Toward a hydrologic classification of map units in the Sante Fe Group, Rio Grande rift, New Mexico

Steven M. Cather

New Mexico Geology, v. 19, n. 1 pp. 15-21., Print ISSN: 0196-948X, Online ISSN: 2837-6420.
https://doi.org/10.58799/NMG-v19n1.15

This page is intentionally left blank to maintain order of facing pages.

Toward a hydrogeologic classification of map units in the Santa Fe Group, Rio Grande rift, New Mexico

by *Steven M. Cather,* New Mexico Bureau of Mines and Mineral Resources, Socorro, NM 87801-4796

Abstract

A sedimentological map-unit classification system is presented that subdivides the Santa Fe Group on the basis of depositional systems and grain-size-related lithofacies. Resulting map-unit designations have the following form: Age/Unit/Depositional system/Textural lithofacies. An optional, unspecified fifth parameter may be appended to add flexibility to the map-unit classification. The classification system is relevant to both hydrogeology and basin analysis and is designed to be useful at a map scale of 1:24,000.

Introduction

The Santa Fe Group (upper Oligocene–middle Pleistocene) is the aggradational fill of the basins of the Rio Grande rift and represents the principal aquifer in the state of New Mexico. During the past decade, the hydrogeology of the Santa Fe Group has become the focus of renewed study. The National Geologic Mapping Act of 1992 has been particularly important in providing funding for collaborative mapping by geologists from universities and state and federal geological surveys. In New Mexico, the emphasis for federally funded mapping has been the Albuquerque–Santa Fe area. Geologic mapping for this program is generally at a scale of 1:24,000. The New Mexico Bureau of Mines and Mineral Resources has concurrently supported hydrogeologic studies in the Albuquerque and Las Cruces areas (Hawley and Haase, 1992; Hawley et al., 1995; Hawley and Lozinsky, 1992).

The Santa Fe Group throughout New Mexico exhibits a broad spectrum of lithologic and hydrologic characteristics, ranging from piedmont deposits that typically coarsen toward the basin margins to basin-floor deposits that vary from low-permeability playa mudstone to high-quality aquifer sands and gravels of the ancestral Rio Grande. Because demarcation of laterally transitional facies is somewhat arbitrary, no standardized methodology yet exists for mapping lithofacies within the Santa Fe Group. An important goal of the ongoing mapping efforts in the Santa Fe Group is to provide a basis for regional ground-water analysis. As such, it is essential that geologists working in the Santa Fe Group eventually come to a consensus concerning a standardized map-unit nomenclature that has relevance to hydrogeologic investigations. The following is an attempt at such a classification that I hope will stimulate discussionand eventual agreement among workers.

The term "Santa Fe Marls" was coined by Hayden (1869) for Tertiary sediments in the Rio Grande valley near Santa Fe. Darton (1922) used the term Santa Fe Formation for these rocks. In a 1938 paper, Kirk Bryan exported the term Santa Fe Formation from its type area throughout the basin-fill of the Rio Grande rift. Santa Fe was raised to group rank by Spiegel and Baldwin (1963), who defined the term to include all sedimentary and volcanic rocks related to the Rio Grande rift, excluding terrace deposits and alluvium inset within present valleys. With a few notable exceptions (e.g., Galusha and Blick, 1971), this definition of the Santa Fe Group has been generally accepted.

Several criteria have been applied to subdivide the Santa Fe Group. Unconformities (allostratigraphic boundaries of NACSN, 1983) define the top of the Santa Fe and are used locally to subdivide the unit. For example, near Socorro, the Santa Fe Group is composed of the Popotosa and Sierra Ladrones Formations. In some areas, an unconformity serves to divide the piedmont deposits of these units (e.g., Machette, 1978; Cather et al., 1994).

The concept of *petrofacies* has been used to define both formal and informal units within the Santa Fe Group. Petrofacies are defined by the lithologic characteristics of detritus within clastic units and thus are related to *provenance.* Ingersoll et al. (1990) used thin-section criteria to subdivide the Santa Fe Group informally into petrosomes in the Espanola Basin. An example of the use of petrofacies in formal stratigraphic nomenclature is the Bishops Lodge Member of the Tesuque Formation, which is distinguished from the main body of the Tesuque Formation by its volcaniclastic nature (Spiegel and Baldwin, 1963).

