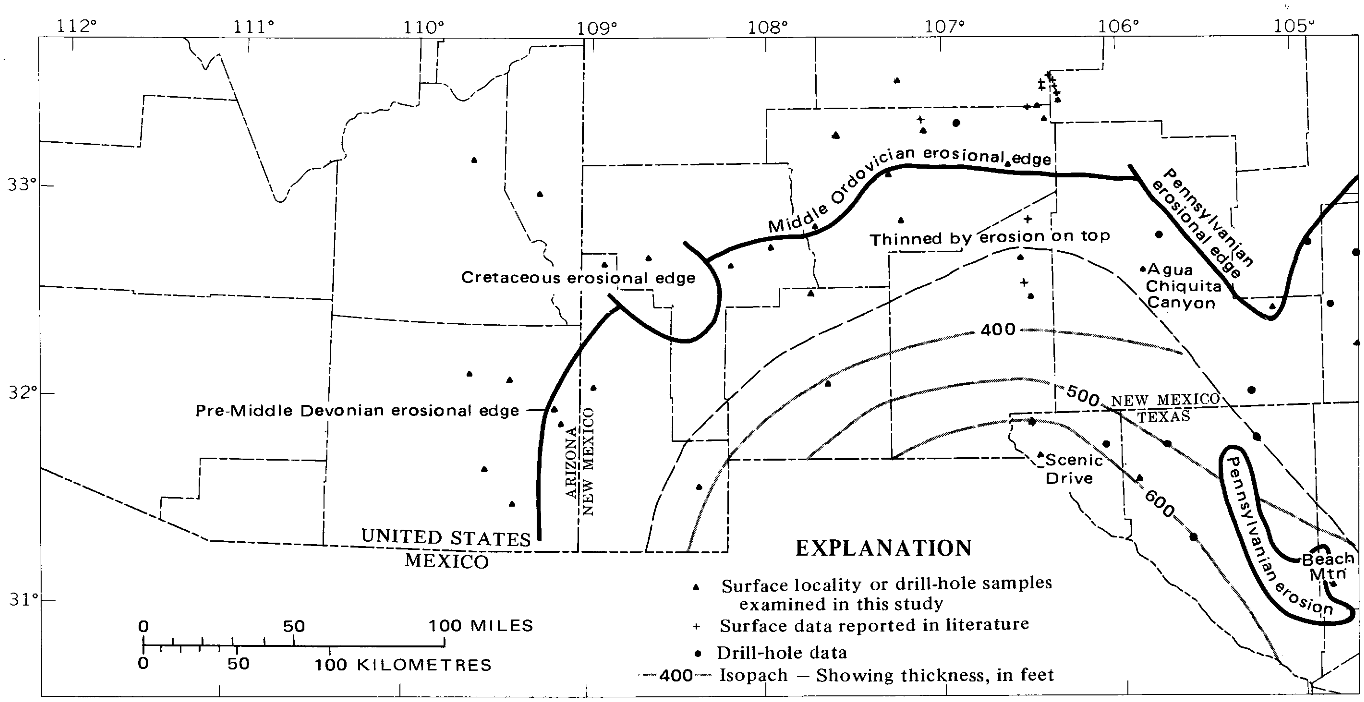


FIGURE 47.—Distribution and thickness of rocks of early late Canadian age.

rine environment. The thickness and distribution pattern of the Second Value Dolomite and broader regional considerations suggest that the sea in which the Second Value sediments were deposited transgressed rapidly across the region from the south or southeast. Inasmuch as the present distributional limits of the Second Value seem everywhere to be erosional wedge edges, it is assumed that the margins of the sea were somewhat farther west and north than the present limits of the Second Value.

Knowledge of the distribution, thickness variations, and nature of the Cable Canyon Sandstone Member at the base of the Second Value Dolomite and observations of the basal contact of the Second Value and the rocks beneath it allow the generalization that the land area that was inundated in late Middle Ordovician time was a nearly featureless plain interrupted by broad slightly elevated areas on which Precambrian rocks may have been exposed. One of these broad slightly elevated terrains was located in the vicinity of the present boundary of Grant and Sierra Counties in southwestern New Mexico (figs. 1, 30). There the Second Value Dolomite is relatively thin and its terrigenous sand content is particularly high. The nature of the sand suggests that much of it was derived from Precambrian rocks rather than from older Paleozoic rocks. A smaller high area is indicated near the southwestern part of Luna County, N. Mex. (figs. 1, 30), and sand percentages, but not thicknesses, suggest the existence of a Precambrian source area near the boundary between Hudspeth and Culberson Counties, Tex. (figs, 1, 30).

EARLY LATE ORDOVICIAN

DEFINITION

Early Late Ordovician as used in this report is the time of deposition of the Aleman Formation of the Montoya Group (fig. 5). As so defined, its beginning and ending are imprecise inasmuch as both the base and the top of the Aleman are conformable and probably vary somewhat in age across the region.

DISTRIBUTION, THICKNESS, AND LITHOLOGY

The distribution, thickness, and lithology of rocks of early Late Ordovician age are described in detail under the description of the Aleman Formation, and the distribution and regional variations in thickness are shown graphically in figure 36.

CONDITIONS OF DEPOSITION

The lithology, fossil types, and sedimentary structures of the Aleman Formation considered together suggest deposition in well-aerated but quiet, warm, shallow, subtidal marine waters. The lithologic change across the conformable contact between the Aleman and the underlying Second Value Dolomite is interpreted to represent primarily a decrease in agitation of the waters at about the beginning of Late Ordovician time, possibly due to a slight deepening of the waters and a greater distance to the shoreline that must have existed to the north and west of the present erosional wedge edges of the Aleman (fig. 36).

LATE LATE ORDOVICIAN

DEFINITION

Late Late Ordovician time as used here is synonymous

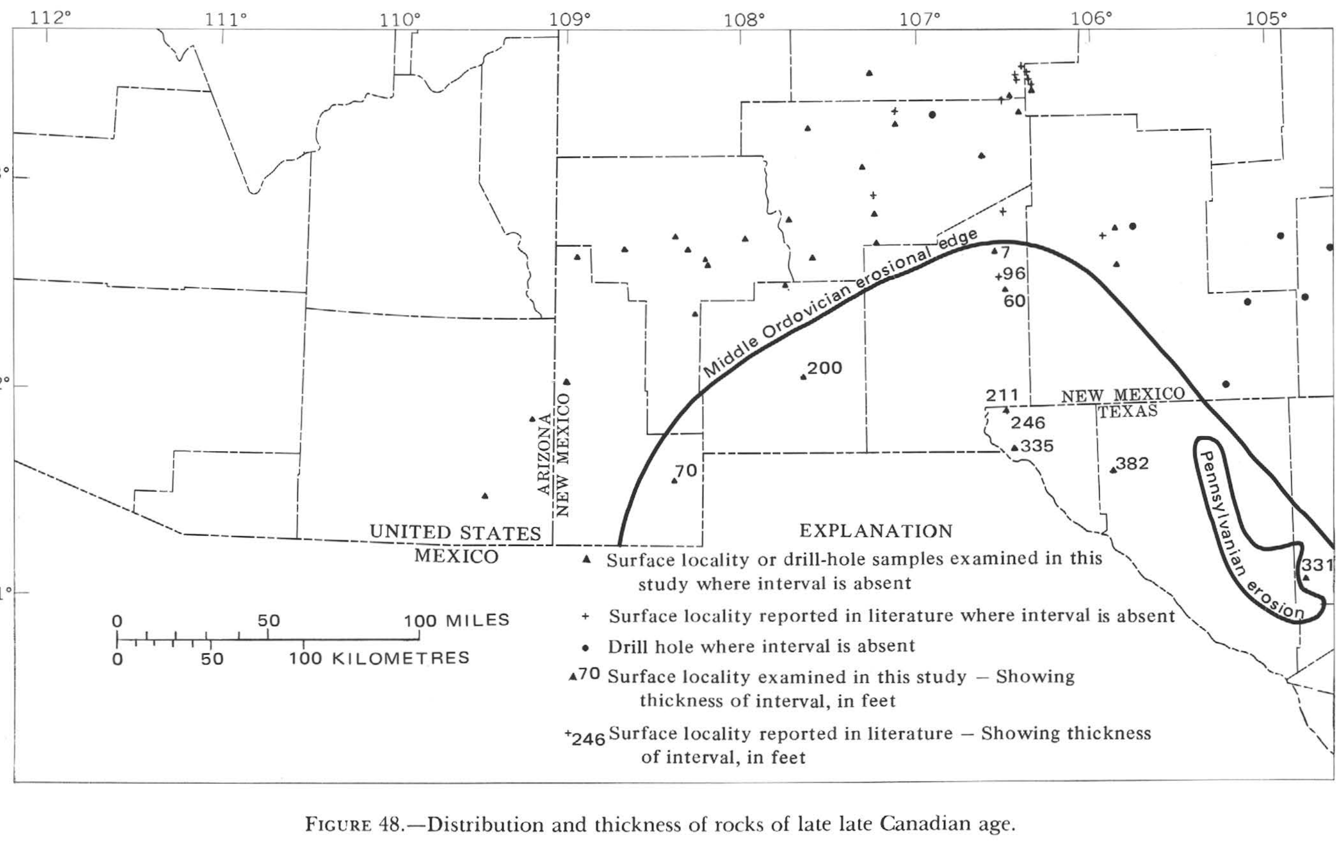


FIGURE 48.—Distribution and thickness of rocks of late late Canadian age.

with the time of deposition of the Cutter Dolomite of the Montoya Group (fig. 5). Because the basal contact of the Cutter with the Aleman Formation is conformable and may be older toward the west, the beginning of late Late Ordovician time as used here is very loosely defined.

DISTRIBUTION, THICKNESS, AND LITHOLOGY

The distribution, thickness, and lithology of rocks of late Late Ordovician age in the region are described in detail under the description of the Cutter Dolomite. Figure 39 shows the distribution and approximate preserved thickness graphically.

CONDITIONS OF DEPOSITION

On the basis of the conformable nature of the contact between the Cutter Dolomite and underlying Aleman Formation, and on the basis of the lithologic similarity of the two formations, except in abundance of chert, it is assumed that the depositional environment in the region changed very little from early Late Ordovician to late Late Ordovician time. The region during late Late Ordovician time is thus believed to have been the site of a warm, shallow, quiet, but aerated, sea that had transgressed northward or northwestward across the region in late Middle Ordovician time. The much greater abundance of chert in the Aleman Formation as compared with the Cutter Dolomite may be due to some possibly subtle change in diagenetic conditions rather than in the conditions of deposition from early to late Late Ordovician time.

OIL AND GAS POSSIBILITIES

The following general comments on the oil and gas possibilities of Cambrian and Ordovician rocks in the report region are not intended to be a thorough evaluation of the subject; oil and gas explorationists must, of necessity, make their own evaluations.

POSSIBLE SOURCE BEDS

Marine shales, which presumably offer the maximum potential for petroleum generation, are sparse in the Cambrian and Ordovician rocks of the region except in a part of the distribution area of the lower member of the Abrigo Formation. Marine carbonates, however, can serve as petroleum source beds and are widely distributed in the Cambrian and Ordovician sequences of the region in the Abrigo Formation and in the El Paso and Montoya Groups. Sandstones such as those in the Bolsa Quartzite, the Coronado and Bliss Sandstones, and the Cable Canyon Sandstone Member of the Second Value Dolomite probably have very low potential as source beds. Sandy carbonates, such as are found in various parts of the Cambrian and Ordovician sequences throughout the region, presumably are intermediate between carbonates and sandstones as potential source rocks. Accepting the conclusion of Cordell (1972) that significant oil generation and flush migration can take place only in rocks that have been buried to depths of at least several thousand feet, I think that the Cambrian and Ordovician rocks of the report region have all been buried deeply enough by later Paleozoic and Mesozoic rocks to have been capable of generating significant amounts of petroleum. However, none of the units was very deeply buried before being elevated and subjected to subaerial erosion, and, as suggested by Gibson (1965), oil that was indigenous may have escaped during the period of erosion and reduced rock pressure. On the basis of the above facts and assumptions, subjective judgments can be made as to which rocks in which areas offer the greatest potential as petroleum source beds.

