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PETROGRAPHY OF MORRISON FORMATION (JURASSIC) SANDSTONE OF THE OJITO SPRING QUADRANGLE, SANDOVAL COUNTY, NEW MEXICO

by
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ABSTRACT

A petrographic study of Morrison Formation (Jurassic) sandstone units in the Ojito Spring Quadrangle, Sandoval County, New Mexico, resulted in delineation of detrital and diagenetic rock components and interpretation of source area rock types and the origin and timing of diagenetic alterations. The Morrison Formation in the area consists of subequal amounts of continental deposited sandstones and intertongued and interbedded claystone. Sandstone units are prevalent throughout the section in every member of the Morrison; i.e., Recapture Shale, Westwater Canyon Sandstone, Brushy Basin Shale and "Jackpile Sandstone" (from the base upward).

Detrital components of Morrison Formation sandstones include framework constituents (67 to 77%), matrix-cement (9 to 31%) and pore spaces (1 to 20%). The generalized mineralogical composition consists of, in order of their abundance, mon ocrystalline quartz, plagioclase, potassium feldspar, igneous and volcanic rock fragments, and minor to trace amounts of polycrystalline quartz, chert, clay clasts, heavy minerals, mica, metamorphic rock fragments, and glauconite. Classification of the mineralogic composition with descriptive adjectives yields the rock name fine to medium-coarse grained, moderately to moderately-well sorted, subarkosic to arkosic arenite.

The distribution of rock components, including framework grains, matrix-cement, and pore spaces varies between and within the sandstone units, however, certain characteristics are unique to the units. Recapture sandstones generally exhibit well developed clay films; Westwater Canyon sandstones are highly variable; Brushy Basin samples generally have more feldspar and include chalcedony cement; and "Jackpile" sandstones have a higher percentage of kaolinite and quartz framework grains.

Interpretation of rocks present in the source area(s) of the Morrison Formation is based upon the composition of rock fragments and framework grains (presumed first-cycle and reworked grains) present in Morrison sandstone units. The source area(s) included acidic igneous (granite, quartz monzonite and possibly granodiorite porphyries), and volcanic rocks (air fall and ash flow tuffs, rhyolites, andesites and quartz latites) with important minor sedimentary rocks (chert, quartz arenites and unknowns) and locally metamorphic rocks (quartz-muscovite schists, gneisses?). Probable source areas have been designated by previous investigators as the Mogollon Highlands in southwestern New Mexico and locally an area in west-central New Mexico, south of Gallup.

The Morrison Formation of the Ojito Spring Quadrangle has experienced an involved sequence of diagenetic alterations. Alterations considered typical of most sandstones in the Morrison Formation are (in order of decreasing age and ignoring overlapping): feldspar overgrowths, smectite or smectite-illite grain coatings, quartz overgrowths, calcite cement, feldspar dissolution, and kaolinite infill. The sequence and distribution of these alterations is related to the detrital composition, unit lithologies, stratigraphic relationships, and burial history of the Morrison Formation.

INTRODUCTION

This article is an outgrowth of a petrographic study of Morrison on sandstone units present in the Ojito Spring 71/2-minute Quadrangle, Sandoval County, New Mexico, undertaken by Flesch as part of a M.S. thesis project, which is nearing completion for the University of New Mexco.

The principal objectives of this investigation are: 1) to describe the detrital and diagenetic components of Morrison Formation sandstone units, 2) to briefly mention the study procedures used to derive data, and 3) to utilize these findings to interpret source rocks and the origin and timing of diagenetic events. In addition, several representative subsurface samples from a Westwater Canyon core located near the study area were studied and compared to surface samples to determine if near-surface weathering had affected the Morrison sandstones.

Acknowledgments

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X-ray diffraction sample preparation and analysis was done by Moon Lee of the University of New Mexico for the senior author. Bill Fugate of Cities Service Oil Company independently analyzed all the samples for the co-author. Allan White of CITGO operated the Scanning Electron Microscope.

The Scanning Electron Microscope (SEM) with X-ray energy spectrometer attachment was made available through the courtesy of the Exploration and Production Research Laboratory, Cities Service Oil Company. Adrienne Skaggs and Avonelle Chitwood of CITGO typed the manuscript.

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Area Location and General Description

The area of investigation comprises the Ojito Spring $7^1/_2$-minute quadrangle, located west of San Ysidro in Sandoval County, New Mexico (Fig. 1). The area lies immediately to the southwest of the Sierra Nacimiento uplift in the southeastern-most portion of the San Juan Basin.

Rugged mesas capped by resistant sandstone and gypsum ledges, and broad claystone valleys dissected by arroyos typify the Mesozoic outcrops in the area. Mesozoic units present include the Triassic Chinle Formation, the Jurassic Entrada, Todilto, Summerville and Morrison Formations, and the Upper Cretaceous Dakota and Mancos Formations. The Dakota unconformably overlies the Morrison in the study area.

Within the study area, a complete section of the Morrison Formation is well exposed and outcrops are laterally continuous, having no structural deformation. The Mesozoic strata in the study area form a homoclinal sequence dipping southwestward at approximately 3 to 5 degrees away from the Sierra Nacimientos.

Procedures

Methods of investigation include the examination of thin sections with a polarizing microscope, X-ray diffraction identification of the <2μ size fraction, Scanning Electron Microscopy (SEM) of aggregate samples, and elemental analysis of rock components viewed with the SEM using an X-ray energy spectrometer attachment.

A total of 74 thin sections was studied, including the Recapture (11), Westwater Canyon (35), Brushy Basin (6), and the "Jackpile" (22). Representative samples (19), <2 micron size, were examined to identify clay mineral types present within the sandstone units. Both unglycolated and glycolated patterns were run. Representative samples (15) from Morrison sandstones were examined with the SEM to identify overgrowths, authigenic clay minerals and feldspar alteration. The X-ray energy spectrometer attachment to the SEM aided in determining the elemental composition of authigcnic and detrital components.

GENERAL MORRISON STRATIGRAPHY AND SEDIMENTO LOGY

Within the Ojito Spring Quadrangle the Morrison Formation includes (in ascending order) the Recapture Shale Member, Westwater Canyon Sandstone, Brushy Basin Shale Members and the "Jackpile Sandstone" (of economic usage) (Fig. 1). The Morrison is predominantly sandstone (54.5% of total average thickness). Much of the remainder is claystone (45%) with thin carbonate beds being only a very minor component (0.5%). Sandstone units form the bulk of the Westwater Canyon (96% of total average thickness) and "Jackpile" (96%) and are important in the Recapture (46%) and Brushy Basin (29%).

In outcrop, the Morrison Formation consists of maroon-brown, orange-red, red-brown and gray-green montmorillonitic claystones and yellow-gray, pale yellow-orange or light brown, fine to medium-coarse grained sandstones (white-yellow or -gray for the "Jackpile"). Recapture sandstones are generally finer grained and Brushy Basin sandstones are relatively coarser grained than the fine- to medium- and occasionally coarse-grained sandstone of the Westwater Canyon and "Jackpile". The sandstones of the Westwater Canyon, Brushy Basin

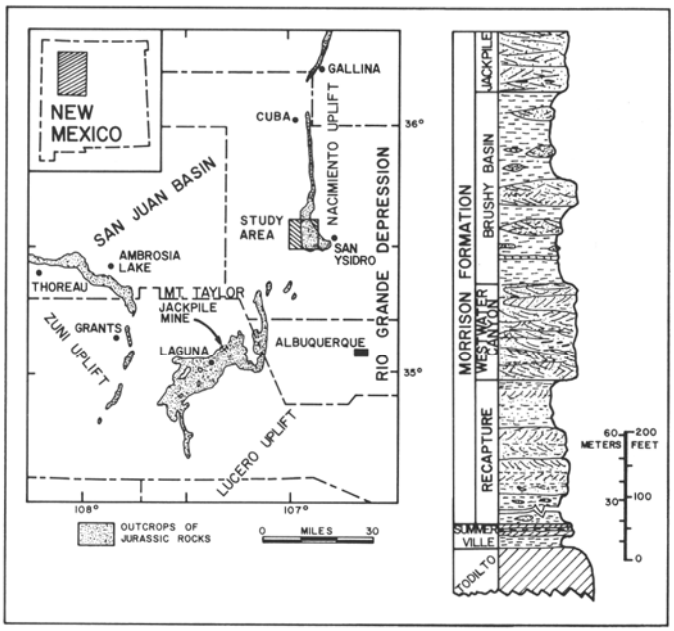


Figure 1. Location map (modified from Woodward and Schumacher, 1973) and composite, representative stratigraphic column of the Morrison Formation, Ojito Spring 7½-minute Quadrangle, Sandoval County, New Mexico.

and "Jackpile" are more resistant than those of the Recapture and form near vertical cliffs or steep ledges.

