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Mechanical and chemical diagenesis of the Hayner Ranch and Rincon Valley Formations (Santa Fe Group, Miocene), San Diego Mountain, New Mexico

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Introduction

The Santa Fe Group in New Mexico consists of nonmarine, syntectonic detritus that was deposited during formation of the Rio Grande rift. In southern New Mexico two major periods of rifting are recognized (Seager, 1975). The initial stage occurred during Miocene time and resulted in large, northwest-trending, closed basins, which received several thousand meters of fanglomerate and playa shale and gypsum. The latter stage of rifting (Pliocene and Pleistocene) segmented some earlier rift basins, produced north-trending basins and uplifts, and culminated in integration of the Rio Grande drainage. The Santa Fe Group is an important ground-water and hydrothermal aquifer in southern New Mexico, and efficient use of these resources requires an understanding



FIGURE 1—Location map of San Diego Mountain, southern New Mexico.

of its stratigraphy, sedimentology, and diagenesis. Toward this end a study was undertaken to unravel the diagenetic history of early basin-fill sandstones of the Santa Fe Group at San Diego Mountain, New Mexico.

The San Diego Mountain section is well suited for study because many of the variables that are influential in diagenesis are constant throughout the section. For example, the 950-m-thick section is almost continuously exposed, with less than 10% covered, which allows for systematic vertical sampling. There also was little change in provenance through time. Andesitic volcanic rocks were the dominant source, although a minor sedimentary contribution in the upper 150 m of the section is indicated by the presence of detrital quartz, chert, and carbonate- and pelitic-rock fragments. Grain size was also held constant by restricting the samples to medium-grained sandstone. Furthermore, facies analysis indicates that there was little change in depositional environment through time. The sediment was deposited by sheetflood and streamflood processes in a midfan or distal-fan environment. Thus, diagenetic trends in the section should be primarily a function of depth of burial and poresolution chemistry.

A variety of diagenetic features, both mechanical and chemical, is found in Santa Fe Group sandstones. Many of the features at San Diego Mountain were described previously by Walker et al. (1978) as part of a larger study of the diagenesis of first-cycle, desert alluvium. This study systematically documents spatial and temporal relationships among the mechanical diagenetic features, such as compaction and clay infiltration, and the chemical diagenetic features, such as hematite and the various cements, in order to develop a comprehensive diagenetic model for the Santa Fe Group at San Diego Mountain.

Methods

Forty-seven samples of medium-grained sandstone were collected from outcrops at 20-m intervals over a 950-m-thick section of the lower Santa Fe Group at San Diego Mountain, New Mexico (Fig. 1). At this location the lower Santa Fe Group is composed of the basal Hayner Ranch and overlying Rincon Valley Formations, both of Miocene age. Before deposition of the uppermost formation of the Santa Fe Group (Camp Rice Formation; Pliocene and Pleistocene), the Hayner Ranch and the Rincon Valley Formations were uplifted and tilted about 45° southward (Seager et al., 1971).

Thin sections of the 47 samples were examined for detrital grain types, texture, and authigenic minerals. Detrital modes were determined by point-counting 300 grains per sample. Compaction was determined by calculating the packing proximity and the packing density (Kahn, 1956). The types of grainto-grain contacts also were recorded under the categories tangential, longitudinal, and concavo-convex. No sutured grain-to-grain contacts were observed.

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FIGURE 2—Packing proximity (solid line) and packing density (dashed line) as a function of stratigraphic position.

Phyllosilicate cement was identified by use of an x-ray diffractometer and an energy-dispersive scanning electron microscope (SEM). Sample preparation for x-ray analysis was done according to Carrol's (1970) method, which includes glycolated and unglycolated runs. Belk's (1974) energy-dispersive SEM technique was used. Thin sections also were examined with a Nuclide ELM–2B Cathode Luminoscope, utilizing a beam energy of 15 kV and a beam current of 0.6 milliamps.