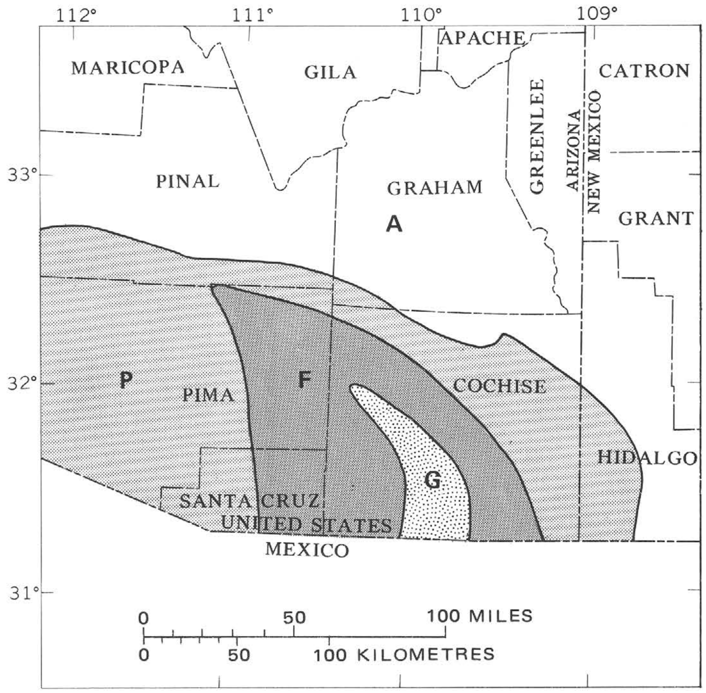


FIGURE 49.—Relative favorability of Cambrian rocks in the region as source beds for petroleum. G, area in which potential is good; F, area in which potential is fair; P, area in which potential is poor; A, area in which Cambrian rocks are either missing or lacking in significant potential.

Cambrian rocks in the region seem to offer the greatest potential as source beds in southwestern Cochise County, Ariz., where the lower member of the Abrigo Formation contains a relatively large percentage of marine shale and where the middle member and Copper Queen Member of the Abrigo are fairly pure marine carbonate (fig. 49). The potential of Cambrian rocks presumably decreases to the west, north, and east of southwestern Cochise County owing either to increased sandiness of the rocks or to absence by erosion of favorable beds or both. Cambrian rocks offer virtually no potential as source beds in western Texas, New Mexico, and Arizona north of lat 33° N.

Probably the best potential petroleum source beds among Lower Ordovician rocks in the region are the fairly pure carbonates of the McKelligon Limestone in extreme western Texas and south-central New Mexico. Moderately pure carbonates also occur in the Hitt Canyon and Padre Formations and in the El Paso Limestone of the New Mexico–Arizona border area, but these formations also contain sandy and silty carbonates that presumably are less favorable. Figure 50 is a subjectively drawn map outlining areas of varying degrees of petroleum source-bed potential in Lower Ordovician rocks in the region based primarily on the total thickness of moderately pure carbonates in the sequence.

The Upper Ordovician carbonates preserved in the Montoya Group are presumed to be potential petroleum source rocks. The greatest potential would seem to be in areas where the Montoya Group is thickest (fig. 29) and where the smallest proportion of the group is made up of terrigenous sandstone (fig. 30). The thickest sequence and the smallest proportion of terrigenous sandstone coincide in southwestern Otero County, N. Mex., and bordering areas.

POSSIBLE RESERVOIR ROCKS

In order for a rock unit to serve as a petroleum reservoir, at least four conditions must be met: (1) the potential reservoir must have direct avenue to petroleum source rock or be its own source rock; (2) it must have sufficient porosity to hold significant quantities of oil or gas; (3) it must be sufficiently permeable to yield oil to a well; and (4) it must be confined by a trapping surface which will prevent any contained oil or gas from escaping naturally. In evaluating the reservoir possibilities of Cambrian and Ordovician rock units in the report region, emphasis in this section is placed on rocks that lie above potential source rocks (as subjectively appraised in the preceding section) on the assumption that petroleum migration is generally upward. (The possibility of downward migration from post-Ordovician rocks is briefly reviewed in the section on trap surfaces.) Accurate appraisal of the porosity characteristics of all the Cambrian and Ordovician rocks that underlie the region cannot be made on the basis of porosity determinations on fewer than 200 weathered rock samples collected at the surface, but some generalizations can be made. No permeability tests were made, but with the knowledge that permeability is directly related to effective porosity and pore size, some generalizations can also be made on relative permeabilities. The subject of reservoir trap surfaces is discussed briefly in the next section.

The Bolsa Quartzite, Coronado Sandstone, and Bliss Sandstone can all be presumed to have a very low probability as reservoir rocks. In addition to the fact that most rock in all three formations is low in porosity, none of the three formations overlies potential source beds.

As noted in the preceding section, Cambrian rocks offer a negligible potential as petroleum source beds in Arizona north of lat 33° N. Regardless of porosity characteristics, therefore, the Abrigo Formation of northern areas can be virtually eliminated as containing petroleum reservoirs. Toward the south, however, the lower and middle members and the Copper Queen Member of the Abrigo do offer some possibility as petroleum source beds. Rocks in the lower member of the Abrigo in the south appear to be very low in porosity, but at least some rock in the middle mem-

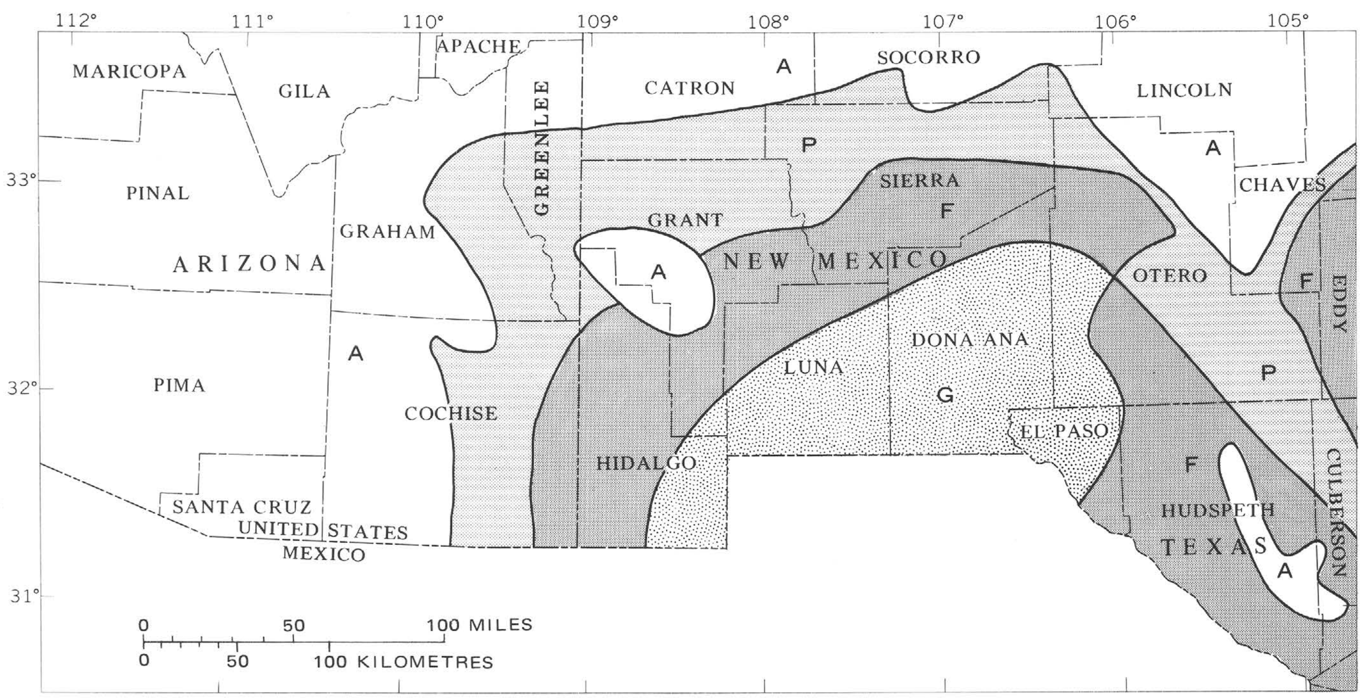


FIGURE 50.—Relative favorability of Lower Ordovician rocks in the region as source beds for petroleum. G, area in which potential is good; F, area in which potential is fair; P, area in which potential is poor; A, area in which Lower Ordovician rocks are absent.

ber, the upper sandy member, and the Copper Queen Member has moderate porosity. The three upper members of the Abrigo of southern areas, therefore, all have at least a modest chance of containing petroleum reservoirs if suitable trap conditions exist.

Because the rocks of the El Paso Group and the El Paso Limestone have at least some potential as source beds wherever they occur, they must be considered also for their possibility as reservoir rocks. Although local porosity may be present in any of these rocks, our studies suggest that the highest effective porosities are found in various rock types in the upper part of the Hitt Canyon Formation and in the basal part of the Padre Formation. The latter overlies the greatest thickness of potential petroleum source rocks so, even though it is more restricted in areal occurrence (compare figs. 46, 48), it is here regarded as the most favorable stratigraphic zone for petroleum reservoirs in Lower Ordovician rocks of the region. Of course, other reservoir possibilities exist in the weathered and brecciated zone beneath the unconformity at the top of the El Paso Group regardless of the stratigraphic position of the unconformity within the group.

The Montoya Group, like the El Paso Group and equivalents, contains potential petroleum source beds wherever it occurs in the region. However, our studies do not indicate the existence of any widespread permeable horizons in the Montoya Group. The Upham Member of the Second Value Dolomite is locally relatively high in vuggy or moldic porosity, but permeabilities are probably low. In general, the probability of the Montoya Group containing productive oil or gas reservoir rocks is moderate at best. Perhaps the greatest possibility in the group is the weathered and fractured rock just beneath the unconformity at its top.

POSSIBLE TRAP SURFACES

A detailed appraisal of possible trap surfaces within the Cambrian and Ordovician rocks of the report region is beyond the scope of this report. Suffice it to say that although impervious shales, which form the best trap rocks, are virtually nonexistent in the sequence, relatively impermeable carbonate beds occur that might serve to trap oil present in some of the more permeable beds. For example, the relatively permeable upper part of the Hitt Canyon Formation is overlain in much of south-central New Mexico and western Texas by the relatively impermeable McKelligon Limestone, and the relatively permeable beds of the basal part of the Padre Formation are overlain by much less permeable beds higher in the formation.