Morrison sandstones are highly cross-bedded, with medium-scale troughs and wedge sets especially well developed in the Westwater Canyon, "Jackpile" and thick Brushy Basin sandstone units. The overall geometry of Morrison sandstone units varies: Recapture sandstones form both continuous, with subequal thicknesses, and discontinuous lenses; those of the Westwater Canyon are continuous, with subequal unit thicknesses and with some lensing of lower and upper sandstone units in the northern half of the study area; Brushy Basin sandstones are laterally discontinuous lenses; and those of the "Jackpile" are of unequal thickness but are laterally continous.

Interpretation of depositional environments of the Morrison Formation sandstone units within the study is possible using unit geometry, sedimentary structures and lithologies (see Flesch, this Guidebook). The Westwater Canyon and "Jackpile" members are believed to have been deposited within braided-stream complexes; the Recapture Member was deposited by braided and/or low sinuosity meandering streams and the Brushy Basin by highly meandering streams.

DETRITAL COMPONENTS

General Description

Morrison Formation sandstones can be subdivided into three basic categories: framework constituents (67 to 77 percent), matrix-cement (9 to 31 percent) and pore spaces (1 to 20 percent). Framework constituents are constant for all the samples studied, although their relative abundance varies with-in and between members. The generalized mineralogical composition of Morrison sandstones is listed in Table 1. Similar detrital components for Morrison sandstones have been previously observed by Knox and Gruner (1965) and Cadigan

Table 1. Mineralogic Composition, Morrison Formation Sandstones Ojito Spring Quadrangle, New Mexico

ROCK COMPONENTS	PERCENTAGES		COMMENTS
	Total	Subtotals	
Framework:	67-77		
Quartz		55-80	Contain abundant vacuoles and mineral inclusions
Monocrystalline		55-77	
Polycrystalline		1-3	Some crenulated grain boundaries
Feldspar		12-36	Potash and sodic varieties
K Feldspar		7-17	Microcline, orthoclase and sanidine
Plagioclase		5-22	An_{0-30}; commonly seritized (includes altered varieties)
Rock Fragments		5-15	Fresh and altered fragments
Volcanic		1-6	Contain crystal laths; sometimes glassy
Igneous		2-10	Phaneritic groundmass, acidic varieties
Metamorphic		Trace	Quartz-muscovite schist
Clay		1-3	Occurs as galls and pebbles
Chert		1-2	Fine-grained variety common
Heavy Minerals		Trace	Opaques predominate
Mica		Trace	Biotite and muscovite; deformed
Glauconite		Trace	Subsurface samples only, pelletal
Matrix-Cement	9-31		Owes origin to diagenesis
Clays (undifferentiated)			Grain coating and pore filling varieties
Silica			Overgrowths and chalcedony cement
Carbonate			Irregular distribution; sparry
Pore Spaces	1-20		Inter- and intra-particle

(Generalized table based on ≥300 point counts per slide for 74 thin-sections)

(1967). In order of their relative abundance, major constituents are: monocrystalline quartz, plagioclase, potassium feldspar, igneous and volcanic rock fragments. Minor constituents consist of: polycrystalline quartz, chert, clay clasts, heavy minerals, mica, and metamorphic rock fragments. Trace amounts of glauconite are present in several subsurface samples.

Matrix-cement and pore space have an obvious inverse relationship and are also important rock components. Interesting variations occur within and between sandstone units depending upon the amount and type of cementation and degree of diagenetic alteration (i.e., formation of secondary clays, feldspar leaching, and overgrowths). These variations will be discussed in considerable detail below under the heading "diagenetic components."

Quartz is predominantly monocrystalline with minor amounts of the polycrystalline varieties (Fig. 2D), including normal and crenulated grain boundaries. Grains contain abundant mineral vacuoles and inclusions and are occasionally strained. Quartz overgrowths and clay films commonly coat the grains (Figs. 2A, B, C, D, E, and 3 E).

Feldspar consists of nearly equal amounts of plagioclase and potash feldspar; occasionally feldspar intergrowths (i.e., perthite and antiperthite) occur. Plagioclase grains exhibit albite and Carlsbad twinning, occasionally have perthitic textures or zonation, and commonly are altering to clay (Figs. 2A and F). Plagioclase feldspars consist of the sodium-rich albite and oligoclase varieties (An_{0-30}), as determined by measuring twin extinction angles. Potash feldspar varieties include, in the order of their abundance, microcline, orthoclase and sanidine. Microcline is typified by "gridiron" twinning. Orthoclase exhibits Carlsbad twinning and is difficult to distinguish from sanidine unless a larger axial angle can be determined. Feldspar overgrowths (potassium-rich) commonly coat the grains (Fig. 2A). Sanidine is characterized in thin-section by a low 2v angle, lack of twinning or presence of Carlsbad twins, and lack of inclusions or alteration products. Leached feldspar grains present may be sanidine.

Rock fragments are important detrital constituents, consisting of igneous, volcanic and (rarely) metamorphic varieties. Igneous rock fragments are most abundant and have a phaneritic groundmass and contain phenocrysts of quartz, feldspar and mica. Volcanic fragments consist of quartz and elongate prismatic laths of feldspar and mica in an altered aphanitic groundmass. Occasionally small openings exist within the grain, suggesting that pumice or glass may have once occupied that space. Trace amounts of quartz-muscovite schist fragments are also present.

Clay galls and pebbles, 1-5 mm in size, are present in minor amounts and are generally concentrated along cross-bedding planes or near the base of a sandstone unit. Fine-grained chert is a minor component, and occasionally coarse-grained or silty chert is present. Heavy minerals occur in trace amounts, consisting mainly of limonite, hematite, pyrite (confined to