Detrital grains

The most abundant detrital grains in the Hayner Ranch and Rincon Valley Formations are volcanic-rock fragments (51%) and plagioclase (38%); the sandstones are classified as feldspathic litharenites. Volcanic-rock fragments exhibit porphyritic and microlitic textures (Dickinson, 1970). Detrital plagioclase and plagioclase phenocrysts in rock fragments display oscillatory zoning and twinning, and they have an anorthite content that ranges from 36 to 43% (andesine), as determined by the Michel-Levy method. Detrital quartz is uncommon (6%) and is found in greater than trace amounts only in the Rincon Valley Formation. Most of the quartz grains are monocrystalline. Minor amounts of detrital chert (2%), pelitic-rock fragments (1.7%), and carbonate-rock fragments (0.3%) also are found in the Rincon Valley Formation. The other 1% of the framework grains is biotite, hornblende, and opaque minerals.

Mechanical diagenesis

There is little variation in the compaction parameters as a function of depth of burial (Figs. 2, 3). Packing proximity shows a slight increase toward the base of the section, but packing density displays no increase down-

section (Fig. 2). Similarly, the percentage of longitudinal grain-to-grain contacts and the percentage of concavo-convex grain-to-grain contacts display no consistent trends as a function of stratigraphic position (Fig. 3). The lack of well-defined vertical trends in compaction parameters is anomalous. Taylor (1950) demonstrated that the percentages of longitudinal and concavo-convex contacts increased systematically with depth in Cretaceous sandstones in Wyoming. The absence of these trends in the Hayner Ranch and Rincon Valley Formations suggests that normal compaction was somehow prevented, or that burial depths were not great enough to produce recognizable differences in compaction. The latter interpretation seems less likely in light of the study by Taylor (1950), which involved burial depths similar to those in the Santa Fe Group.

Another diagenetic feature of mechanical origin consists of clay rims, which display a tangential orientation of the long axes of clay minerals around detrital grains (Fig. 4). Clay rims are found in roughly half of the samples, and their occurrence does not appear to be controlled by stratigraphic position. Walker et al. (1978) demonstrated that these clays are the result of infiltration at shallow depths of burial, and they are common in desert alluvium. Locally, the clay rims are intimately intermixed with hematite rims.

Chemical diagenesis

Hematite rims

Almost all detrital grains in the Hayner Ranch and Rincon Valley Formations are rimmed by dark-red hematite. Walker et al. (1978) established a diagenetic origin for hematite rims in Cenozoic desert alluvium, including the Hayner Ranch and Rincon Valley Formations. Hematite formed early in the



FIGURE 3—Percentage of longitudinal grain-to-grain contacts (solid line) and concavo-convex grain-to-grain contacts (dashed line) as a function of stratigraphic position.

burial history of the sandstones, because it is the first authigenic mineral to rim detrital grains. Locally, hematite is intermixed with tangentially oriented clay, indicating that at least some of the clay infiltrated simultaneously with the creation of authigenic hematite.



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Cements

Calcite cement is found in all but two of the thin sections examined in this study. Calcite is commonly coarse grained and occasionally exhibits a poikolitic texture (Fig. 4). In some samples calcite almost completely fills all of the original pore spaces, whereas other calcite-cemented samples are quite friable. Calcite may also replace volcanic-rock fragments, plagioclase, and hornblende, although less than 1% of the grains are affected.

Examination of calcite cement with the cathode luminoscope reveals two types of luminescence. The oldest cement, closest to the detrital grains, luminesces moderately bright to dull orange, and there is a tendency for the brightness to diminish systematically, but without distinct zonation, toward the center of pore spaces. In about half of the samples, the youngest calcite cement, which occupies the center of pore spaces, is nonluminescent. Luminescence of calcite is due primarily to the Mn/Fe ratio (Frank et al., 1982; Grover and Read, 1983; Fairchild, 1983). Manganese is an activator ion and causes luminescence, whereas ferrous iron inhibits luminescence. Orange luminescence implies the presence of Mn^{+2} and Fe^{+2} in subequal amounts in the calcite cement. The lack of luminescence indicates the absence of Mn⁺² and Fe⁺² or a very low ratio of Mn⁺² and Fe⁺²

Calcite cement postdates hematite rims and most clay rims. However, in one sample an infiltrated clay rim coated the edge of a calcite-cement crystal that was growing into an empty pore space (Fig. 4). This textural observation suggests that at least some of the calcite cement precipitated early in the diagenetic history of the sandstones.