With regard to trap surfaces, it may be particularly significant that most commercial occurrences of oil in Ordovician rocks in easternmost New Mexico and western Texas east of the present report region are just beneath unconformities (Gibson, 1965). In many of these reservoirs, shales correlated with the Simpson Group of Oklahoma directly overlie reservoirs at the top of rocks correlated with the El Paso Group; in others, Devonian shales overlie reservoirs in either Lower or Upper Ordovician rocks. Jones and Smith (1965) believed that most oil in these

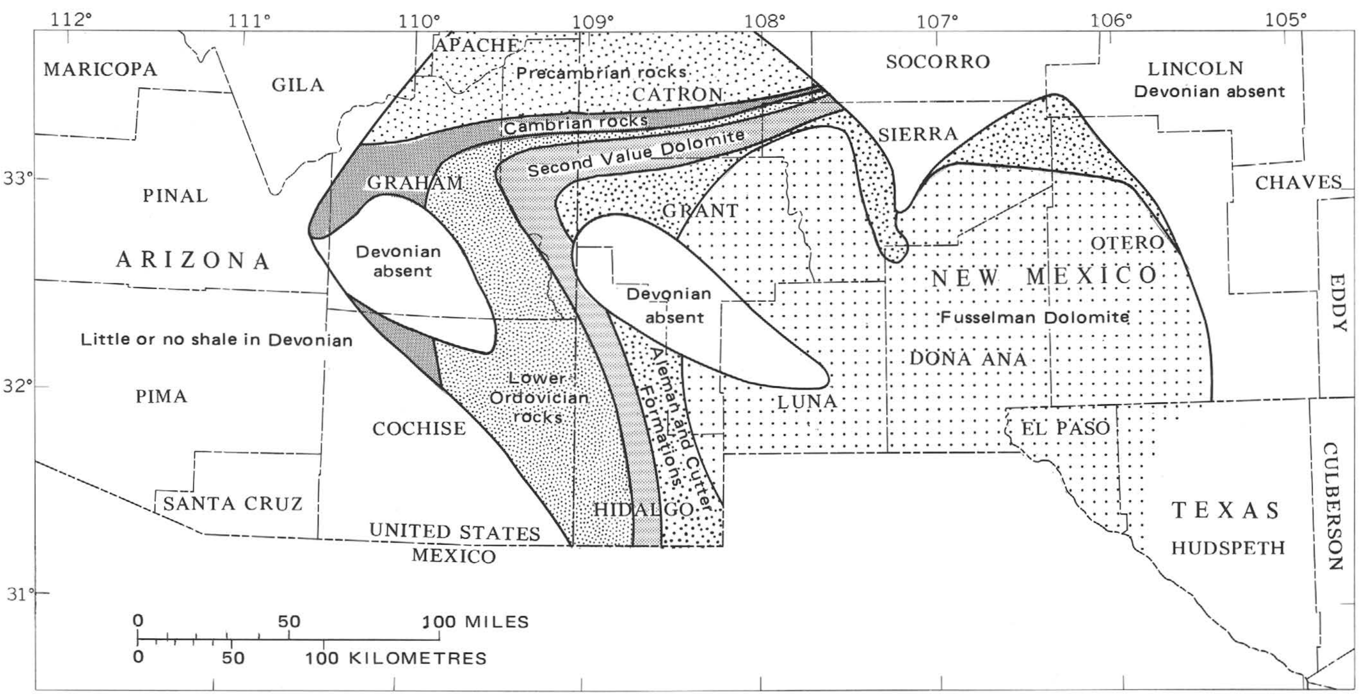


FIGURE 51.—Generalized map showing rock units that underlie dark shale-bearing rocks of Devonian age.

reservoirs migrated downward from younger rocks. Rocks correlated with the Simpson Group are not present in the report region west of the easternmost edge, but Devonian shale-bearing rocks overlie Cambrian, Ordovician, or Silurian rocks over a large part of the region. Figure 51 is a generalized map showing the rock units that unconformably underlie Devonian shale-bearing rocks in the New Mexico and Arizona parts of the region; note that the Devonian sequence contains little or no shale in much of Arizona. The Devonian shales, where present, besides being possible source rocks for downward migrating oil, might form an excellent trap surface for oil accumulated in porous weathered zones beneath the unconformity. On the bases of known oil occurrences east of the region, porosity determinations made during this study, and observations on the distribution of solution breccias beneath unconformities in the report region, speculations can be made that the most favorable areas for oil accumulations beneath Devonian shales in the report region would be where such shales unconformably overlie Lower Ordovician rocks—that is, in northeastern Cochise County or southeastern Graham County, Ariz.

CONTROL POINTS

A total of 105 control points was used in preparing the various isopach and facies maps appearing in this report; of these, 88 are surface localities and 17 are drill holes. We visited 68 of the surface localities during our fieldwork and examined samples from 3 of the drill holes in the laboratory. Table 1 (end of report) gives information on each control point, including location, principal references in the literature, the nature of our work (if any) at each locality, and a subjective appraisal of the quality and accessibility of each visited surface locality; it also gives the stratigraphic and time divisions for which each control point was used.

SELECTED MEASURED SECTIONS

Five important stratigraphic sections that we measured and described in the field and for which there are no adequate descriptions in previously published reports are reproduced on the following pages. The descriptions of 10 other sections, most of which have previously been reported, have been placed on open file (Hayes, 1975) because our measurements or descriptions differ markedly from those already published and because the sections are not shown graphically on plate 1.

PASOTEX SECTION (loc. 56)

[Section of Bliss Sandstone, Hitt Canyon Formation, McKelligon Limestone, and Padre Formation measured in offset segments starting at about lat 31°40′45″ N. and long 105°54′35″ W. in the Hueco Mountains, Hudspeth County, Tex. (fig. 1). The Hitt Canyon was measured about 2,000 feet to the east of the Bliss, the McKelligon was measured about 1,500 feet to the northwest of the Bliss, and the Padre Formation was measured about 2,500 feet northeast of the Bliss. This section includes the type section of the Padre Formation. The geology of the area that includes the section was mapped by King, King, and Knight (1945)]

	Thickness (feet)
Second Value Dolomite.	
Padre Formation:	
71. Covered. Probably dolomite like unit 69	15
70. Dolomite, very fine grained, silty, yellowish-orange; in ledge	2
69. Dolomite, very fine grained, pale-yellowish-gray to light-gray; thinly bedded; poorly exposed	11
68. Dolomite, very fine grained, silty, yellowish-orange	1
67. Dolomite, like unit 69	27
66. Limestone, light-gray; interlaminated, skeletal and lithiclast packstone; thinly bedded; poorly exposed	1
65. Dolomite, like unit 69	3
64. Dolomite, like unit 68	1
63. Dolomite, like unit 69	36
62. Limestone, like unit 66	20
61. Dolomite, fine-grained, pale-yellowish-gray; thinly laminated in part; mostly thinly bedded; contains scattered very irregular nodules of reddish-brown-weathering chert; contains some intraformational conglomerate; top of ledgy slope	80
60. Dolomite, fine- to medium-grained, yellowish-brown-weathering; thinly laminated; mostly in beds 6-12 in. thick; contains a lenticular chert bed as much as 6 in. thick at 33 ft above base; grades upward into unit 61	103
59. Dolomite, sandy and silty, yellowish-brown; very poorly exposed; in slope	4
58. Dolomite, fine- to medium-grained; thinly laminated; in beds 6-12 in. thick; contains some intraformational conglomerate 10 ft above base	13
57. Dolomite, like unit 59	3
56. Dolomite, fine- to medium-grained, yellowish-brown-weathering; thinly laminated; in beds 6-12 in. thick; 1 ft of intraformational conglomerate begins 38 ft above base	48
55. Dolomite, medium-grained, sandy, yellowish-brown-weathering; thickly bedded; top of unit forms a conspicuous ledge	14
Total thickness of Padre Formation	382
McKelligon Limestone:	
54. Dolomite, fine-grained, light-olive-gray, yellowish-gray-weathering; in beds 6-12 in. thick	21
53. Dolomite, slightly silty, yellowish-brown; very poorly exposed; in slope	12
52. Dolomite, thinly laminated	25
51. Alternating ledges of crudely laminated light-gray detrital limestone that contains scattered lenses and nodules of chert and slopes of poorly exposed nodular limestone; there are thin beds of brownish-gray-weathering dolomite at 17 and 122 ft above base	166
50. Dolomite, yellowish-brown-weathering; laminated	2
49. Limestone, light-gray, detrital; crudely laminated; thickly bedded; contains some burrowed limestone; in steep slope; alternates with slopes of poorly exposed nodular limestone	102
48. Limestone, like unit 49 but lacks slopes of nodular limestone; contains some *Calathium* sp. at base	47
47. Limestone, light-gray, detrital; crudely laminated; contains scattered endoceroid cephalopod siphuncles in middle part; in steep slope	100 ±
46. Limestone, light-medium-gray and medium-gray; irregularly laminated in part; contains mounds of	

	Thickness (feet)
light- medium-gray skeletal lime mudstone channeled by medium-gray skeletal-lithochast lime wackestone to packstone; contains several beds that contain up to 5 percent reddish-brown-weathering chert nodules; in steep slope	110 ±
Total thickness of McKelligon Limestone	585 ±
Hitt Canyon Formation:	
45. Limestone, partly sandy medium-gray and medium-dark-gray, thinly bedded; consists of alternating medium-gray skeletal lime wackestone and medium-dark-gray sandy lithiclast lime packstone; abundant gastropods in basal bed	88
44. Limestone, light-medium-gray and medium-gray; has some laminae and burrow fillings of light-brown-weathering silty limestone; contains widely scattered chert nodules and cephalopod siphuncles; skeletal lime wackestone is dominant, but lithiclast lime packstone, stromatolitic limestone and minor limestone intraformational conglomerate are present	110
43. Limestone, medium-light-gray; skeletal lime wackestone type; contains a few laminae of medium-gray lithiclast lime packstone; contains a few 1- to 2-in.-thick lenses of chert and scattered nodules of chert; contains cephalopod siphuncles 5 ft above base	28
42. Limestone, medium-light-gray; skeletal lime wackestone type; contains some silty brown-weathering limestone as laminae and burrow fillings, some stromatolitic limestone, and some limestone intraformational conglomerate	37
41. Limestone, medium-light-gray and medium-gray, massive; dominantly fossil-bearing lime mudstone with digitate algal structures that contains channel fillings of lithiclast lime packstone	8
40. Limestone; interlaminated medium-light-gray limestone and abundant dark-brown-weathering very silty limestone that gives unit an overall dark banded appearance; contains some limestone intraformational conglomerate and some fucoidal markings; grades upward into unit 41	38
39. Limestone, medium-light-gray; thinly laminated; contains considerable limestone intraformational conglomerate and abundant fucoidal markings	30
38. Limestone, medium-light-gray; thinly interlaminated sandy and nonsandy limestone whose sandy laminae stand out in relief and decrease upward; contains a few thin beds of limestone intraformational conglomerate	30
37. Sandstone, very dolomitic, slightly hematitic and glauconitic, fine-grained, well-sorted, grayish-orange-weathering; thinly laminated; contains abundant gastropods in top 1 in.	2
36. Limestone, like unit 38	10
35. Dolomite, very sandy, light-brown to grayish-orange-weathering; thinly laminated; in 1- to 2-in.-thick beds at base, massive above; forms basal part of cliff	26
34. Conglomerate; pebbles and cobbles of sandstone like unit 33 in a matrix of gray-weathering medium-grained glauconitic, hematitic, dolomitic sandstone; unconformity(?) at base	2
Total thickness of Hitt Canyon Formation	409
Bliss Sandstone:	
33. Sandstone, grayish-orange-weathering, medium-grained, subangular, very glauconitic, slightly hematitic, dolomitic; thinly laminated; thinly bedded	3
32. Sandstone, like unit 33, but crudely cross-laminated in beds 1-5 ft thick; forms ledge	30
31. Covered. May be shaly thin-bedded dolomitic sandstone	11
30. Sandstone, moderate-yellowish-brown- to grayish-orange-weathering, medium-grained, subangular, very glauconitic, slightly hematitic, slightly dolomitic; crudely cross-laminated; in beds 1-3 ft thick; forms ledge	8
29. Sandstone, light-brown-weathering, medium- to coarse-grained, dolomitic; cross-laminated; mostly in thin beds; contains poorly exposed shaly partings	18
28. Dolomite, moderate-yellowish-brown-weathering, medium-grained; contains very sandy laminae in lower one-third, brown shaly sandstone in middle one-third, and edgewise conglomerate in upper one-third	2
27. Sandstone, grayish-red, medium-grained, hematitic; very glauconitic near top; cross-laminated; thinly bedded; in slope; mostly covered in middle part	17
26. Sandstone, grayish-red, medium-grained, hematitic, cross-laminated; in 6- to 24-in.-thick beds; in a conspicuous ledge	6
25. Sandstone, pale-red to yellowish-gray, medium- to coarse-grained; hematitic streaks increase upward; crudely laminated; displays fucoidal markings; in thick beds; alternates with subordinate similar but glauconitic sandstone in thin beds that are poorly exposed	59
24. Sandstone, pale-yellowish-gray, medium- to coarse-grained, with rounded grains; laminated; contains fucoidal markings; in rounded ledge	2
23. Sandstone, like unit 24, but very friable and poorly exposed; in slope	10
22. Sandstone, pinkish-gray, reddish-brown-weathering, medium- to coarse-grained, subangular to subrounded; cross-laminated in part; in indistinct thick beds; in conspicuous rounded ledge	20
21. Sandstone, light-pinkish-gray, medium- to coarse-grained, subangular to subrounded; cross-laminated in part; in indistinct thick beds; grades into unit 22; in humpy slope	41
20. Sandstone, light-pinkish-gray, medium- to coarse-grained, subangular to subrounded, friable; massively bedded; iron-oxide-stained upper contact; in slope	19
19. Sandstone, pale-red, coarse-grained, with fairly well sorted subrounded grains; cross-laminated; in beds 1-2 ft thick; fairly resistant	4
18. Sandstone, pale-red, medium- to coarse-grained, with fairly well sorted subrounded grains; cross-laminated; in beds 3-12 in. thick	13
17. Mostly covered. A few inches of pale-red coarse-grained sandstone in middle	6
16. Sandstone, pale-red, coarse-grained, with fairly well sorted subrounded grains; cross-laminated; in rounded ledge	3
15. Covered	2
14. Sandstone, like unit 16	5
13. Interbedded sandstone and sandy shale; sandstone is	