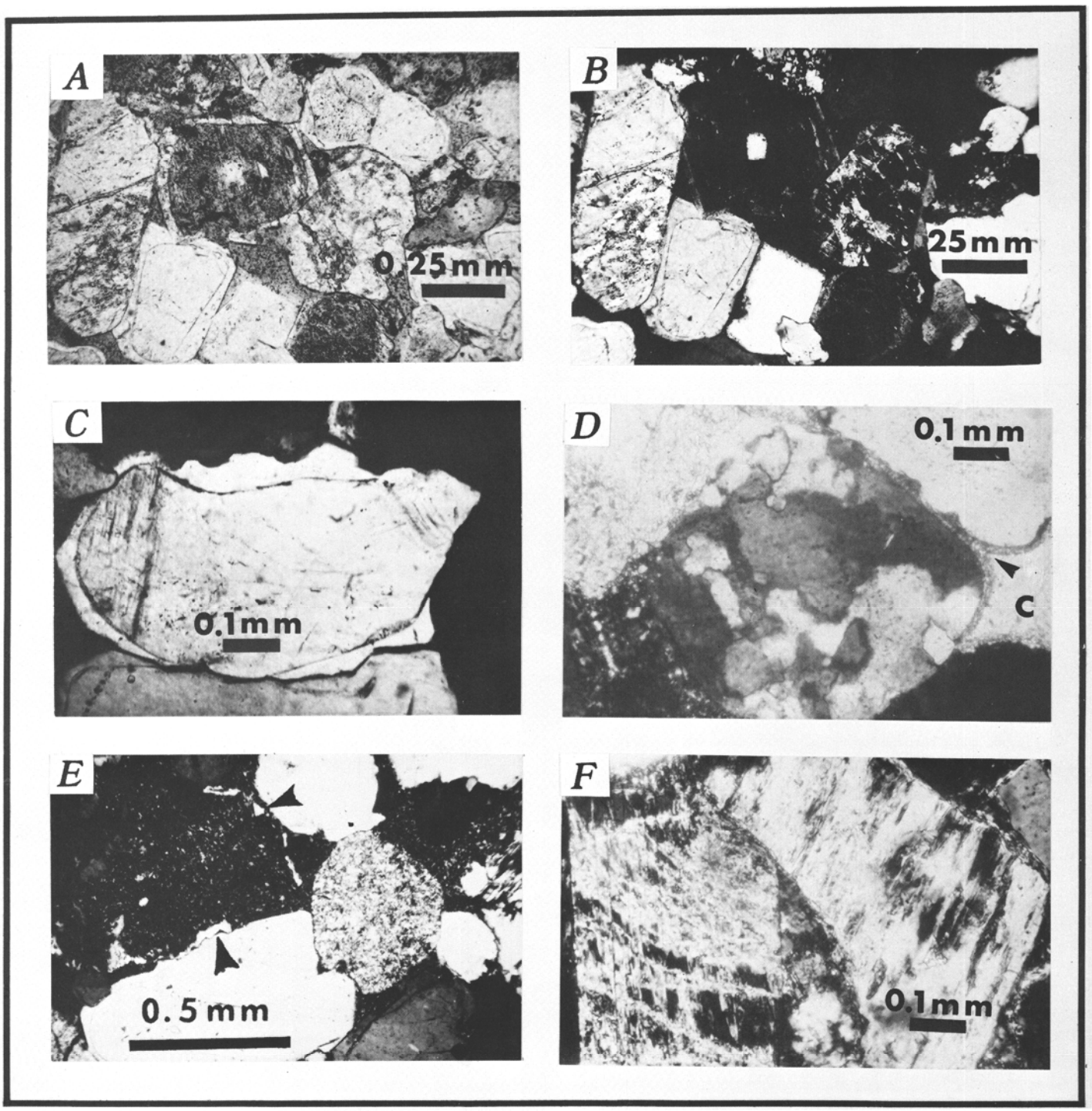


Figure 2. Thin section photo micrographs of sandstones of the Westwater Canyon Sandstone Member, Morrison Formation: **A,** *Subarkosic arenite—feldspar grains with leached cores but well preserved overgrowths; well developed quartz overgrowths, long and convaco-convex grain contacts, plain light;* **B,** *Subarkosic arenite—crossed nicols;* **C,** *Monocrystalline quartz grain with strain lamellae which do not cross overgrowth;* **D,** *Polycrystalline quartz grain with normal grain boundaries, arrow indicates thin chlorite clay film and C is calcite cement, (subsurface, Valencia County);* **E,** *Partially leached feldspar with kaolinite infilling, quartz grains with well developed overgrowths;* **F,** *Fractured and altered plagioclase grains exhibiting albite and Carlsbad twinning, indistinct clay films coating grains, crossed nicols (subsurface, Valencia County).*

the subsurface samples), and zircon. Mica, biotite and some muscovite occur in trace amounts in all samples and may be deformed between larger framework grains. Glauconite was observed in trace amounts in the subsurface samples only, occurring as green to olive-green pellets.

Combining the percentages of plagioclase, potassium feldspar and authigenic clay exhibiting relict twinning gives a feldspar content of between 12 and 36 percent. Combining the percentages of igneous, volcanic and metamorphic rock fragments gives a lithic content of between 5 and 15 percent.

Following the rock classification proposed by Pettijohn, Potter and Siever (1972), the rock name of subarkosic to arkosic arenite is established for Morrison Formation sandstones. Adding descriptive adjectives regarding grain adjectives regarding grain size and sorting yields the final rock name: fine- to medium-coarse grained, moderately- to moderately-well sorted, subarkosic to arkosic arenite.

Sandstone fabric (grain to grain relations) varies for the units, but generally long contacts, concavo-convex contacts and point contacts between grains are most common, sutured grains occur infrequently, and floating grains occur only when there is abundant carbonate cement (see figs. 3-10 of Pettijohn, Potter and Siever, 1972).

The shape of framework grains varies within and between sandstone units and is in some cases dependent upon mineralogy. Generally grains are subequant and subrounded, however, rounded grains (quartz) occur commonly and are locally abundant and subangular grains (usually feldspar, occasionally rock fragments) are also present.

Stratigraphic Distribution

Recapture Shale Member

Recapture sandstone exhibits variations in the rock components and framework grain percentages but generally to a lesser extent than Westwater Canyon and Brushy Basin sandstone units. Quartz (60-75%) feldspar (20-26%) and rock fragments (5-8%) are the main framework constituents and matrix-cement (10-20%) is predominantly composed of prominent clay films. Porosity varies from 5-20% of the total sample.

Westwater Canyon Sandstone Member

A wide range in rock components exist, generally including framework constituents of quartz (55-70%), feldspar (20-34%) and rock fragments (5-15%), and matrix-cement (9-30%) and pore spaces (1-20%). Feldspar content commonly increases in coarser grained samples. Pyrite generally is present in trace amounts in surface and subsurface samples and glauconite is present in trace amounts in the subsurface. Details of the matrix-cement components will be discussed below under "Diagenesis."

Brushy Basin Shale Member

Sandstones commonly include less quartz (55-65%) and more feldspar (25-30%) than the other units and have highly varying amounts of matrix-cement (including chalcedony). Chert pebbles may be abundant locally.

"Jackpile Sandstone" Member

"Jackpile" sandstones contain a higher percentage of quartz (65 to 80%) and correspondently slightly less feldspar (15-26%); igneous rock fragments may be slightly less common. Kaolinite is a very common matrix-cement constituent, while calcite cement occurs less frequently than in previous units.

Source of Detrital Components

Morrison Formation sandstone units are submature, as indicated by their composition (subarkosic to arkosic arenites) and texture (fine to coarse grained, subangular to rounded shape and moderate to moderately-well sorting). The maturity has been influenced by the specific depositional environment of the sandstone unit (i.e., braided stream versus highly meandering stream); however, the submaturity of the sandstones along with mineral composition does give us information concerning the sediment source area(s).

Two basic sediment populations are seen to exist based upon grain shape and to a lesser extent texture. The most important population volumetrically is composed of subrounded and subangular grains, believed to be the result of first cycle erosion and transport, (the grain shape being influenced by mineralogy). Rounded grains comprise the subordinate population and probably represent reworked sedimentary and/or unconsolidated older sediments.

Rock fragments and framework grains are useful in hypothesizing the rock make-up of the source area(s) of these rocks (Folk, 1968). Caution must be exercised, however. An attempt should be made also to recognize diagenetic alterations of the original constituents and to obtain a detailed regional understanding of directional sedimentary features and the mineralogy of Morrison Formation sandstone units and associated older and younger Mesozoic formations. Therefore, the following conclusions can only be considered tentative and generalized. References from previous workers dealing in more detail with this subject include Craig (1955), Stewart and others (1972), and Cadigan (1967).

The source area(s) for Morrison Formation sandstone units consisted of predominantly igneous and volcanic rocks with minor amounts of sedimentary rocks and very minor amounts (volumetrically) of metamorphic rocks.

Acidic igneous rocks were common in the source area(s) and supplied rock fragments, feldspar, mica, opaques, and quartz to the sandstone units. Compositionally, granite and quartz monzonite porphyries and possibly granod iorite porphyry were present. This range reflects the uncertainty in using the present nearly equal percentage of potash feldspars and plagioclase to indicate a specific igneous rock-type.

Volcanics are an important source of detrital material (i.e., rock fragments, sanidine and zoned plagioclase) for the sandstone units and volcanic ash and glass (altering to montmorillonite) is believed to be the main constituents of Morrison Formation claystones. Air fall and ash flow tuffs, rhyolites, andesites and possibly quartz latites could all have been present in the source area(s). Further work in delineating the possible percentages of occurrences for volcanic constituents would prove very informative.

Sedimentary rocks present in the source area(s) include chert, possibly quartz arenites and probably many other unstable rock types of which there is no record. The trace of glauconite pellets present in the subsurface samples probably was a minor constituent of an unknown sedimentary rock. Locally, in west-central New Mexico, Saucier (1967) and Dodge (1973) have found abundant chert pebbles in the Westwater Canyon, indicating locally important quantities of chert in the source area.

Quartz-muscovite schist and possibly other metamorphic rocks (as indicated by polycrystalline quartz) were exposed locally within the source area(s).

Regional workers, including Craig (1955), Stewart and others (1972), and Cadigan (1967) have previously designated the probable source area of the Morrison Formation in New Mexico as the Mogollon Highlands, in southwestern New Mexico, and an area in west-central New Mexico, south of Gallup, as a more local source.

DIAGENETIC ALTERATIONS

Types

Diagenetic alterations are defined as those physical and chemical changes which affect a sediment subsequent to deposition. The criteria used to distinguish materials produced by diagenetic processes include (1) delicate external and internal morphologies which preclude sedimentary transport, (2) spatial relationships of detrital or diagenetic components indicating an origin which post-dates deposition or an earlier diagenetic stage, (3) compositions which differ radically from similar materials of detrital origin, and (4) textures which are unlikely to have been produced by depositional processes.