Phyllosilicate cement occurs sporadically in the Hayner Ranch and Rincon Valley Formations, and it is the dominant cement in only two samples. Phyllosilicate and calcite cements are never found together in the same pore space, although one portion of a thin section may be cemented by calcite and an adjacent portion by phyllosilicate. There does not appear to be a stratigraphic control on the distribution of the phyllosilicate cement. The phyllosilicate cement has white to gray birefringence and extends as blade-like crystals into the pore spaces (Fig. 5). Analysis by x-ray diffraction and by energy-dispersive SEM indicates that the phyllosilicate is calcium smectite (Grigsby, 1984). The smectite cement postdates hematite rims and infiltrated clay matrix. The paucity of phyllosilicate cement in the Hayner Ranch and Rincon Valley Formations is anomalous. Feldspathic litharenites derived from intermediate to mafic volcanic rocks commonly are cemented by phyllosilicates. An important source of ions for the clays is chemical breakdown of detrital feldspars and volcanic-rock fragments (Galloway, 1974; Wilson and Pittman, 1977; Davies et al., 1979). This process was obviously inhibited in the Hayner Ranch and Rincon Valley Formations.

Quartz and feldspar cements are very uncommon in the Hayner Ranch and Rincon Valley Formations. Quartz cement is found only in the Rincon Valley Formation, where it occurs as overgrowths around detritalquartz grains and postdates hematite rims. The paucity of quartz overgrowths is probably a function of the paucity of detrital quartz to act as nuclei. Feldspar cement also occurs as overgrowths, but it is extremely rare and will not be considered further. Anomalous by their absence are zeolites, specifically the calcium zeolites laumontite and heulandite, which are common as alteration products and cements in volcanicarenites (Merino, 1975; Surdam and Boles, 1979; Davies et al., 1979).

Interpretation of diagenetic history

The diagenetic history of the Hayner Ranch and Rincon Valley Formations at San Diego Mountain can be separated into three stages. Each stage is characterized by a unique set of processes, authigenic phases, and groundwater chemistry. Stages I and II were probably going on simultaneously but at different depths within the basin. As deposition and burial proceeded, sediment passed sequentially from shallow stage I diagenesis to deeper stage II diagenesis. Stage III, however, is associated with regional uplift and postdates stages I and II.

The earliest stage involves the development of hematite rims by interstratal solution of magnetite, biotite, and amphibole, the infiltration of clay matrix, and minor compaction. This stage is discussed in detail by Walker et al. (1978). The precipitation of hematite indicates that pore fluids in stage I were oxidizing.

The second stage of diagenesis was dominated by the precipitation of cement, principally the orange-luminescent calcite cement, but also calcium smectite and quartz cement. At least some calcite cementation overlapped in time with infiltration of clay, and thus some of the calcite cement was relatively early in the burial history. The "early" precipitation of some calcite cement may account for the anomalously low amount of phyllosilicate cement and for the lack of significant stratigraphic trends in compaction. Calcite cementation would inhibit the precipitation of phyllosilicate cement by filling pore spaces and limiting the chemical interaction between detrital grains and pore solutions. An "early" calcite cement also would inhibit compaction of detrital grains by providing a relatively rigid framework. The state of compaction inherited from stage I would persist through deeper levels of burial.

The composition of authigenic phases allows speculation on the chemistry of the pore solutions during stage II diagenesis. The presence of both Mn⁺² and Fe⁺² in the calcite cement, indicated by orange luminescence, suggests that the pore solutions were reducing (Grover and Read, 1983). The increasing dullness of the luminescence toward the center of the pore space further indicates that the pore solutions became progressively more reducing through time. The change from oxidizing pore solutions in stage I to reducing pore solutions in stage II is consistent with





FIGURE 4—Photomicrograph of sandstone of the Hayner Ranch Formation exhibiting detrital volcanic-rock fragments, infiltrated clay rims (arrow), and coarse calcite cement (C). Calcite cement crystal, which was growing into empty pore space (black), is rimmed by infiltrated clay. Scale bar is 0.25 mm.