	Thickness (feet)
coarse grained, friable, thinly bedded and displays fucoidal markings on the tops of some beds	8
12. Covered	5
11. Sandstone, dark-yellowish-gray, medium-brown-weathering, medium to very coarse grained, with poorly sorted subrounded grains; cross-laminated; resistant	2
10. Covered	3
9. Sandstone, like unit 11	6
8. Sandstone, brownish-gray, moderate-brown-weathering, coarse-grained, with poorly sorted subangular grains; arkosic, slightly glauconitic, slightly hematitic; thinly bedded; poorly exposed	10
7. Sandstone, like unit 11	2
6. Sandstone, like unit 8	16
5. Sandstone, dark-yellowish-gray, moderate-brown-weathering, medium to very coarse grained, with poorly sorted subrounded grains; cross-laminated; two beds in resistant ledge	3
4. Sandstone, like unit 8	14
3. Sandstone, like unit 8, but well exposed	4
2. Sandstone, like unit 8	11
1. Sandstone, brownish-gray, moderate-brown-weathering, coarse-grained, with scattered granules and poorly sorted subangular grains; arkosic, slightly glauconitic, slightly hematitic; laminated; 4-ft-thick bed at base and 2-ft-thick beds above; in resistant ledge; unconformable at base	10
Total thickness of Bliss Sandstone	373

Precambrian granite.

GARDEN CANYON SECTION (loc. 66)

[Section of Bolsa Quartzite and Abrigo Formation measured in sec. 5 (projected), T. 23 S., R. 20 E., and on ridge south of Garden Canyon in the Huachuca Mountains, Cochise County, Ariz. (fig. 1). The geology of the area that includes the section was mapped by Hayes and Raup (1968)]

	Thickness (feet)
Martin Formation.	
Abrigo Formation:	
Upper sandy member:	
43. Dolomite, very sandy, very poorly exposed; unconformable at top	3
Total thickness of upper sandy member	3
Middle member:	
42. Limestone, medium-dark-gray, medium-light-gray-weathering; contains laminae of yellowish-brown-weathering silty limestone that stands out in relief; in 1- to 12-in.-thick beds except 180-210 ft above base, where it is nearly massive, and top 30 ft, where it is platy bedded; moderately resistant; mostly interlaminated lime mudstone, algal(?) lime packstone, and skeletal lime wackestone	270
41. Claystone, calcareous, platy, very poorly exposed	7
40. Limestone, medium-dark-gray, medium-light-gray-weathering, microcrystalline; contains a few layers of limestone edgewise conglomerate; in beds 3-12 in. thick; in cliff	29
Total thickness of middle member	306
Lower member:	
39. Limestone, platy-bedded, argillaceous, and calcareous shale with crinkly laminae; poorly exposed	11
38. Covered. Float of yellow-brown-weathering fissile shale	24
37. Like unit 39	47
36. Limestone, medium-dark-gray, medium-light-gray-weathering, microcrystalline; in ¼-in.thick laminae separated by 1-mm-thick laminae of yellowish-brown-weathering silty limestone that stands out in relief	13
35. Limestone, medium-dark-gray, medium-light-gray-weathering, microcrystalline; in ¼-in.-thick laminae chert	3
34. Limestone, medium-dark-gray, medium-light-gray-weathering, microcrystalline; in 3- to 12-in.-thick beds that are separated by claystone partings	23
33. Claystone, pale-yellowish-brown-weathering; contains minor thin beds of light-gray-weathering medium-gray limestone	13
32. Limestone, like unit 36, but with thin argillaceous streaks	10
31. Like unit 33	15 ±
30. Limestone, medium-gray, light-gray-weathering, fine-grained; contains crinkly laminae of silty limestone about ¼-in. thick	2 ±
29. Like unit 33	15 ±
28. Like unit 30	2
27. Like unit 33	28
26. Limestone, medium-gray, light-gray-weathering, fine-grained; contains irregular crinkly laminae ¼-in. thick of silty limestone; in beds 3-12 in. thick; about 40 percent of unit is interbeds of less resistant platy shale in 2- to 4-ft-thick intervals	27
25. Shale, partly silty, medium-gray, brown-weathering, fissile; poorly exposed	4½
24. Limestone; algal(?) packstone type; contains crinkly laminae; in 3- to 12-in.-thick beds	3
23. Shale, like unit 25	6
22. Limestone; algal(?) packstone type; contains minor partings of shale; in 3- to 12-in.-thick beds	6
21. Shale, partly silty, medium-gray, brown-weathering, fissile; contains very minor interbedded limestone	8½
20. Limestone, glauconitic(?), laminated, in beds 3-12 in. thick	3
19. Shale, calcareous, partly silty, medium-gray, brown-weathering, platy; poorly exposed	12
18. Limestone, medium-gray; contains irregular crinkly laminae up to ½ in. thick of brown-weathering silty limestone; contains interbeds of calcareous shale	35
17. Shale, calcareous, partly silty, medium-gray, brown-weathering; contains very minor interbedded limestone; imperfectly exposed	6
16. Limestone, medium-gray; contains irregular crinkly laminae up to ½-in. thick of brown-weathering silty limestone; in beds 3-18 in. thick; contains partings of brown-weathering medium-gray silty shale	18
15. Like unit 17	75
14. Limestone, like unit 16, but without shale partings	3
13. Shale, platy, and minor interbedded dolomite; poorly exposed	14
12. Dolomite, very fine grained, medium-gray, dark-yellowish-brown-weathering; laminated	4
11. Shale, platy; poorly exposed	4
10. Dolomite, like unit 12	6
9. Sandstone, dolomitic, dark-yellowish-brown-weathering, fine-grained; faintly laminated; in	

	Thickness (feet)
1-in.-thick beds	6
8. Sandstone, siliceous, fine-grained, cross-laminated; resistant	8
7. Covered	2
6. Dolomite, slightly silty, very fine grained, medium-gray, dark-yellowish-brown-weathering; in 1- to 4-in.-thick beds	9
Total thickness of lower member	466
Total thickness of Abrigo Formation	775
Bolsa Quartzite:	
5. Shale, platy, siliceous; contains about 10 percent interbedded siliceous sandstone like unit 4; in slope	26
4. Sandstone, fine-grained, siliceous; in 6- to 12-in.-thick beds; interbedded with considerable claystone; in steep ledgy slope	64
3. Like unit 5	43
2. Sandstone, fine-grained, siliceous, pale-red- to pale-reddish-purple-weathering; strongly cross-laminated; contains thin interbeds of brown-weathering siliceous shale	12
1. Sandstone, siliceous, pale-red- to pale-reddish-purple-weathering; largely strongly cross-laminated; grain size decreases upward from very coarse grained and granular at base to fine grained at top; mostly in beds 2-10 ft thick; contains occasional partings of shaly sandstone in upper 275 ft; entire unit in cliff; unconformable at base	354
Total thickness of Bolsa Quartzite	499

Precambrian granite.

McKELLIGON CANYON SECTION (loc. 92)

[Principal reference section of Bliss Sandstone measured at about lat 31°50½' N. and long 106°29½' W. in McKelligon Canyon in Franklin Mountains, El Paso County, Tex. (fig. 1). The geology of the area that includes the section was mapped by Richardson (1909)]

	Thickness (feet)
Hitt Canyon Formation.	
Bliss Sandstone:	
8. Sandstone, fine- to coarse-grained, largely hematitic, partly glauconitic, pale-brown, pale-brown- to grayish-red-weathering; grains are subrounded and poorly sorted; in beds 6 in.-2 ft thick; top is covered	30
7. Sandstone, fine-grained, pale-brown; in beds less than 1 ft thick; imperfectly exposed	35
6. Sandstone, medium- to fine-grained, hematitic, slightly glauconitic, pale-brown, grayish-red-weathering; cross-laminated in part; some beds contain *Scolithus* tubes; mostly in beds less than 1 ft thick; imperfectly exposed	44
5. Sandstone, coarse-grained to slightly granular, slightly glauconitic, grayish-orange-pink, pale-brown-weathering; in beds 2-6 in. thick; imperfectly exposed	15
4. Sandstone, fine-to coarse-grained, slightly feldspathic, very pale red, pale-brown-weathering, cross-laminated	44
3. Sandstone, medium- to fine-grained, pale-yellowish-brown, mostly in beds 3-12 in. thick; poorly exposed; may have shale partings; in slope	29
2. Sandstone, medium- to coarse-grained, slightly feldspathic, pale-yellowish-brown, light-brown-weathering; grains are fairly well sorted and subrounded; in beds 2-6 in. thick with shale partings between beds	61
1. Sandstone, like unit 2, but poorly exposed; unconformable at base	9
Total thickness of Bliss Sandstone	267

Precambrian granite.

BRANDENBURG MOUNTAIN SECTION (loc. 102)

[Section of Bolsa Quartzite and Abrigo Formation measured on ridge in N½SW¼ sec. 7, T. 6 W., R. 17 E., on a spur on the west side of Brandenburg Mountain in the northern Galiuro Mountains, Pinal County, Ariz. (fig. 1). The geology of the area that includes the section was mapped by Krieger (1968d)]

	Thickness (feet)
Martin Formation.	
Abrigo Formation:	
Copper Queen Member:	
17. Dolomite, fine- to medium-grained, partly glauconitic; contains sandy and silty laminae; contains some intraformational chip conglomerate; poorly exposed	25
Total thickness of Copper Queen Member	25
Upper sandy member:	
16. Sandstone, coarse-grained, dolomitic, medium-brown-weathering; cross-laminated in 2- to 6-in. sets; thickly bedded; fairly resistant	91
Total thickness of upper sandy member	91
Middle member:	
15. Sandstone, medium-grained, pale-yellowish-brown-weathering; cross-laminated in part; contains some fucoidal markings; fairly nonresistant except for hardening of weathered surfaces of some beds	41
14. Sandstone, fine- to medium-grained, feldspathic, siliceous, banded very light and medium gray; in ledgy slope in which about one-third of sandstone is in ledges made resistant by hardening of weathered surfaces and two-thirds is unhardened pale-yellowish-brown-weathering sandstone in slopes	23
13. Sandstone, like unit 14 but only about two-thirds is in ledges and one-third in slopes	143
12. Sandstone, like unit 14	38
Total thickness of middle member	245
Lower member:	
11. Sandstone, fine-grained, silty, pale-red-weathering, friable; poorly exposed	16
10. Sandstone, fine-grained, grayish-red-weathering; in beds of variable thickness; weakly resistant	39
9. Siltstone, argillaceous, very slightly sandy, moderate-yellow-weathering; nonresistant, very poorly exposed; has thin interbeds of fine to very fine grained yellowish-brown- to reddish-brown-weathering sandstone	70
8. Siltstone, like unit 9 but without sandstone interbeds	87
7. Sandstone, fine-grained, slightly feldspathic,	

Thickness (feet)

light-gray- to light-brown-weathering, laminated; contains abundant fucoidal markings; mostly friable; mostly thinly bedded 30

Total thickness of lower member 242

Total thickness of Abrigo Formation 603

Bolsa Quartzite:

6. Sandstone, fine to slightly coarse grained, siliceous, very light gray to light-yellowish-gray, cross-laminated; in 6- to 24-in.-thick beds; very resistant; grades abruptly into unit 7 24
5. Sandstone, medium-grained, poorly sorted, banded very light gray, reddish-brown, and grayish-orange-pink; cross-laminated in beds 3-36 in. thick; less resistant than units 4 and 6 43
4. Sandstone, very fine to very coarse grained, siliceous; weathers yellowish-gray but has some reddish-gray streaks; cross-laminated; in 1- to 3-ft-thick beds; resistant 36
3. Sandstone, coarse grained to granular, grayish-orange-pink-weathering; very thinly bedded; poorly exposed 6
2. Siltstone, sandy, hematitic, argillaceous, dark-reddish-brown; poorly exposed in part 16
1. Conglomerate; composed of pebbles and cobbles of diabase; unconformable at base 2

Total thickness of Bolsa Quartzite 127

Precambrian diabase.