The primary criterion used to determine the relative timing of diagenetic alterations is based on the assumption that pores fill inward. If a sequence of materials lines a pore, that material closest to the detrital grains is assumed to be the oldest and the material in the center of the pore is the youngest. It is also assumed that a cement will tend to fill or line all types of available pores (with the exception of cements requiring a nucleus of similar structure or composition upon which they can develop). Thus if cavities in partially dissolved grains are not lined or filled with cementing agents present in the rock, these cavities post-date the cements.

A large number of diagenetic alterations have affected the Morrison Formation in the Ojito Spring Quadrangle. Most of the alterations observed also have been described by Austin (1963) and Cadigan (1967). The most common diagenetic alterations involve cementation by grain coatings (smectite, mixed-layer smectite-illite, chlorite, chalcedony), overgrowths (quartz, feldspar), or pore fillings (calcite, kaolinite) and dissolution of detrital grains (feldspars). Many of these features are shown in Figures 3, A-F. Volumetrically unimportant are such alterations as precipitation of grain-coating cliachite, gibbsite, pyrite, and anatase(?) and replacement of pyrite and iron-rich materials by hematite and limonite.

Smectite (montmorillonite?) and mixed-layer smectite-illite occur as 1-10 micron thick detrital grain coatings which exhibit a bright yellow biefringence in thin section (Figs. 3 E, F). When well developed, smectite has a honeycomblike structure as seen in SEM micrographs (Fig. 4A). Mixed-layer coatings are more sheet-like in character, although the edges of individival flakes often curl up at high angles to the detrital grain surfaces. Chlorite forms pseudohexagonal flakes aligned at high angles to the detrital grain surface in an edge-to-face (often referred to as cardhouse) structure (Fig. 4B). These clay coatings are covered by almost all other diagenetic components but in a few samples were observed to cover quartz overgrowths.

Kaolinite occurs as well-formed books distributed in irregular clots up to several centimeters in diameter (Fig. 4C). It is possible that some or all of these books are dickite, a polytype of kaolinite. Kaolinite books fill pores and leached feldspars and cover all other diagenetic materials except hematite and limonite.

Quartz overgrowths form prismatic and bipyramidal projections a few microns (Fig. 2B) to several hundred microns across (Fig. 4D). Overgrowths cover clay coatings and, in turn, are covered by all other diagenetic phases.

Very coarse spar calcite (often poikilitic) is present both as sporadic patches a few millimeters to a centimeter in diameter and as complete pore fillings. Calcite covers quartz overgrowths (Fig. 4E) and often occurs within feldspar grains.

Sanidine and zoned plagioclase feldspars often are partially dissolved while microcline and orthoclase generally are unaffected. Paritally sericitized palioclase grains, many of which occur in granitic rock fragments, seldom are leached. In thin section and SEM micrographs the dissolved grains appear as skeletal relicts of the original grains (Fig. 4F). Occasionally kaolinitc, anatase(?), and pyrite (often altered to hematite) are found within dissolved feldspars.

Chalcedony cement occurs as concentrically banded pore linings with radial fibrous structure (Fig. 3C). The chalcedony is formed of small well developed quartz crystals whose alignment varies slightly (Fig. 5A). Chalcedony covers both clay coatings and quartz overgrowths.

Overgrowths on potash feldspars are observed occasionally, particularly in association with quartz overgrowths. Elemental analysis with an x-ray energy spectrometer indicates these overgrowths are relatively pure potash feldspar (adularia?). Occasionally plagioclase overgrowths on plagioclase are observed. The potash feldspar overgrowths appear tooth-like in thin section and rhombohedral in SEM micrographs (Fig. 5B). Generally feldspar overgrowths are covered at least partially by clay coatings.

Tabular crystals of anatase (? tentatively, identified by its crystal habit and composition) are present in trace amounts in almost all samples (Fig. 5D). In thin section it appears as clusters of small (5-50 microns across) yellowish crystals with rectangular outlines. It occurs on the surfaces of detrital grains and overgrowths and within partially dissolved feldspars. It is coated by kaolinite.

Pyrite occurs as masses of interlocking cubes or octahedrons which fill pores and partially dissolved feldspar grains. It is primarily observed in subsurface samples; surface samples contain only trace amounts. Hematite pseudomorphous after pyrite is common in many surface samples (Fig. 5C).

In thin section cliachite, an amorphous aluminum hydroxide, forms brownish botryoidal or hemispherical masses which cover quartz overgrowths. It is found in only one sample in association with gibbsite. In SEM micrographs its morphology can best be compared to a carnation with ruffled petals (Fig. 5E).

Gibbsite occurs as microcrystalline pore linings which resemble chert in thin section. In SEM micrographs it occurs as irregular masses of slightly elongate crystals 1-2 microns in length (Fig. 5F). It generally coats cliachite and is transitional into kaolinite.

Stratigraphic Distribution

Recapture Shale Member

Sandstones in this unit are characterized by the presence of thin (1-10 microns) smectite or mixed-layer smectite-illite grain coatings. (Fig. 6A) and the absence of significant amounts of quartz and feldspar overgrowths or kaolinite pore fill. Coarse spar calcite cement is absent in many samples and present in trace to large amounts in others. Partially dissolved feldspars are present only in trace to minor amounts. Suturing of detrital grains is occasionally observed at points of grain-to-grain contact where diagenetic clay is present. The sequence of alterations considered typical of each of the members of the Morrison Formation in the study area is presented in Table 2.

Westwater Canyon Sandstone Member

Sandstones in this unit are generally indistinguishable from sandstones in the Recapture Shale Member. However, a few