Numerous workers have subdivided the Santa Fe Group on the basis of genetically related lithofacies associations *(depositional systems* of Fisher and McGowen, 1967). Depositional systems are distinguished by lateral and vertical variation of grain size, sorting, composition of sediments, paleocurrents, nature of contacts, bedding characteristics, etc., which together are indicative of *depositional environment.* Beginning with the work of Kirk Bryan, many geologists have differentiated basin-floor deposits (playa or axial-fluvial) from piedmont deposits in the Santa Fe Group. A few geologists have also delineated transitional units between basin-floor and piedmont depositionalsystems (e.g., Machette, 1978; Seager et al., 1987; Hawley et al., 1995; Gather, 1995a, b). Because of their gradational boundaries, depositional systems in the Santa Fe are not commonly used as formal stratigraphic units.

The application of grain-size parameters as proxies for hydraulic conductivity is well-known in hydrologic studies (e.g. Shepard, 1989; Vukovic and Soro, 1992). Indeed, recent permeability studies of the Santa Fe Group by Davis et al. (1993, fig. 4) and of the Santa Fe Group and similar younger deposits by Detmer (1995a, b) have shown strong correlation between grain size and permeability. Detmer (1995b, pp. 80-82) notes that mean grain size is the only traditional statistical distribution parameter that shows meaningful correlation with permeability. Other parameters such as skewness and standard deviation of grain size, porosity, and percent fines correlate poorly with permeability. Although Detmer's conclusions apply only to shallowly buried sediments of axial-fluvial and piedmont origin, it is clear that grain size is an important hydrogeologic parameter, at least in the shallow subsurface. As such, one aspect of the map-unit classification proposed in this report is based in part on *textural* criteria that provide the basis for subdivision of the Santa Fe Group into *textural lithofacies.* It is important to note that the lithofacies defined herein are restricted in scope and are defined entirely by grain-size parameters. Other parameters such as bedding thickness, style of stratification, etc., are not factors in delineating textural lithofacies, but they are important classification criteria for depositional systems.

In an often-cited study, Anderson (1989) delineated hydrogeologic facies in glacial and glaciofluvial sediments, on the basis of both measured and assumed hydrologic parameters. In contrast to the deposits studied by Anderson, hydrogeologic characterization of the Santa Fe Group is far from complete. For this reason, confident delineation of quantitatively determined hydrogeologic units within the Santa Fe Group is not yet possible at the scale of ongoing mapping. The proposed classification system subdivides the depositional systems of the Santa Fe Group on the basis of a parameter of known hydrologic significance (i.e., grain size), but each textural subdivision is *arbitrary* (Fig. 1). This map-unit classification system provides geologists with a fairly precise method of subdividing the Santa Fe Group into about as many units as can be reasonably depict-