NANTAC RIM SECTION (loc. 150)

[Section of Coronado Sandstone and El Paso Limestone measured at about lat 33°13′ N. and long 109°40½′ W. east of Cold Spring Trail on escarpment of Nantac Rim, Graham County, Ariz. (fig. 1). The geology of the area including the section was mapped by Bromfield, Eaton, Peterson, and Ratté (1972)]

Thickness (feet)

Morenci Shale.

El Paso Limestone:

Upper member:

21. Dolomite, grayish-red, yellowish-gray-weathering, fine- to medium-grained; irregularly laminated; contains many layers of intraformational chip conglomerate; contains abundant fucoidal markings on bedding planes; thinly bedded; contains about 1 ft of sandstone like unit 19 at 83 ft above base; poorly exposed, especially near top; position of upper contact approximate .... 140 ±
20. Dolomite, much like unit 21, but somewhat better exposed 28

Total thickness of upper member .... 168 ±

Lower member:

19. Dolomite, very sandy, very glauconitic, fine-grained, dark-reddish-brown-weathering, laminated; thinly bedded; imperfectly exposed 6
18. Dolomite, partly sandy, glauconitic; laminated in part; contains many fucoidal markings; imperfectly exposed 13
17. Dolomite, very sandy, very glauconitic, fine- to medium-grained; cross-laminated in part; contains 4-in.-thick layer of dolomite chip conglomerate 2
16. Dolomite, silty, slightly glauconitic, fine- to medium-grained, grayish-red, yellowish-gray-weathering; crudely laminated in part; contains abundant fucoidal markings 15 ft above base; in 3- to 12-in.-thick beds; poorly exposed in part 25
15. Dolomite, very silty, glauconitic, very fine grained, grayish-red, reddish-brown-weathering; contains abundant fucoidal markings; thinly bedded 9
14. Dolomite, silty, slightly glauconitic, fine- to medium-grained, grayish-red, yellowish-gray-weathering; crudely laminated in part; contains some mud cracks; in 3- to 12-in.-thick beds; poorly exposed near top; fossil colln. USGS 7036-CO from 26 ft above base 49
13. Limestone, dark-gray, crystalline; thinly bedded; poorly exposed 2
12. Covered 24

Total thickness of lower member 130

Total thickness of El Paso Limestone .... 298 ±

Coronado Sandstone:

11. Sandstone, medium-grained to slightly granular, glauconitic, reddish-brown-weathering, laminated; poorly exposed; on dip slope 22
10. Sandstone, siliceous, medium-grained to locally gritty, pale-yellowish-gray to very light gray, cross-laminated; imperfectly exposed 100
9. Sandstone, arkosic, coarse-grained and gritty; cross-laminated in thin sets; resistant 13
8. Sandstone, arkosic, medium-grained; cross-laminated in part; thinly bedded; poorly exposed 13
7. Sandstone, very arkosic, coarse-grained and gritty, yellowish-brown-weathering; cross-laminated in 2- to 4-in.-thick sets; resistant 25
6. Conglomerate, granule, arkosic, orange-brown-weathering; indistinctly bedded in 1- to 4-in.-thick beds; in knobby ledge 9
5. Sandstone, arkosic, siliceous, coarse-grained and gritty, reddish-brown to brownish-red; weathers to a banded reddish brown and yellowish brown; cross-laminated in part; contains some fucoidal markings; in beds up to 3 ft thick; resistant 30
4. Sandstone, arkosic, siliceous, medium-grained to partly gritty, reddish-brown to brownish-red; weathers to a banded reddish brown and yellowish brown; cross-laminated in part; contains some fucoidal markings in beds 1-6 in. thick; resistant; in ledges 47
3. Sandstone, very arkosic, coarse-grained, reddish-brown- to yellowish-brown-weathering; contains some layers of granule conglomerate; cross-laminated; in beds 3-18 in. thick; fairly resistant; top 3 ft covered 46
2. Sandstone, much like unit 3, but mostly covered 38
1. Conglomerate, granule, very arkosic; contains some pebbly layers; in beds 2 in. to 2 ft thick that are very indistinct except in top 12 ft; a few beds are faintly cross-laminated; contains minor interbedded coarse-grained arkosic sandstone in top 12 ft; mostly nonresistant; in slope interrupted by a few ledges; poorly exposed in part in basal 68 ft; unconformable at base 193

Total thickness of Coronado Sandstone 536

Precambrian granodiorite.

FOSSIL LISTS

Fossils that were collected from Cambrian and Ordovician rocks during the present investigation and that have been retained in the collections of the U.S. Geological Survey are listed on the following pages; fossils that were discarded after identification are not listed. Localities are shown in figure 1.

Abrigo Formation, lower member:
  Locality 64 (northern Swisshelm Mountains):
    Collection 7308-CO—collected from 249 feet above base of member and identified by M. E. Taylor (written commun., Jan. 24, 1973).
      Trilobite:
        Eldoradia sp.
      Other:
        Inarticulate brachiopod, gen. and sp. indet.
  Locality 69 (French Joe Canyon):
    Collection 7032-CO—collected from 165 feet above base of member and identified by M. E. Taylor (written commun., Aug. 16, 1971).
      Trilobite:
        ?*Modocia* sp. A.
      Other:
        cf. *Chancelloria* sp.
        Hyolithid, undet.
        Problematicum, undet.
  Locality 80 (Waterman Mountains):
    Collection 7285-CO—collected from 588 feet above base of member and identified by M. E. Taylor (written commun., Jan. 24, 1973).
      Trilobite:
        Olenoides sp.
      Other:
        Inarticulate brachiopod, gen. and sp. indet.
    Collection 7035-CO—collected from 595 feet above base of member and identified by M. E. Taylor (written commun., Aug. 16, 1971).
      Trilobites:
        Alokistocare sp.
        Baltagnostus or *Kormagnostus* sp.
        cf. *Elrathia* sp.
        ?*Modocia* sp. indet.
        Ptychopariid, gen. and sp. indet.
    Collection 7286-CO—collected from 600 feet above base of member and identified by M. E. Taylor (written commun., Jan. 24, 1973).
      Trilobites:
        Olenoides sp.
        cf. *Modocia* sp.
        Bolaspidid, gen. and sp. indet.
Abrigo Formation, middle member:
  Locality 64 (northern Swisshelm Mountains):
    Collection 7309-CO—collected from 2 feet above base of member and identified by M. E. Taylor (written commun., Jan. 24, 1973).
      Trilobites:
        cf. *Bolaspidella* sp.
        cf. *Modocia* sp.
        Ptychopariid, gen. and sp. undet.
    Collection 6979-CO—collected from 91 feet above base of member and identified by M. E. Taylor (written commun., Sept. 14, 1970).
      Trilobites:
        Cedarina aff. *C. obtusans* Duncan
        cf. *Kormagnostus* sp.
        Meteoraspis sp.
        Undet. trilobite fragments
    Collection D2089—collected from 92 feet above base of member and identified by A. J. Rowell (written commun., Oct. 19, 1970).
      Brachiopods:
        Lingulella sp.
        Curticia sp.
  Locality 65 (Mount Martin):
    Collection 7291-CO—collected from above base of member, and identified by M. E. Taylor (written commun., Jan. 24, 1973).
      Trilobites:
        Arapahoia sp.
        cf. *Bynumia* sp. A
        ?*Cedaria* sp.
        Coosia-like pygidium
        Kormagnostus sp.
        cf. *Meteoraspis* sp.
        Granulose ptychopariid, gen. and sp. indet.
      Other:
        Hyolithid, gen. and sp. indet.
    Collection 7292-CO—Collected from 133 feet above base of member and identified by M. E. Taylor (written commun., Jan. 24, 1973).
      Trilobites:
        Arapahoia sp.
        ?*Menomonia* sp.
        "*Modocia*" sp.
        Cedariid, gen. and sp. indet.
      Other:
        Inarticulate brachiopod, gen. and sp. indet.
    Collection 7293-CO—collected from 148 feet above base of member and identified by M. E. Taylor (written commun., Jan. 24, 1973).
      Trilobites:
        Arapahoia sp.
        Bynumia sp. A
        Cedaria sp.
        Kormagnostus sp.
        Ptychopariid, gen. and sp. undet.
    Collection 7294-CO—collected from 164 feet above base of member and identified by M. E. Taylor (written commun., Jan. 24, 1973).
      Trilobites:
        Arapahoia spp.
        cf. *Meteoraspis* spp.
  Locality 69 (French Joe Canyon):
    Collection 7033-CO—collected from 10 feet above base of member and identified by M. E. Taylor (written commun., Aug. 16, 1971).
      Trilobites:
        cf. *Blountia* sp.
        ?*Brassicephalus* sp.
        ?*Cedaria* sp.
        Kormagnostus sp.
      Brachiopod:
        cf. *Dicellomus* sp.
    Collection 7034-CO—collected from 118 feet above base of member and identified by M. E. Taylor (written commun., Aug. 16, 1971).
      Trilobites:

?*Ankoura* sp.
Arapahoia sp.
Crepicephalid, indet.
Kingstonia cf. *K. montanensis* Lochman
Kormagnostus sp.
cf. *Meteoraspis* sp.
Other:
Oboloid brachiopod, indet.
Echinodermal debris
Locality 81 (Slate Mountains):
Collection 7289-CO—collected from 18 feet above base of member and identified by M. E. Taylor (written commun., Jan. 24, 1973).
Trilobites:
cf. *Kormagnostus* sp.
Cedariid, gen. and sp. indet.
Other:
Obolinoid brachiopod, gen. and sp. indet.
Burrows
Hyolithid, gen. and sp. indet.
Collection 7290-CO—collected from 34 feet above base of member and identified by M. E. Taylor (written commun., Jan. 24, 1973).
Trilobite:
Ptychopariid, gen. and sp. indet.
Other:
Inarticulate brachiopod, gen. and sp. indet.
Sponge spicule
Collection 7287-CO—collected from 135 feet above base of member and identified by M. E. Taylor (written commun., Jan. 24, 1973).
Trilobite:
Arapahoia sp.
Other:
Obolinoid brachiopod, gen. and sp. indet.
Burrows
Locality 160 (Picacho de Calera):
Collection 7281-CO—collected from about 265 feet above base of member and identified by M. E. Taylor (written commun., Jan. 24, 1973).
Trilobites:
Crepicephaliid, gen. and sp. indet.
cf. *Holcacephalus* sp.
?Coosiid, gen. and sp. indet.
Other:
Linguloid brachiopod, gen. and sp. indet.
Collection 7282-CO—collected from about 275 feet above base of member and identified by M. E. Taylor (written commun., Jan. 24, 1973).
Trilobites:
?*Modocia* sp.
Crepicephaliid, gen. and sp. indet.
Granulose ptychopariid, gen. and sp. indet.
Abrigo Formation, upper sandy member:
Locality 160 (Picacho de Calera):
Collections 7283-CO and 7284-CO—collected from about 10 feet above base of member and identified by M. E. Taylor (written commun., Jan. 24, 1973).
Trilobite:
Aphelaspis sp.
Abrigo Formation, Copper Queen Member:
Locality 65 (Mount Martin):
Collection 7295-CO—collected from 30 feet above base of member and identified by M. E. Taylor (written commun., Jan. 24, 1973).
Trilobites:
Drumaspis cf. D. *maxwelli* Resser
Idahoia sp.
Agnostid, gen. and sp. undet.
Brachiopods:
Billingsella sp.
Inarticulate brachiopod, gen. and sp. indet.
Other:
Pelmatozoan debris
Collection 7396-CO—collected from 35 feet above base of member and identified by M. E. Taylor (written commun., Jan. 24, 1973).
Trilobites:
Drumaspis cf. *D. walcotti* Resser
Idahoia sp.
Maladia sp.
Ptychaspis cf. *P. miniscaensis* (Owen)
Agnostid, gen. and sp. undet.
Dikelocephalid, gen. and sp. undet.
Undet. trilobite, *Lecanopyge*-like
Brachiopods:
Acrotretid, gen. and sp. undet.
Linguloid, gen. and sp. indet.
Other:
Pelmatozoan columnals
Sponge spicules (monaxon)
Problematical tubular fossils, undet.
Collection 7298-CO—collected from 78 feet above base of member and identified by M. E. Taylor (written commun., Jan. 24, 1973).
Trilobites:
Briscoia sp.
?*Prosaukia* sp.
Rasettia sp.
Catillicephalid, gen. and sp. undet.
Ptychopariid, gen. and sp. undet.
Other:
Inarticulate brachiopod, gen. and sp. undet.
Hyloithid, gen. and sp. indet. (??*Kygmaeoceras* sp.)
Gastropod, gen. and sp. undet. (high-spired form).