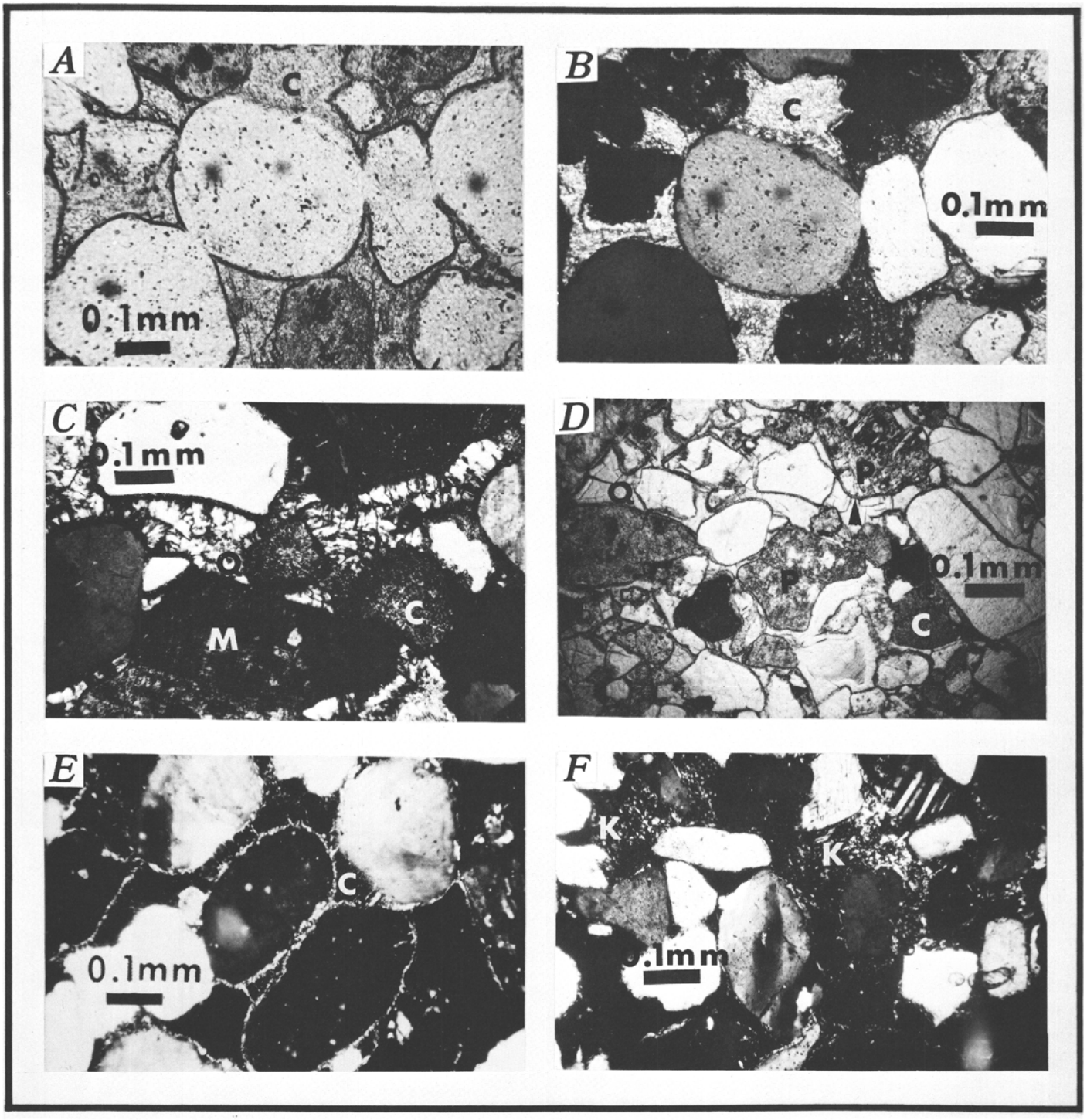


Figure 3. Thin section photomicrographs of Morrison Formation sandstones: **A,** *Point-to-point grain fabric with clay coatings missing at grain contacts, (C) nearly complete calcite cementation of pores, plain light, Westwater Canyon Member, subsurface, Valencia County;* **B,** *Crossed nicols of photograph A, (K) infilling of kaolinite which appears in this case to have been formed prior to calcite cementation, Westwater Canyon Member, subsurface, Valencia County;* **C,** *(Q) Chalcedony cement (probably was originally opal) with thin clay films below, (M) microcline and (C) chert grains, Brushy Basin Member, Ojito Spring Quadrangle;* **D,** *(Q) Chalcedony cemented subarkosic arenite, (P) partially altered plagioclase grains, a (C) chert grain and (arrow) well developed clay films, Westwater Canyon Member, Ojito Spring Quadrangle;* **E,** *Photograph emphasizing bridging clay films (C) common to the Recapture, montmorillonitic (honeycomb) clay, Recapture Member, Ojito Spring Quadrangle;* **F,** *Subarkosic arenite with indistinct complete clay films (having high birefringence) and abundant kaolinite pore filling (K), "Jackpile Sandstone", Ojito Spring Quadrangle.*

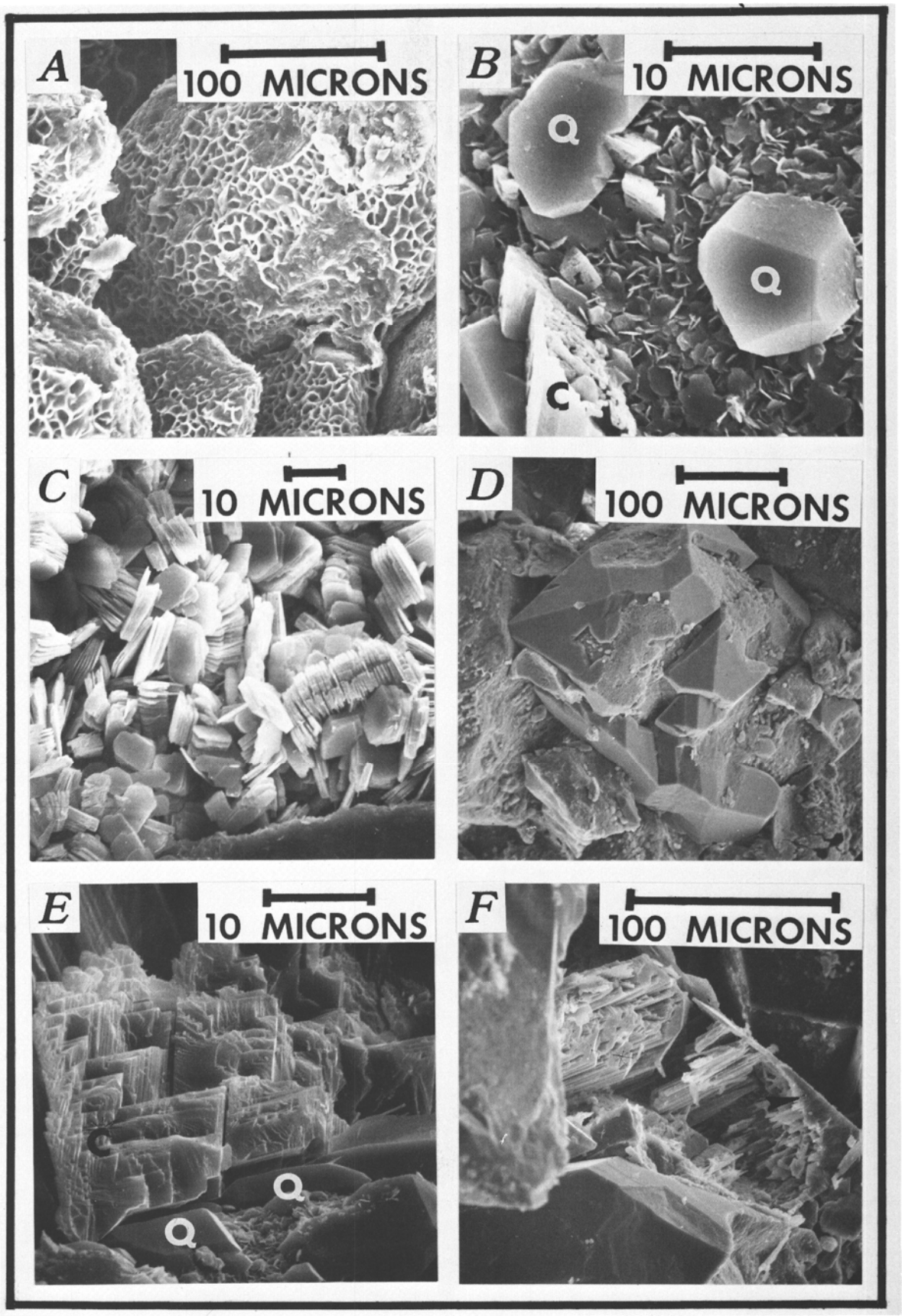

A
100 MICRONS
B
10 MICRONS
Q
Q
C
C
10 MICRONS
D
100 MICRONS
E
10 MICRONS
C
Q
Q
F
100 MICRONS

Figure 4.

thin (1-20 ft) zones exhibit more extensive quartz and feldspar overgrowth development (Fig. 6B) and corresponding reduction in the abundance of smectitc or mixed-layer grain coatings. Kaolinite is often abundant, but no pattern to its distribution was noted. Trace to abundant coarse spar calcite cement is distributed irregularly both vertically and laterally.

Pore filling chalcedony is common in the somewhat coarser grained basal beds and at the very top of the unit. The chalcedony is probably an alteration product of opal.

Well samples from the Westwater Canyon Member about 25 miles from the Ojito Spring quadrangle generally resemble the sandstones in this unit in the study area with the exception that the grain coating clay commonly is chlorite rather than a swelling clay. Trace amounts of glauconite pellets also are present in subsurface samples.

Brushy Basin Shale Member

Sandstones in this unit tend to be tightly cemented by chalcedony (Fig. 6C) or poikilitic spar calcite. Smectite or mixed-layer clay grain coatings and thin quartz overgrowths are usually present beneath these cements. If cementation by chalcedony or calcite is extensive, kaolinite is generally minimal or lacking.

"Jackpile Sandstone" Member

The sandstones of the "Jackpile" are very similar to those in the Recapture Shale Member. However, as in the Westwater Canyon Sandstone Member, zones up to 20 feet thick occur in which quartz and feldspar overgrowth development is more advanced. Kaolinite is more abundant than in the lower three members (Fig. 6D). Calcite was noted in only the basal few feet of the "Jackpile". One sample associated with abundant carbonaceous material contains minor amounts of gibbsite, cliachite, and kaolinite.

Timing and Origin of Diagenetic Alterations

A chart summarizing the chronologic sequence of diagenetic alterations in sandstones of the Morrison Formation is shown in Figure 7. This chart is based on a combination of petrographic and scanning electron microscope analysis.

The sequence of diagenetic alterations in the Morrison Formation, with the exception of the Brushy Basin Shale Member, proceeds from components requiring relatively silica-rich pore waters (feldspar overgrowths, clays) to those (quartz overgrowths, kaolinite) in equilibrium with pore waters relatively depleted in silica (see phase equilibria diagrams of Hess, 1966, Helgeson, Garrells, and Mackenzie, 1969, Curtis and Spears, 1971).