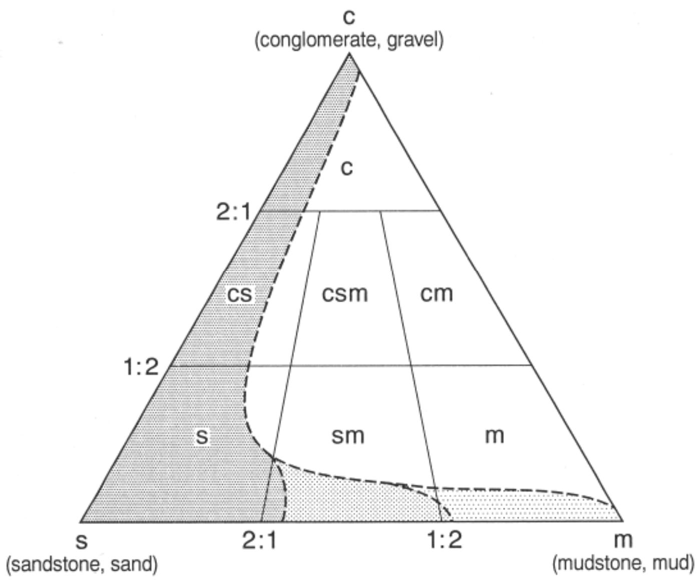

FIGURE 1—Ternary diagram for classification of textural lithofacies of Santa Fe Group. Mean grain size for conglomerate/gravel is >2.0 mm; for mudstone/mud, <0.0625 mm (Wentworth, 1922). Fields are: **c**, conglomerate (or gravel); **cs**, conglomerate-sandstone (or gravel-sand); **csm**, conglomerate-sandstone-mudstone (or gravel-sand-mud); **cm**, conglomerate-mudstone (or gravel-mud); **s**, sandstone (or sand); **sm**, sandstone-mudstone (or sand-mud); **m**, mudstone (or mud). Note that these letter designations apply to both indurated and nonindurated deposits and that cementation is not a factor in classification of textural lithofacies. Cementation may be described using the optional, fifth classification parameter. Dark pattern indicates typical textural trends present in narrow piedmont systems; medium pattern shows additional textural trend common in distal portions of broad piedmont systems. Light pattern corresponds to lacustrine (playa) system mudstones in closed-basin deposits or, less commonly, to mud-dominated distal piedmont deposits in broad, open basins.

ed at a scale of 1:24,000, but the hydrogeologic characteristics (magnitude and spatial correlation structure of permeability) of these units will have to be determined empirically. Future hydrogeologic studies may show that the proposed classification divides the Santa Fe too finely and that, for the purposes of defining hydrogeologic units, amalgamation of two or more textural lithofacies is desirable. More finely divided textural classes, such as those of Folk (1974), provide greater geologic specificity but generally would require mapping at scales larger than 1:24,000.

Because the relationship between *petrofacies* and permeability is unstudied in the Santa Fe Group, provenance-related parameters are accorded only ancillary consideration in the proposed classification (see below). It is probable, however, that volcaniclastic deposits will prove to be generally less permeable than siliciclastic deposits, as a result of the greater diagenetic reactivity of volcanic detritus. The hydrologic effects of *allostratigraphic* boundaries (unconformities) within the Santa Fe are largely unknown, but such boundaries should be mapped routinely, particularily where they happen to coincide with contacts between differing lithofacies, depositional systems, or formal stratigraphic units.

The classification proposed in this report was devised during mapping of Santa Fe deposits in parts of the Socorro, Albuquerque, Santo Domingo, and La Jencia Basins and builds on concepts devised by earlier workers. The classification differs from earlier systems primarily in that textural subdivisions are superimposed on paleoenvironmentally defined depositional systems. The present classification is similar to systems devised for subsurface hydrogeologic characterization of aquifer systems near Las Cruces (Hawley and Lozinsky, 1992) and near Albuquerque (Hawley and Haase, 1992; Hawley et al., 1995) and differs primarily in that lithofacies are graphically determined (Fig. 1). The textural subdivision of depositional systems results in considerable lithologic specificity in mapping; for example, piedmont deposits that are commonly mapped as a single unit can be texturally subdivided into several units that reflect the typical coarsening of these deposits toward the basin margin. The areal distribution of high-permeability sand and gravel versus low-permeability mud in axial river deposits also becomes easier to envision through this mapping technique. The proposed classification is somewhat similar to the engineering geology system of Keaton (1984) but is better adapted to the needs of geological mapping at the quadrangle scale.

The classification system in this report was designed for geological mapping at ascale of 1:24,000, although it may be successfully applied at other scales. It also may be utilized in subsurface analysis but requires sufficient well-sample and geophysical data to allow confident identification of depositional systems and clastic textures in the subsurface. The system evolved during mapping of Santa Fe exposures in parts of eight 7½-min quadrangles [Silver Creek (Cather et al., in prep.), Lemitar (Cather, in prep.), Mesa del Yeso (Cather, 1995a), Loma de los Cañas (Cather, 1995b), Placitas (Cather et al., in prep.), San Antonio (Cather, in prep.), Hubbell Spring (Love et al., in prep.), and Luis Lopez (Gather, in prep.)] quadrangles. The classification system is easy to use in the field and has built-in flexibility to accommodate unanticipated map-unit complications and the personal bias of individual researchers. It is designed to provide a basis for hydrogeologic characterization of aquifers without surrendering its utility to basin analysis and physical stratigraphy.