Bliss Sandstone:
Locality 20 (Werney Hill):
Collection D2187-CO—collected from 30 feet above base of formation and identified by R. J. Ross, Jr. (written commun., May 11, 1970).
Brachiopod:
Eorthis sp.
El Paso Limestone, lower member:
Locality 57 (Portal):
Collection D2247-CO—collected from 98 feet above base of member. Brachiopod identified by R. J. Ross, Jr. (written commun., Oct. 9, 1970), and mollusk by E. L. Yochelson (written commun., Dec. 6, 1971).
Brachiopod:
Plectotrophia sp.
Mollusk:
Matthevia? sp.
Locality 150 (Nantac Rim):
Collection 7036-CO—collected from 52 feet above base of member from unit 14 (see description of Nantac Rim measured section) and identified by M. E. Taylor (written commun., Aug. 16, 1971).
Brachiopod:
Billingsella cf. *B. coloradoensis* (Shumard)

Other:
Hyolithid, undet.

Hitt Canyon Formation:

Locality 1 (Agua Chiquita Canyon):

Collection D2274-CO—collected from 73 feet above base of formation and identified by L. A. Wilson (written commun., Apr. 22, 1971).

Conodonts:
Drepanodus suberectus (Branson and Mehl)
Oistodus forceps Lindstrom
O. parallelus Pander
Drepanodus sp.
Oneotodus variabilis Lindstrom
Scolopodus sp.
Paltodus sp.

Collection 6987-CO—collected from 195 feet above base of formation and identified by J. W. Huddle and J. J. Kohut (written commun., Sept. 28, 1970).

Conodonts:
Drepanodus parallelus (Branson and Mehl)
D. sculponea Lindstrom
D. suberectus (Branson and Mehl)
D. sp.
Oistodus sp.
Paltodus sp.
Scolopodus quadruplicatus Branson and Mehl

Locality 21 (West Lone Mountain):

Collection D2256-CO—collected from 122 feet above base of formation. Brachiopod and trilobites identified by R. J. Ross, Jr. (written commun., Jan. 13, 1971), and conodonts by L. A. Wilson (written commun., Mar. 17, 1971).

Brachiopod:
Nanorthis sp.

Trilobites:
Hystricurus sp.
Indeterminate scraps

Conodonts:
Distacodus? simplex Furnish
Drepanodus homocurvatus Lindstrom
D. suberectus (Branson and Mehl)
Scolopodus cornutiformis (Branson and Mehl)
S. lineatus (Furnish)
Scandodus furnishi Lindstrom
S. pipa Lindstrom
Oistodus lanceolatus Pander
O. sp.
Paltodus variabilis Furnish

Collection D2257-CO—collected from 190 feet above base of formation. Mollusks identified by E. L. Yochelson (written commun., Jan. 28, 1971), and conodonts by L. A. Wilson (written commun., Mar. 1, 1971).

Mollusks:
Indet. genus like *Ophileta* or *Lecanospira*
Indet. bellerophontacean

Conodonts:
Oistodus sp.
Acontiodus sp.
Scolopodus cornutiformis Branson and Mehl
S. quadruplicatus Branson and Mehl
S. sp.
Paltodus sp.

Locality 24 (Mescal Canyon):

Collection D2204-CO—collected from 73 feet above base of formation and identified by R. J. Ross, Jr. (written commun., July 22, 1970).

Trilobites:
Kainella sp.
Leiostegium sp.

Collection D2205-CO—collected from 117 feet above base of formation and identified by L. A. Wilson (written commun., Dec. 2, 1970).

Conodonts:
Oistodus inaequalis Pander
O. parallelus Pander
O. abundans Branson and Mehl
Oneotodus sp.
Drepanodus homocurvatus Lindstrom
D. lineatus Furnish
Acodus oneotensis Furnish
Paltodus cf. *P. inconstans* Lindstrom

Collection D2209-CO—collected from 375 feet above base of formation. Trilobites and brachiopod identified by R. J. Ross, Jr. (written commun., July 22, 1970, and Dec. 2, 1970), echinoderm material by James Sprinkle (written commun., Dec. 2, 1970), and conodonts by L. A. Wilson (written commun., Dec. 2, 1970).

Trilobites:
Asaphellus cf. *A. riojanus* Harrington and Leanza
Hystricurinid

Brachiopod:
Small camerellid(?), fragmentary

Echinoderm material:
One rhombiferan cystoid(?) plate with rhombs
Two large fold plates of unknown origin
Several different types of possible crinoid radial plates
One disklike columnal

Conodonts:
Drepanodus homocurvatus Lindstrom
Oistodus inaequalis Pander
Drepanodus suberectus (Branson and Mehl)

Locality 38 (San Lorenzo):

Collection D2190-CO—collected from about 65 feet above base of formation and identified by L. A. Wilson (written commun., July 22, 1970).

Conodonts:
Acontiodus staufferi Furnish
A. sp.
Drepanodus sp.
Oistodus parallelus Pander
Scolopodus sp.
Cordylodus sp.

Collection D2191-CO—collected from about 80 feet above base of formation. Trilobite identified by R. J. Ross, Jr. (written commun., July 22, 1970), and conodonts by J. W. Huddle (written commun., Sept. 25, 1970).

Trilobite:
Bellefontia sp.

Conodonts:
Acanthodus cf. *A. uncinatus* Furnish
A. sp.
Acontiodus aff. *A. propinquus* Furnish
A. aff. *A. staufferi* Furnish
A. aff. *A. sulcatus* Furnish
Cordylodus sp.
Drepanodus parallelus Branson and Mehl
D. suberectus (Branson and Mehl)
Oistodus sp.
Paltodus sp.
Scolopodus cf. *S. cornutiformis* Branson and Mehl *S.* sp.

Collection D2192-CO—collected from about 250 feet above base of formation. Trilobites identified by R. J. Ross, Jr. (written commun., July 22, 1970), conodonts by L. A. Wilson (written commun., Dec. 2, 1970), and echinoderm material by James Sprinkle (written commun., Dec. 2, 1970).
Trilobites:
Leiostegium sp. (probably new)
Aulacoparia? huygenae of Flower
(probably same as *Asaphellus riojanus* of Ross, 1970)
Hystricurid, unidentified
Bathyurid pygidium
Conodonts:
Drepanodus suberectus (Branson and Mehl)
D. homocurvatus Lindstrom
D. sp.
Oistodus forceps Lindstrom
Echinoderm material:
Two highly silicified cylindrical stem segments(?)
Two possible oblong columnals(?) showing a possible "twist" in the orientation of the two faces like columnals in the Carboniferous *Platycrinus* - crinoid?
Seventeen calyx plates with exospire-type respiratory folds developed as external ridges radiating to the plate sides; the two types—one where whole plate folds into ridges and troughs and the other where the plate is thick and has slits covered over externally by a thin calcite sheet—both resemble plates found in the crinoid *Palaeocrinus,* in some paracrinoids, and in the eocrinoid(?) *Macrocystella*

Locality 39 (Capitol Dome):
Collection D2193-CO—collected from about 300 feet above base of formation. Trilobites and brachiopod identified by R. J. Ross, Jr. (written commun., July 22, 1970, and Dec. 2, 1970), and conodonts by J. W. Huddle (written commun., Sept. 25, 1970).
Trilobites:
Asaphellus cf. *A. riojanus* (See Ross, 1970, pl. 13.)
Leiostegium cf. *L. tyboensis* Ross
Hystricurid (See Ross, 1970, pl. 10, figs. 32-34.)
Brachiopod:
Nanorthis? sp.
Conodonts:
Drepanodus suberectus (Branson and Mehl)
Oistodus sp.
Scandodus sp.

McKelligon Limestone:
Locality 27 (San Andres Canyon):
Collection D2248-CO—collected from 87 feet above base of formation and identified by J. K. Rigby (written commun., June 3, 1970).
Receptaculitid?:
Calathium fittoni Billings

Locality 39 (Capitol Dome):
Collection D2232-CO—collected from about 220 feet above base of formation. Conodonts identified by L. A. Wilson (written commun., Nov. 27, 1970), and other fossils by R. J. Ross, Jr. (written commun., Sept. 24, 1970, and Nov. 27, 1970).
Brachiopod:
Nanorthis cf. *N. hamburgensis* (Walcott)
Conodonts:
Scolopodus triplicatus Ethington and Clark
S. cf. *S. alatus* Bradshaw
Drepanodus homocurvatus Lindstrom
Ulrichodina sp.
Oistodus forceps Lindstrom
Other:
Gastropods, indet.
Sponges

Padre Formation:
Locality 24 (Mescal Canyon):
Collection D2210-CO—collected from 94 feet above base of formation. Brachiopods identified by R. J. Ross, Jr., and conodonts by L. A. Wilson (written commun., Dec. 2, 1970).
Brachiopods:
Diparelasma sp.
Hesperonomia sp.
Conodonts:
Drepanodus homocurvatus Lindstrom
Scolopodus n. sp. of Lindstrom, 1954
S. gracilis Ethington and Clark
S. variabilis Ethington and Clark
S. sp.
Oistodus longiramis Lindstrom
O. inaequalis Pander
O. sp.
Panderodus sp.

Collection D2211-CO—collected from 100 feet above base of formation and identified by L. A. Wilson (written commun., Dec. 2, 1970).
Conodonts:
Drepanodus homocurvatus Lindstrom
D. arcuatus Pander
Scandodus sp.
Paltodus sp.

Locality 39 (Capitol Dome):
Collection D2194-CO—collected from 27 feet above base of formation. Trilobites and brachiopod identified by R. J. Ross, Jr. (written commun., July 22, 1970, and Dec. 2, 1970), and conodonts by L. A. Wilson (written commun., Dec. 2, 1970).
Trilobites:
Ptyocephalus sp.
Peltabellia? sp.
Brachiopod:
Diparelasma sp.
Conodonts:
Gothodus sp.
Drepanodus homocurvatus Lindstrom
Scolopodus quadruplicatus Branson and Mehl
Scolopodus sp.
Falodus prodentatus Graves and Ellison
Oistodus sp.
Acodus sp.