Enrichment of the pore water sufficient to initiate the diagenetic alterations observed can be accomplished in several ways. Although feldspar dissolution is an acceptable source, the timing of this dissolution is too late to provide materials for components formed during the early stages of diagenesis. Alternative sources in the Morrison Formation are dissolution of volcanic glass and rock fragments and dissolution of unstable heavy minerals. Though unstable heavy minerals such as pyroxenes, amphiboles, ilmenite, and magnetite are sparse or lacking in the Morrison Formation, it is likely at least some of these were present at the time of deposition (Austin, 1963, p. 41). However, their abundance is not expected to have been adequate to provide the necessary volume of silica, alumina and other cations.

Quantitatively volcanic rock fragments provide a more adequate source. These fragments, up to 6 percent of Morrison sandstones, are known to have been present at the time of deposition. Additional volcanic rock fragments, especially glass-rich varieties, also may have been eliminated during prolonged diagenesis. Dissolution of both unstable heavy minerals and volcanic rock fragments would certainly be more than adequate to account for the volume of diagenetic components (excluding kaolinite) in most samples.

The antithetical relationship between clay grain coatings and quartz overgrowths is related to the degree of which clay coatings coat the detrital grains. Where clay coatings are complete they prevent the nucleation of quartz overgrowths on detrital quartz grains. If the clays films are incomplete the overgrowths can develop on the exposed detrital grain surfaces and expand out over the adjacent clay. The best developed clay coatings probably occur in those beds in which unstable detrital grains (volcanic rock fragments, amphiboles, etc.) were most abundant.

Pressure solution (suturing) is not sufficiently extensive to serve as an adequate source of cements and void filling material. Also, suturing appears to have occurred only after diagenetic clay coatings were formed and rotated into zones of grain contact by compaction. Suturing is likely to have generated minor amounts of silica at the time when the Morrison was most deeply buried (middle Tertiary); burial depths of between 4,000 and 7,000 feet may have been reached. Most diagenetic components probably had developed well before burial to maximum depth (see below).

If unstable detrital components are dissolved at a very early stage, the sequence of diagenetic materials can be attributed to the subsequent depletion of the pore waters in both silica and cations. The vertical variations in abundance of the various diagenetic components suggests that the pore water-detrital

Figure 4. SEM photomicrographs of Morrison Formation sandstones: A, *Srnectite coating detrital grains, coating is about 70 microns thick and has well developed honeycomb pattern, bare patches present points of contact with plucked adjacent grains, Recapture Member, Ojito Spring Quadrangle;* **B,** *Pseudohexagonal flakes of grain coating chlorite covered by small quartz overgrowths (Q) and calcite cement* (C), *chlorite flakes are generally 2-5 microns in diameter and exhibit an edge-to-face (cardhouse) structure, Westwater Canyon Member, subsurface, Valencia County;* C, *Pore filling pseudohexagonal booklets of kaolinite (or dickite?), books range from 5 to 20 microns, Westwater Canyon Member, subsurface, Valencia County;* **D,** *Large quartz overgrowths with bipyramidal facets on detrital quartz grain, Westwater Canyon Member, Ojito Spring Quadrangle;* E, *Calcite cement (C) covering quartz overgrowths (Q) which, in turn, partially coat chlorite grain coating, Westwater Canyon Member, subsurface, Valencia County;* F, *Partially leached detrital potash feldspar partially covered by unaltered potash feldspar overgrowth (arrow), the overgrowth is virtually pure potash feldspar based on analysis with x-ray energy spectrometer, Westwater Canyon Member, 0jito Spring Quadrangle.*

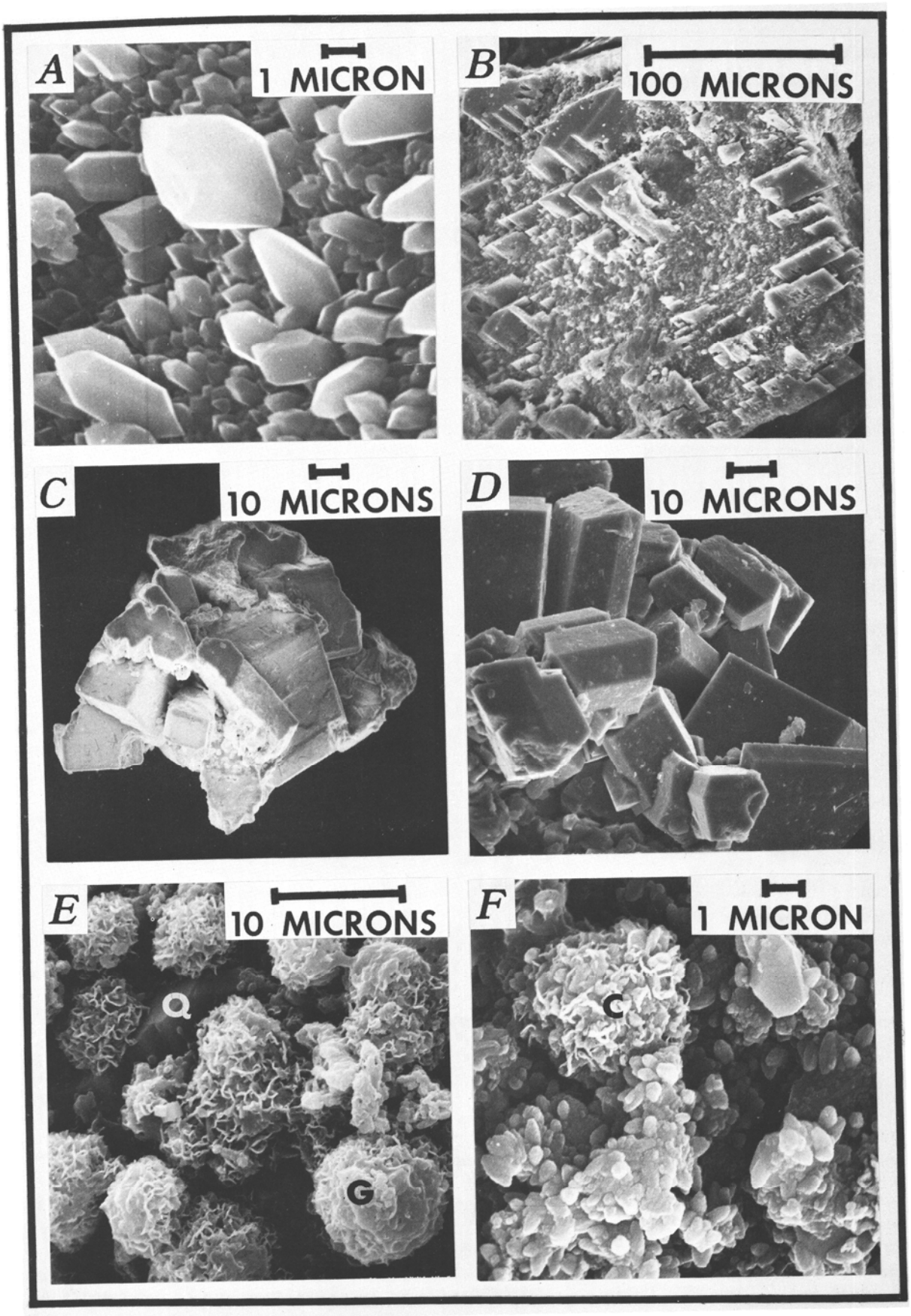

A
1 MICRON
B
100 MICRONS
C
10 MICRONS
D
10 MICRONS
E
10 MICRONS
Q
G
F
1 MICRON
C

Figure 5.

grain system must have been closed, at least over distances of more than a few feet.

A more likely partial alternative to the depletion hypothesis explains the late stage feldspar dissolution and kaolinite, anatase(?), cliachite, and gibbsite genesis as a result of a late-stage invasion of the pore water system by near-surface ground waters. These ground waters must have had a low cation and silica content.

Millot (1970, p. 327) stresses the importance of acid solutions on the origin of diagenetic kaolinite. He also notes that the hexacoordination of aluminum required for development of kaolinite may be favored by organic complexing (humic matter is specifically mentioned in this regard).

As noted by Pettijohn, Potter, and Siever (1972, p. 409) it is more accurate to state that kaolinitc is favored by solutions low in silica and with low cation (K^+, Mg^{++}, Fe^{++}) to hydrogen ion rations. Phase equilibria studies in which the stability field for kaolinite is determined assume alumina is virtually in-soluble in solution. However, alumina must have been trans-ported in solution in order for pore filling kaolinite to form. Consequently the conditions under which kaolinite develops cannot be defined adequately until the influence of alumina is understood.