FIGURE 5—Photomicrograph of sandstone of the Hayner Ranch Formation, composed of volcanic-rock fragments and plagioclase. Smectite cement is growing into empty pore space (black). Scale bar is 0.25 mm.



FIGURE 6—(left diagram) Activity diagram in the system $CaO-A_2O_3-SiO_2-H_2O$ at 25°C, 1 bar, and unit activity of water. Free energy data used in construction of diagram is from Drever (1982). Vertical dashed lines represent quartz saturation at the temperatures indicated, and horizontal dashed lines represent calcite saturation at the values of P_{CO_2} indicated. Data points are modern subsurface water compositions from the San Diego Mountain area, taken from Swanberg (1976) and Wilson et al. (1981).

FIGURE 7—(right diagram) Activity diagram in the system $CaO-Al_2O_3-SiO_2-H_2O$ at 25°C, 1 bar, and unit activity of water. See Fig. 6 caption (above) for further explanation.

changes in the oxidation potential of modern ground water from the surface or edge to the center of depositional basins (Champ et al., 1979).

The chemistry of stage II pore solutions can be defined further by the use of activity diagrams in the system CaO-Al₂O₃-SiO₂-H₂O (Figs. 6, 7). Stage II pore solutions, assuming equilibrium, must have been in the calcium smectite field and near the calcite saturation lines. Quartz overgrowths also have implications to pore-solution chemistry. Although quartz overgrowths are rare, their presence probably was controlled not only by poresolution chemistry but by the distribution of detrital quartz, which acted as nuclei for crystallization. The pore fluids may have been saturated with respect to quartz, but quartz cement only precipitated in the detrital quartzbearing Rincon Valley Formation. If this argument is correct, the chemistry of stage II pore solutions can be fixed at the intersection between the quartz and calcite saturation lines within the smectite field. Support for this model comes from the composition of ground waters that exist today in the vicinity of San Diego Mountain (Swanberg, 1976; Wilson et al., 1981). These ground waters "plot" on the activity diagrams at the position predicted for the ancient pore solutions (Figs. 6, 7). Finally, the absence of zeolites, specifically laumontite, may be explained by the activity diagram in Fig. 7. Calcite cementation may have buffered the pore solution at a ratio of Ca+2 to 2H+ that was too low to allow precipitation of laumontite.

The final stage of diagenesis corresponds to the time of precipitation of the nonluminescent calcite cement. The absence of luminescence in calcite indicates the paucity of Mn⁺² as a result of oxidizing ground waters (Grover and Read, 1983). Furthermore, the nonluminescent calcite cement is found in small amounts at all stratigraphic levels. The model that best fits these constraints involves uplift and tilting of the Hayner Ranch and Rincon Valley Formations before deposition of the Camp Rice Formation. During uplift deeply buried rocks were brought into the realm of near-surface, oxidizing ground waters.

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New Mexico Geological Society news

At the annual NMGS business meeting in April members voted to return to the 1984 dues structure for 1986, which will mean \$7.00 dues for active members, \$5.00 for associate members, and \$3.00 for students. A subscription to New Mexico Geology will no longer be included as part of the dues payment. Members are, however, urged to continue to subscribe to the magazine, and it has been suggested that subscription notices be included in NMGS mailings. The society will award a total of \$8,500 in 1985 to students studying New Mexico geology. The society fellowship, worth \$1,000, was given to Richard P. Lozinsky of New Mexico Tech. Twenty-six other students will share the remaining \$7,500. Twenty-seven papers were presented at the spring meeting technical sessions (see abstracts, pp. 64-67), which were organized by John MacMillan. After the meeting, a field trip was led by Clay Smith to the ore districts near Socorro. Ron Broadhead, who was registration chairman, reported that 104 geologists registered for the meeting, and George Austin, who was general chairman, indicated that the meeting essentially broke even financially. Special attention is called to the NMGS fall field conference to be held September 26–28 in the Santa Rosa area. NMGS members will receive notices about the conference this month. Spencer Lucas and Barry Kues of the University of New Mexico are in charge of the field trip, and questions may be directed to them.