Collection D2195-CO—collected from 42 feet above base of formation. Brachiopod identified by R. J. Ross, Jr., and conodonts by L. A. Wilson (written commun., Dec. 2, 1970).
Brachiopod:
Diparelasma sp.
Conodonts:
Oistodus lanceolatus Pander
O. parallelus Pander
O. aff. *O. forceps* Lindstrom
Scandodus pipa Lindstrom
S. sp.
Panderodus sp.
Drepanodus arcuatus Lindstrom
D. homocurvatus Lindstrom
Acontiodus sp.
Scolopodus filosus Ethington and Clark

Collection D2196-CO—collected from 90 feet above base of formation and identified by R. J. Ross, Jr. (written commun., July 22, 1970).
Trilobite:
Pseudocybele sp. (indet. but more like *P. lemurei* Hintze than like *P. nasuta* Ross)
Collection D2197-CO—collected from about 200 feet above base of formation and identified by R. J. Ross, Jr. (written commun., July 22, 1970).
Brachiopods:
Diparelasma? sp.
Hesperonomia? sp.
Syntrophid, perhaps *Syntrophopsis*
Trilobites:
Indet. asaphids
Aleman Formation:
Locality 16 (Molinas Canyon):
Collection D2234-CO—collected from 7 feet above base of formation and identified by R. J. Ross, Jr. (written commun., Sept. 24, 1970).
Brachiopod:
Zygospira sp.
Collection 6988-CO—collected from 7 feet above base of formation and identified by J. W. Huddle and J. J. Kohut (written commun., Sept. 28, 1970).
Conodonts:
Phragmodus undatus Branson and Mehl
Oulodus oregonia Branson, Mehl, and Branson
Locality 93 (Sugarloaf):
Collection 6908—collected from 145 feet above base of formation and identified by O. L. Karklins (written commun., June 23, 1970).
Bryozoans:
Cyphotrypa? sp.
Calloporella? sp.
Hallopora? sp.
Cutter Dolomite:
Locality 24 (Mescal Canyon):
Collection D2212-CO—collected from 75 feet above base of formation. Brachiopods identified by R. J. Ross, Jr., and conodonts by L. A. Wilson (written commun., Dec. 2, 1970).
Brachiopods:
Paucicrura? sp.
Fragments of large orthids
Conodonts:
Belodina ornatus (Branson and Mehl)
B. wykoffensis (Stauffer)
B. grandis (Stauffer)
Oistodus inclinatus Branson and Mehl
Trichonodella sp.
Panderodus intermedius (Branson, Mehl, and Branson)
P. sp.
Drepanodus sp.
D. homocurvatus Lindstrom
Cyrtoniodus sp.
Collection 6986-CO—collected from 288 feet above base of formation and identified by J. W. Huddle and J. J. Kohut (written commun., Sept. 28, 1970).
Conodonts:
Belodina profunda (Branson and Mehl)
Drepanodus suberectus Branson and Mehl
Ozarkodina tenuis Branson and Mehl
Oistodus sp.
Panderodus gracilis (Branson and Mehl)
Plectodina furcata? (Hinde)
N. Genis?
Locality 39 (Capitol Dome):
Collection D2233-CO—collected from 9 feet above base of formation. Brachiopods identified by R. J. Ross, Jr., and conodonts by L. A. Wilson (written commun., Sept. 24, 1970).
Brachiopods:
Paucicrura sp.
Hebertella sp.
Rhynchonellis undet.
Conodonts:
Trichonodella sp.
Ligonodina sp.
Ozarkodina sp.
Locality 93 (Sugarloaf):
Collection 6989-CO—collected from 49 feet above base of formation and identified by J. W. Huddle and J. J. Kohut (written commun., Sept. 28, 1970).
Conodonts:
Belodina profunda (Branson and Mehl)
Drepanodus suberectus Branson and Mehl
Ozarkodina polita (Hinde)
Panderodus sp.

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[Page numbers of major references are in italic]

TABLE 1

TABLE 1.—*Data on control points used in compilation of thickness and facies maps*

Locality: Number followed by W indicates drill hole.
Coordinates: Drill-hole locations are given by land coordinates rather than by geographic coordinates.
Stratigraphic units: 1, Bolsa Quartzite; 2, Abrigo Formation; 2c, upper sandy member; 2d, Copper Queen Member; 3, Coronado Sandstone; 4, Bliss Sandstone; 5, El Paso Group (or Limestone); 6, correlatives of Simpson Group; 7, Montoya Group; 7a, Cable Canyon Sandstone Member; 7b, Upham Dolomite Member; 7c, Aleman Formation.
Ages: A, Middle Cambrian; B, Dresbachian (of Howell and others, 1944); C, Franconian and Trempealeauan (of Howell and others, 1944); D, early and middle Canadian; E, early late Canadian; F, late late Canadian; G, early Middle Ordovician; H, late Middle Ordovician; I, early Late Ordovician; J,, late Late Ordovician.
Quality or accessibility: E, excellent; G, good; F, fair; P, poor.
Land status: G, accessible local, State, or federal government lands; R, restricted government lands; I, Indian lands; P, private property.
References: NMBMMR, New Mexico Bureau of Mines and Mineral Resources; PBSL, Permian Basin Sample Library.
Remarks: Spld., section sampled during this investigation; remeas., section remeasured and described during this investigation; meas., section measured for first time during this investigation; spls. ex., drill-hole samples examined; mod. th., previous descriptions used but thickness modified by measurements made during this investigation; illus., Sauk sequence rocks of this locality are graphically illustrated on pl. 1; desc., written description of section is given in text; OF, written description of section is in an open-file report (Hayes, 1975); mod. strat., locality visited and original stratigraphic assignment changed during this investigation.

Locality (fig. 1)	Locality name	County	Lat N.	Long W.	Stratigraphic units	Ages ABC	DEF	A-F	GHIJ	H-J	Quality	Accessibility	Land Status	References	Remarks
					NEW MEXICO										
1	Agua Chiquita Canyon------	Otero------	32°41'20"	105°52'30"	4,5	---	XX-	X	----	-	G	F	G	Pray (1961)-----------	Spld.
2	Alamo Canyon--------------	---do------	32°51'	105°51'45"	7	---	---	-	-XXX	X	G	P	G	----do----------------	Do.
3	Lead Canyon---------------	---do------	32°48'45"	105°56'	7	---	---	-	-XXX	X	-	-	-	Howe (1959)-----------	
4	Bishop Cap----------------	Dona Ana---	32°11'15"	106°33'30"	7	---	---	-	-XXX	X	E	E	R	----do----------------	Remeas.
5	Webb Gap------------------	---do------	32°05'	106°32'45"	7	---	---	-	-XXX	X	-	-	-	----do----------------	
6	Jose----------------------	Luna-------	32°34'30"	107°44'20"	7	---	---	-	-XXX	X	-	-	-	----do----------------	
7	Johnson Park Canyon-------	Socorro----	33°29'	106°27'40"	4,5,7	---	X--	X	-XXX	X	G	G	R	Bachman (1965, 1968)--	Spld.
8	Fairview Mountain---------	Sierra-----	33°28'	106°30'45"	4,5,7	---	X--	X	-X--	X	-	-	-	Bachman (1965)--------	
9	Capitol Peak--------------	---do------	33°25'15"	106°25'30"	4,5,7	---	X--	X	-XX-	X	G	F	R	----do----------------	Remeas., illus.
10	Rhodes Canyon-------------	---do------	33°16'30"	106°37'15"	4,5,7	---	X--	X	-XXX	X	G	G	R	Kottlowski and others (1956).	Spld.
11	Hembrillo Canyon----------	Dona Ana---	32°56'30"	106°36'30"	4,5,7	---	XX-	X	-XXX	X	-	-	-	----do----------------	
12	Ash Canyon----------------	---do------	32°37'30"	106°32'	4,5,7	---	XXX	X	-XXX	X	-	-	-	----do----------------	
13	Mud Springs Mountains-----	Sierra-----	33°09'15"	107°18'15"	4,5,7	--X	XX-	X	-XXX	X	G	F	G	Kelley and Silver (1952).	Remeas., illus.
14	South Ridge---------------	---do------	33°01'30"	107°14'	4,5,7	--X	---	X	-XXX	X	-	-	-	----do----------------	
15	Cable Canyon--------------	---do------	32°55'45"	107°14'	4,5,7	--X	XX-	X	-XXX	X	E	G	G	----do----------------	Remeas. part, illus.
16	Molinas Canyon------------	---do------	32°47'45"	107°13'40"	4,5,7	--X	---	-	-XXX	X	F	P	G	----do----------------	Remeas. part.
17	Cooks Range (north)-------	Luna-------	32°35'15"	107°44'20"	4,5,7	--X	XX-	X	-XXX	X	F	F	P	Jicha (1954)----------	Remeas., OF.
18	Little San Nicholas Canyon.	Dona Ana---	32°34'15"	106°30'40"	4,5,7a, 7b, 7c	---	XXX	X	-XX-	-	E	G	R	Bachman and Myers (1969).	Remeas. part, illus.
19	Lake Valley---------------	Sierra-----	32°44'30"	107°35'15"	7	---	---	-	-XXX	X	F	G	P	Jicha (1954)----------	Remeas.
20	Werney Hill---------------	Grant------	32°26'45"	108°15'20"	4	--X	---	-	----	-	F	F	P	Ballman (1960)--------	Do.
21	Lone Mountain (west)------	---do------	32°42'45"	108°12'	4,5	--X	XX-	X	----	-	E	G	P	Pratt (1967)----------	Spld.
22	Lone Mountain (east)------	---do------	32°42'	108°11'	7	---	---	-	-XXX	X	E	G	P	----do----------------	Do.
23	Preacher Mountain---------	Hidalgo----	32°07'	108°59'	3,5	-XX	XX-	X	----	-	F	G	G	Gillerman (1958)------	Do.
24	Mescal Canyon-------------	---do------	31°40'	108°23'15"	4,5,7	--X	XXX	X	-XXX	X	G	G	G	Zeller (1965)---------	Remeas., illus.
25	Ram Gorge-----------------	---do------	31°41'	108°23'15"	4	--X	---	-	----	-	-	-	-	----do----------------	
26	Bear Mountain-------------	Grant------	32°49'45"	108°21'45"	7	---	---	-	-XXX	X	G	G	G	Pratt and Jones (1961)	Spld.
27	San Andres Canyon---------	Dona Ana---	32°44'30"	106°33'45"	4,5,7	---	XXX	X	-XXX	X	E	G	R	Bachman and Myers (1963).	Remeas.,OF.
28	Sierra Oscura (south)-----	Lincoln----	33°32'	106°19'45"	4,5,7	---	X--	X	-XX-	X	E	G	R	Bachman (1968)--------	Remeas., illus.
29	Sierra Oscura (middle-south).	---do------	33°33'	106°20'15"	4,5,7	---	X--	X	-X--	X	-	-	-	----do----------------	
30	Sierra Oscura (middle)----	---do------	33°35'	106°21'	4,5	---	X--	X	----	-	-	-	-	----do----------------	
31	Sierra Oscura (middle-north).	---do------	33°36'30"	106°21'40"	4,5	---	X--	X	----	-	-	-	-	----do----------------	
32	Sierra Oscura (north)-----	Socorro----	33°38'	106°22'15"	4,5	---	X--	X	----	-	-	-	-	----do----------------	
33	Mockingbird Gap (south)---	---do------	33°34'20"	106°25'45"	4,5	---	X--	X	----	-	-	-	-	----do----------------	
34	Mockingbird Gap (north)---	---do------	33°35'30"	106°25'45"	4	---	X--	X	----	-	-	-	-	----do----------------	
35	Eaton Ranch---------------	---do------	33°37'15"	107°16'	4,5,7	--X	X--	X	-X--	X	F	G	G	Kelley and Furlow (1965).	Remeas., illus.
36	Amphitheater Canyon-------	Sierra-----	33°22'30"	107°06'45"	4,5	---	X--	X	----	-	F	P	P	Kelley and Silver (1952).	Remeas., illus.
37	Fra Cristobal Range (north).	---do------	33°24'45"	107°06'45"	4	---	X--	X	----	-	-	-	-	----do----------------	
38	San Lorenzo---------------	Grant------	32°48'15"	107°57'	4,5,7a, 7b	--X	XX-	X	-X--	-	F	E	P	Jones and others (1967).	Remeas. part.
39	Capitol Dome--------------	Luna-------	32°08'40"	107°39'	4,5,7	--X	XXX	X	-XXX	X	G	G	G	Lochman-Balk (1958)---	Remeas., illus.
40	Cedar Mountain Range------	---do------	32°02'	108°09'15"	7a,7b, 7c	---	---	-	-XX-	-	F	F	G	Bromfield and Wrucke (1961).	Meas.
41	Winston-------------------	Sierra-----	33°21'	107°36'20"	4,5,7	--X	X--	X	-XXX	X	G	F	G	Jahns (1955)----------	Mostly remeas., OF.
42	Robledo Mountain----------	Dona Ana---	32°27'15"	106°55'	7	---	---	-	-XXX	X	F	F	G	Kottlowski (1960a)----	Remeas. part.
43	South Percha Creek--------	Sierra-----	32°53'45"	107°43'30"	4,5,7	--X	X--	X	-XXX	X	P	G	G	Kuellner (1954)-------	Spld.