The process of feldspar destruction and kaolinite genesis should have been most intense when the Morrison was exposed at the surface. This condition has been met both during the Early Cretaceous when the Triassic and Jurassic rocks of northwestern New Mexico were uplifted and then truncated beneath the transgressive Dakota Sandstone; and possibly in late Tertiary to Holocene time. The relatively arid climate of northwestern New Mexico during much of the late Tertiary and Holocene does not favor the large influx of waters necessary to promote extensive leaching.

No relationship between kaolinite abundance in the Morrison Formation and Dakota Sandstone and the present erosion surface was observed. The distribution of kaolinite is apparently related to proximity to the unconformable contact with the overlying Dakota Sandstone. In the 0jito Spring Quadrangle kaolinite is most abundant in the "Jackpile" sandstone and is relatively uncommon in the Recapture Member. In other areas of northwestern New Mexico, kaolinite is reported to be common in those units immediately below the Dakota sandstone and much less common where these units diverge from the Dakota (Leopold, 1943, Moench and Schlee, 1967, p. 21).

The higher percentages of detrital quartz in the "Jackpile" sandstone, when compared with the members below, may be attributable to the dissolution of sanidine and plagioclase and genesis of kaolinite related to a pre-Dakota period of nearsurface leaching. Moench and Schlee (1967, p. 21) suggest such a hypothesis to explain the upward increase in mineralogical maturity of "Jackpile" sandstones in the Laguna District 30 to 40 miles southwest of the 0jito Spring Quadrangle. The lack of calcite cement throughout much of the "Jackpile" sandstone may be the result of the same episode of leaching which produced kaolinite at the expense of selected feldspars.

The origin of calcite cement in the Morrison Formation of the 0jito Spring Quadrangle is not well understood at the present time. Some calcite cement may have formed by the precipitation in reducing ground waters of downward percolating acid ground waters relatively rich in dissolved bicarbonate. The bicarbonate is acquired by dissolution of detrital carbonate clasts (possibly supplemented by carbonate cements formed during early diagenesis).

The presence of cliachite and gibbsite require pore waters very low in silica content (Curtis and Spears, 1971). These alterations require very extensive fresh water influx and are likely to have coincided closely with feldspar dissolution. The throughput of fresh meteoric waters necessary for genesis of gibbsite and cliachite could best be maintained in the laterally extensive coarse permeable units such as the "Jackpile Sandstone" and Westwater Canyon Member.

The fact that pyrite occurs in the subsurface but is oxidized to hematite and limonite in the surface samples suggests that the latter minerals are related to the Late Tertiary-Holocene erosion surface.

The fact that hematite also is found within rather than coating detrital grains suggests this hematite was formed prior to transport of these grains. Such an interpretation is favored by the fact that such hematite staining occurs in subsurface samples where unaltered pyrite is also present.

Anatase(?) was almost certainly derived by late-stage alteration of titanium-rich minerals, particularly ilmenite, as it often is found within partially dissolved feldspars.

The restriction of chalcedony to the Brushy Basin Shale Member and lowermost and uppermost Westwater Sandstone Canyon Member is probably related to the close association of these sandstones to volcanic ash deposits in the claystone units. Volcanic glass in the ash beds has devitrified to a montomorillinite-rich reddish-brown stained mass in which the spine-like shapes of glass shards can still be discerned. The lack of chalcedony in the central portions of the Westwater Canyon Sandstone Member suggests that (1) the silica in the pore waters was transported by diffusion and could therefore migrate only short distances from the ash deposits in which it was derived, or (2) the initial cementation of the border of

Figure 5. SEM photomicrographs of Morrison Formation sandstones: **A,** *Well developed bipyramidal outlines of quartz crystals forming chalcedony cement, prism faces also are present on some crystals, note that the crystals have a strong preferred, but not identical, alignment, Brushy Basin Member, Ojito Spring Quadrangle;* **B,** *Rhomb-shaped potash feldspar overgrowths (adularia?) on detrital potash feldspar, the detrital grain surface and some of the overgrowths are covered by o'iagenetic clay coatings, Westwater Canyon Member, subsurface, Valencia County;* **C,** *Interlocking cubes of pyrite altered pseudomorphously to hematite, small octahedral faces occur on some crystals, Brushy Basin Member, 0jito Spring Quadrangle;* **D,** *Interlocking tabular crystals of titanium dioxide (anatase?) covered by kaolinite flakes and books, Brushy Basin Member, 0jito Spring Quadrangle;* **E,** *Flower-like morphology typical of cliachite, an amorphous aluminum hydroxide, analysis with x-ray energy spectrometer indicates minor manganese also is present, the cliachite covers a quartz overgrowth (Q) and is covered in part by gibbsite (G), "Jackpile Sandstone", 01/to Spring Quadrangle;* **F,** *Interlocking crystals of gibbsite (aluminum hydroxide) partially covering cluster of cliachite (C), "Jack pile Sandstone", O1/to Spring Quadrangle.*