TABLE 1.—*Data on control points used in compilation of thickness and facies maps*—Continued

Locality (fig. 1)	Locality name	County	Lat N.	Long W.	Stratigraphic units	Ages ABC	Ages DEF	Ages A-F	Ages GHIJ	Ages H-J	Quality	Accessibility	Land Status	References	Remarks
					TEXAS										
44	Hitt Canyon	El Paso	31°59'	106°30'	4,5,7	--X	XXX	X	-XXX	X	E	F	P	Pray (1958), Harbour (1972).	Spld.
45	Scenic Drive	do	31°47'	106°29'	5	---	-XX	-	----	-	G	E	G	Cloud and Barnes (1946); others.	Do.
46	Long Canyon	Hudspeth	31°46'30"	105°59'	7	---	---	-	-XXX	X	G	F	P	Howe (1959)	Do.
47	Baylor Mountains (north)	Culberson	31°14'30"	104°45'15"	6,7	---	---	-	XXX-	X	-	-	-	King (1965)	
48	Beach Mountain	do	31°09'	104°51'	4,5,7	---	XXX	X	-XXX	X	G	E	P	Cloud and Barnes (1946); King (1965).	Do.
50	Point of Mountains	do	31°28'20"	104°51'45"	7	---	---	-	-XX-	X	G	F	P	King (1965)	Do.
52	Baylor Mountains (south)	do	31°11'40"	104°46'	6,7	---	---	-	XXX-	X	G	G	P	do	Mod. th.
56	Pasotex	Hudspeth	31°41'	105°54'	4,5	--X	XXX	X	----	-	F	G	P	This report	Meas.
					ARIZONA										
57	Portal	Cochise	31°56'30"	109°09'	3,5	XXX	XX-	X	----	-	F	G	P	Sabins (1957)	Meas. 3, remeas. unit 5, illus.
58	Blue Mountain	do	32°06'15"	109°12'	3,5	---	XX-	-	----	-	F	G	G	do	Remeas.
59	Apache Pass	do	32°10'	109°26'45"	3,5	XXX	X--	X	----	-	F	G	G	do	Do.
60	Dos Cabezas	do	32°11'20"	109°39'	3,5	XXX	X--	X	----	-	G	G	P	Hayes (1972)	Spld.
61	Pedregosa Mountains	do	31°33'45"	109°24'45"	1,2,5	--X	---	-	----	-	P	P	G	Epis (1958)	Remeas.
63	Leslie Pass	do	31°34'30"	109°30'30"	2c,2d, 5	--X	X--	-	----	-	P	G	P	Epis and Gilbert (1957).	Spld.
64	Northern Swisshelm Mountains.	do	31°43'	109°33'30"	1,2,5	XXX	X--	X	----	-	G	P	P	Epis and Gilbert (1957); Hayes (1972).	Do.
65	Mount Martin	do	31°26'15"	109°56'15"	1,2	XXX	---	X	----	-	F	P	P	Hayes and Landis (1965).	Do.
66	Garden Canyon	do	31°27'45"	110°20'15"	1,2	XX-	---	X	----	-	F	F	R	This report	Meas., desc.
67	Northern Whetstone Mountains.	Pima	31°52'45"	110°27'15"	2	-X-	---	-	----	-	F	P	G	Tyrrell (1957)	Spld.
69	French Joe Canyon	Cochise	31°47'45"	110°23'20"	1,2	XX-	---	X	----	-	G	F	G	Creasey (1967b)	Remeas.
70	Tombstone	do	31°40'15"	110°04'40"	1,2	XX-	---	X	----	-	F	F	G	Gilluly (1956)	Do.
71	Dragoon Mountains	do	31°49'45"	109°56'15"	1,2	XX-	---	X	----	-	P	P	G	do	Spld.
72	Rattlesnake Ridge	do	32°12'20"	110°12'	2	-XX	---	-	----	-	-	-	-	Cooper and Silver (1964).	
74	Johnny Lyon Hills	do	32°06'40"	110°13'15"	2	-XX	---	-	----	-	-	-	-	do	
75	Johnson Peak	do	32°06'45"	110°06'	1,2	XXX	---	X	----	-	E	P	P	do	Remeas. part, illus.
76	Imperial Mountain	Graham	32°56'30"	110°20'15"	3	X--	---	X	----	-	P	P	P	Simons (1964)	Remeas., OF.
77	Nugget Canyon	Pinal	32°31'40"	110°43'15"	1,2	XXX	---	X	----	-	E	F	G	Creasey (1967a)	Remeas., illus.
80	Waterman Mountains	do	32°21'15"	111°28'20"	1,2	X--	---	X	----	-	P	G	G	McClymonds (1959a)	Remeas. part., illus.
81	Slate Mountains	do	32°35'15"	111°54'	1,2	XX-	---	X	----	-	E	E	I	McClymonds (1959b)	Remeas. part, OF.
82	Vekol Mountains	do	32°35'15"	112°06'45"	1,2	X--	---	X	----	-	G	P	I	do	Remeas., illus.
83	American Peak	Santa Cruz	31°25'45"	110°42'30"	1,2	XX-	---	X	----	-	P	E	G	F. S. Simons (written commun., 1973).	Spld.
84	Morenci	Greenlee	33°04'30"	109°18'	3,5,7	-XX	X--	X	-X--	X	G	E	P	Lindgren (1905)	Remeas. part, illus.
					TEXAS										
88	Anthonys Nose	El Paso	31°57'	106°29'45"	4,5,7	--X	XXX	X	-XXX	X	-	-	-	Harbour (1972)	
					NEW MEXICO										
89	North Anthonys Nose	Dona Ana	32°02'30"	106°31'30"	7	---	---	-	-XXX	X	-	-	-	Harbour (1972)	
90	Victorio Mountains	Luna	32°11'	108°05'	7	---	---	-	-XXX	X	P	G	G	Kottlowski, in Griswold (1961).	Spld.
91	Boston Hill	Grant	32°45'45"	108°17'30"	7	---	---	-	-XXX	X	F	G	P	Entwistle (1944)	Do.
					TEXAS										
92	McKelligon Canyon	El Paso	31°50'30"	106°29'30"	4	--X	---	-	----	-	E	E	G	This report	Meas., desc.
93	Sugarloaf	do	31°49'45"	106°28'	7	---	---	-	-XXX	X	F	G	G	do	Meas., OF.

TABLE 1.—*Data on control points used in compilation of thickness and facies maps*—Continued

Locality (fig. 1)	Locality name	County	Lat N.	Long W.	Stratigraphic units	Ages ABC	Ages DEF	Ages A-F	Ages GHIJ	Ages H-J	Quality	Accessibility	Land Status	References	Remarks
NEW MEXICO															
94W	Humble Oil and Refining Huapache 2.	Eddy-------	(sec. 23, T. 23 S., R. 22 E.)		4,5,6, 7.	---	XX-	X	XXXX	X	-	-	-	NMBMMR sample library--	Spls. ex.
98	Northern Animas Mountains-	Hidalgo----	31°53'	108°43'30"	4,5,7	---	---	X	----	-	P	F	G	J. M. Soule (written commun., 1973).	Spld.
ARIZONA															
102	Brandenburg Mountain------	Pinal------	32°55'20"	110°39'	1,2	XXX	---	X	----	-	G	F	I	This report------------	Meas., desc.
NEW MEXICO															
105W	Turner State 1------------	Otero------	(sec. 36, T. 25 S., R. 16 E.)		4,5	---	XX-	X	----	-	-	-	-	NMBMMR sample library--	Spls. ex.
108W	Plymouth Federal 1--------	---do------	(sec. 15, T. 20 S., R. 9 E.)		7	---	---	-	----	X	-	-	-	PBSL log---------------	
110W	Standard Oil of Texas Scarp (Blaize) 1.	---do------	(sec. 18, T. 21 S., R. 18 E.).		4,5,7	---	X--	X	-XXX	X	-	-	-	NMBMMR sample library--	Spls. ex.
111W	Magnolia Petroleum Co. Black Hills 1.	Chaves-----	(sec. 31, T. 17 S., R. 21 E.).		4,5,7	---	---	X	----	X	-	-	-	Roswell Geol. Soc. (1952).	
112W	Standard Oil of Texas 1 State E6584.	Eddy-------	(sec. 16, T. 21 S., R. 22 E.).		4,5,7	---	---	X	----	X	-	-	-	Roswell Geol. Soc. (1957).	
113W	Southern Prod. Co. et al., Cloudcroft 1 (Swank).	Otero------	(sec. 5, T 17 S., R. 12 E.).		4,5,7	---	---	X	----	X	-	-	-	Roswell Geol. Soc. (unpub.).	
114W	Southern Prod. Co. Elliott 1.	Eddy-------	(sec. 24, T. 18 S., R. 23 E.).		4,5,7	---	---	X	----	X	-	-	-	----do-----------------	
116W	Sun Oil Co. Victorio 1----	Sierra-----	(sec. 25, T. 10 S., R. 1 W.).		4,5,7	---	---	X	----	X	-	-	-	Kottlowski (1963)------	
117W	Sunray-Midcontinent Oil Co. Federal 1-M.	---do------	(sec. 23, T. 15 S., R. 2 W.).		7	---	---	-	----	X	-	-	-	----do-----------------	
119W	Turner Everett 1----------	Otero------	(sec. 34, T. 22 S., R. 10 E.).		7	---	---	-	----	X	-	-	-	----do-----------------	
120W	Turner Evans 1------------	---do------	(sec. 22, T. 24 S., R. 12 E.).		7	---	---	-	----	X	-	-	-	----do-----------------	
TEXAS															
121W	Magnolia Oil Co. 1-39881--	Hudspeth---	(sec. 36, Blk. 70 Univ. Lands).		7	---	---	-	----	X	-	-	-	Kottlowski (1963)------	
122W	California Co. University-Theissen 1..	---do------	(sec. 24, Blk. E, Univ. Lands).		4,5,7	---	---	X	----	X	-	-	-	----do-----------------	
123W	Jones Sorley 1------------	El Paso----	(sec. 17, Blk. 5, PSL Survey).		4,5	---	---	X	----	-	-	-	-	----do-----------------	
129W	General Crude Merrill and Voyles 1.	Hudspeth---	(sec. 8, Blk. 69, T-2).		4,5	---	---	X	----	-	-	-	-	PBSL log---------------	
135W	Gulf Oil Corp. I-J Burner-State "B."	---do------	(sec. 14, Blk. 19, PSL Survey).		4,5,7	---	---	X	----	X	-	-	-	USGS records-----------	
ARIZONA															
150	Nantac Rim----------------	Graham-----	33°13'	109°40'45"	3,5	XXX	X--	X	----	-	G	F	I	Hayes (1972)-----------	Spld.,desc.
151	Coolidge Dam--------------	Pinal------	33°10'30"	110°31'20"	3	X--	---	X	----	-	G	E	I	This report------------	Meas.
154	Superior------------------	---do------	33°18'30"	111°06'	2	XX-	---	X	----	-	F	G	P	Peterson (1969)--------	Spld., mod. strat.
158	Eagle Peak----------------	Cochise----	32°09'45"	110°25'15"	1,2	-XX	---	-	----	-	P	P	G	F. W. Plut (written commun., 1973).	Spld.
160	Picacho de Calera---------	Pima-------	32°21'20"	111°11'45"	1,2	---	---	X	----	-	P	G	P	Bryant (1952)----------	Do.
162	Barlow Pass---------------	Graham-----	33°16'30"	109°45'30"	4	--X	---	-	----	-	F	F	I	This report------------	Meas.

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