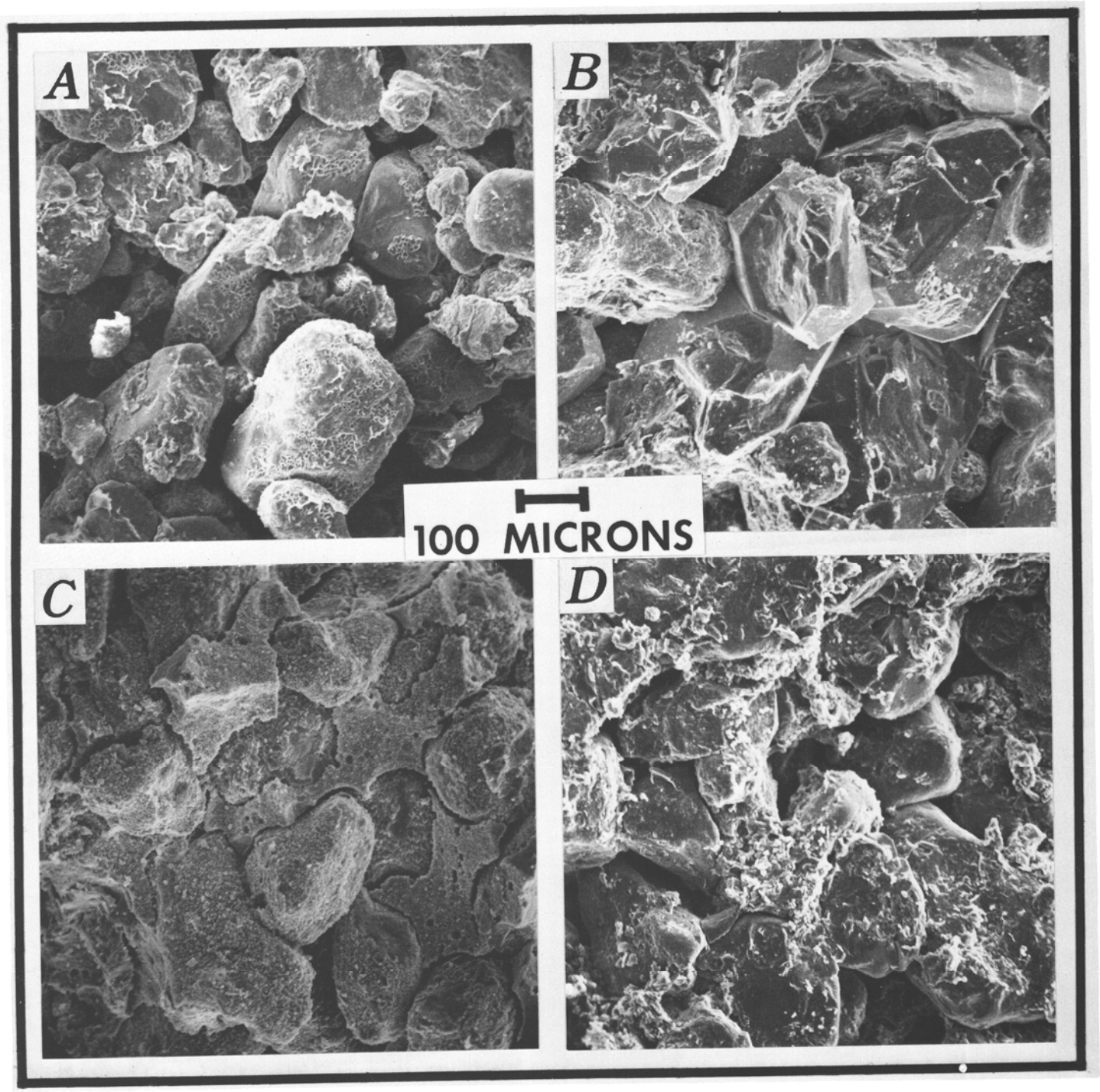


Figure 6. SEM photomicrographs of Morrison Formation sandstones: **A,** *Porous medium-grained moderately sorted arkosic arenite with well developed smectite grain coatings, note lack of quartz and feldspar overgrowth development, Recapture Member, Ojito Spring Quadrangle;* **B,** *Well developed quartz overgrowths on detrital quartz grains in medium-grained arkosic arenite, many of the small white grains are kaolinite, Westwater Canyon Member, Ojito Spring Quadrangle;* **C,** *Chalcedony cement filling pores in fine-grained well sorted arkosic arenite, gap between chalcedony and detrital grain surfaces is often partially filled by grain-coating clay and small quartz overgrowths, Brushy Basin Member, Ojito Spring Quadrangle;* **D,** *Medium-grained well sorted feldspathic arenite with numerous clots of kaolinite books clogging pores, "Jackpile Sandstone", Ojito Spring Quadrangle.*

Table 2. Generalized Sequence of Diagenetic Alterations in Sandstones of Morrison Formation, Ojito Spring Quadrangle

Stage	Recapture Member	Westwater Canyon Member	Brushy Basin Member	Jackpile Sandstone
1.		Feldspar overgrowths in some zones		Feldspar overgrowths in some zones.
2.	Smectite or smectite-illite	Smectite or smectite-illite	Smectite or smectite-illite	Smectite or smectite-illite
3.		Quartz overgrowths in some zones.	Quartz overgrowths and chalcedony	Quartz overgrowths in some zones
4.	Calcite	Calcite	Calcite	Calcite(?)
5.	Minor feldspar dissolution	Minor feldspar dissolution, kaolinite, pyrite, anatase	Minor kaolinite pyrite, anatase	Calcite(?) and feldspar dissolution, kaolinite, pyrite, anatase
6.	Minor pressure solution			
7.	Hematite and limonite	Hematite and limonite	Hematite and limonite	Hematite and limonite

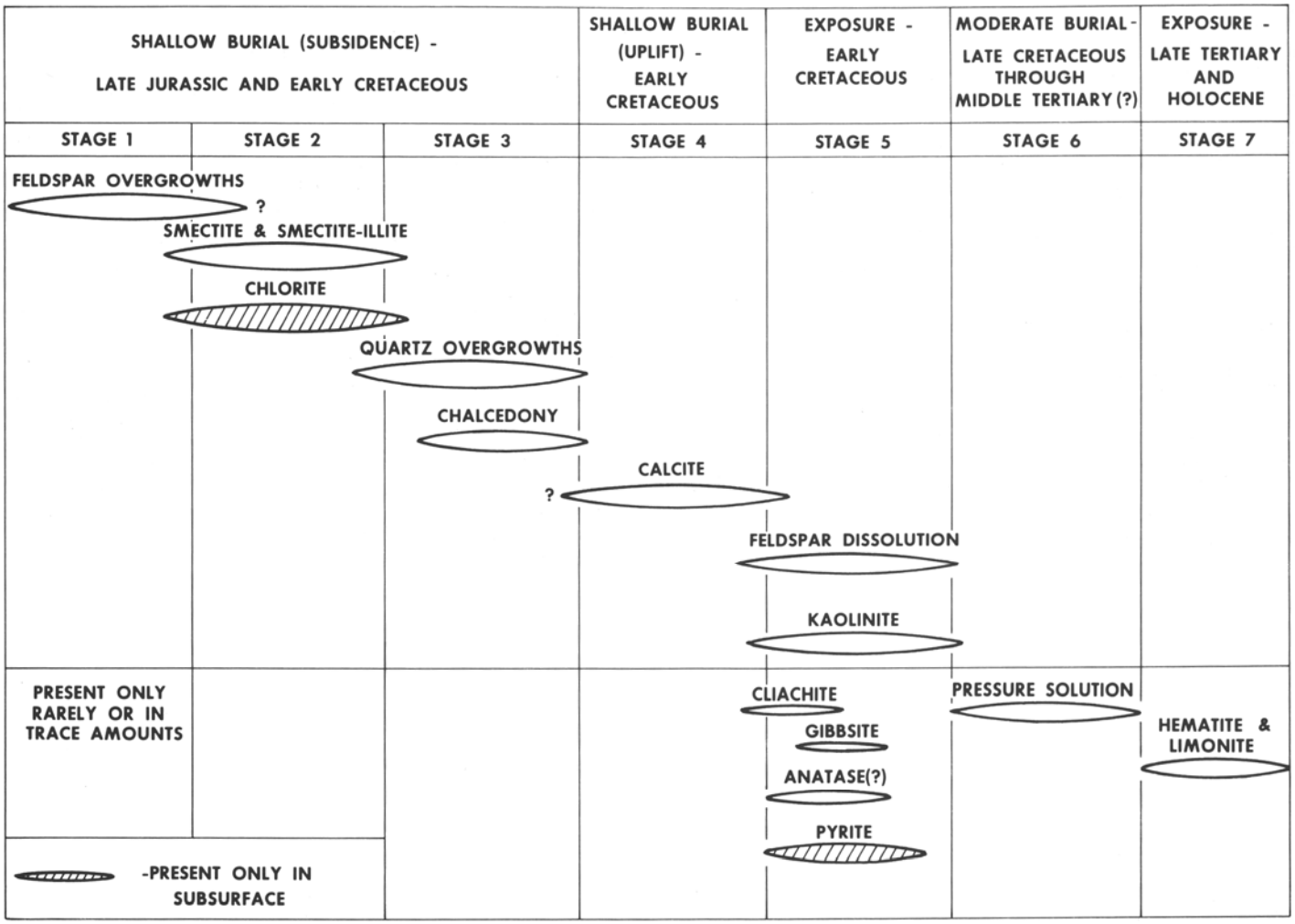


Figure 7. Timing of diagenetic alterations in Morrison Formation, Ojito Spring Quadrangle, New Mexico.

thick sandstone bodies like the Westwater Canyon so drastically reduced the permeability that the interior was effectively protected from further cementation.

Summary of Diagenetic Components

Sandstones of the Morrison Formation generally exhibit the following sequence of diagenetic alterations (in order of decreasing age):

1. Feldspar overgrowths (often absent or poorly developed).
2. Smectite or smectite-illite grain coatings.
3. Quartz overgrowths (presence dependent on completeness of clay coatings).
4. Calcite cementation.
5. Feldspar dissolution, kaolinite infill, pyrite and anatase grain coatings.
6. Pressure solution (minor suturing at grain contacts).
7. Oxidation of iron-rich minerals to hematite and limonite.

The first three alterations above are probably related to dissolution at shallow depths of unstable volcanic rock fragments and heavy minerals. Chalcedony forms during stage three in sandstones closely associated with abundant volcanic ash deposits. Calcite cementation may be explained by the reaction of downward percolating bicarbonate-rich acidic groundwaters and somewhat deeper reducing ground waters.

Destruction of sanidine and plagioclase and genesis of kaolinite, pyrite, and anatase appear to be related to exposure of the Morrison formation during a period of pre-Dakota uplift and truncation. Renewed subsidence during the Late Cretaceous and Tertiary produced only minor pressure solution at grain contacts. Uplift and exposure in the Late Tertiary and Holocene brought about the oxidation of iron-rich minerals, particularly pyrite, to hematite and limonite.

DISCUSSION

Typical of most geologic investigations, research of specific problems is never really completed and generally raises many new questions. In discussing the detrital and diagenetic components of Morrison Formation sandstone units we have left unanswered many questions where further research is necessary. These include a better understanding of the source area(s), including rock types present, the tectonic history and the interaction of local sources. Further field work and petrography is necessary in other areas of New Mexico. The diagenetic sequence generally is consistent throughout the study area, but regionally we need to know the sequence, geochemistry and timing of diagenetic alterations in many areas to construct a working framework. Also, how does the emplacement of uranium fit into or modify the diagenetic sequence?

Owing to the economic significance of the Morrison Formation, hopefully, attention to these and other problems can come about through funding of additional research and integration of much of the data which is presently held confidential.

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