Classification system

The map-unit classification consists of a nested hierarchy of four parts, with an optional fifth part (Table 1). The first two parts of the map-unit designation consist of the traditional geologic age and formal or informal unit name. These parameters have probable hydrologic significance primarily in that older and/or more deeply buried units tend to have lower porosity and permeability resulting from increased compaction and cementation (e.g., Baldwin and Butler, 1985; Haneberg, 1995). The remaining three classification parameters are discussed below.

Depositional systems

A depositional system is a genetically defined, three-dimensional, physical stratigraphic unit composed of a contiguous set of process-related sedimentary facies (Fisher and McGowen, 1967; Fisher and Brown, 1972; Davis, 1992). Within each recognized geologic unit (parts one and two above), strata are divided on the basis of depositional systems. In my experience, at least six depositional systems in the Santa Fe Group are easily recognized and mappable at a scale of 1:24,000 (Table 1). These include the axial-fluvial, transitional piedmont-axial, piedmont, eolian, and lacustrine systems that have been recognized by earlier workers, as well as a locally important variant of the piedmont system that contains abundant debris-flow deposits and appears to be significantly better indurated and presumably less permeable than alluvial piedmont rocks. Although these six depositional systems have proven sufficient for purposes of mapping to date, it is possible that additional systems may be recognized or that

TABLE 1—Map-unit designations for Santa Fe Group. Example: **QTspcs(s)**, strongly indurated conglomerate-sandstone piedmont deposits of Quaternary–Tertiary Sierra Ladrones Formation of upper Santa Fe Group.

	Age of unit	Name of unit	Depositional system	Lithofacies	(Optional parameter)
Significance of designation in example	**QT**, Quaternary–Tertiary	**s**, Sierra Ladrones Fm.	**p**, piedmont	**cs**, conglomerate-sandstone	Cementation is indicated in this example [**(s)**, strongly indurated], but other variables may be depicted.
Other designations	**T**, Tertiary **Q**, Quaternary	Letter-designations for various group-, formation-, or member-rank units.	**a**, axial-fluvial **l**, lacustrine (playa) **t**, transitional piedmont-axial **e**, eolian **d**, debris-flow-dominated piedmont	See Fig. 1.; identical notation applies for non-indurated sediments. **c**, conglomerate **s**, sandstone **sm**, sandstone-mudstone **csm**, conglomerate-sandstone-mudstone **cm**, conglomerate-mudstone **m**, mudstone	Some possible examples: cementation (**s**, strong, **m**, moderate, **w**, weak); provenance (**v**, volcaniclastic, **s**, siliciclastic, etc.); sorting (**vw**, very well, **w**, well, etc.); tributary axial deposits (**J**, Rio San Jose, **P**, Rio Puerco, etc.).
Hydrologic significance	Age and stratigraphic position appear to correlate with compaction, induration, and permeability. Older, more deeply buried units are typically better cemented, more compacted and less permeable.		Probably relates directly to permeability. Some qualitative examples: (1) playa mudstone and debris-flow deposits have very low permeability; (2) axial-fluvial sands are more permeable than similar-texture deposits of piedmont system.	Grain size correlates well with permeability (Detmer, 1995a,b), at least for young, shallowly buried deposits.	Variable

further subdivision or amalgamation of these six may be necessary, especially at map scales other than 1:24,000.

The axial-fluvial system consists largely of two components: (1) channel-related, typically crossbedded sands and gravels form channel-shaped to lenticular units approximately 0.5-3 m thick; these units are commonly coalesced to form broad multilateral bodies that are as thick as a few tens of meters and may have across-basin widths of kilometer scale; and (2) floodplain deposits consisting dominantly of mud and very fine to fine-grained sand form tabular to lenticular beds generally 0.1-5 m thick and as much as several kilometers in lateral extent. The ratio of coarse-grained channel-related deposits to fine-grained floodplain deposits in the axial-fluvial system in most areas is high, resulting from destruction of floodplains by poorly stabilized, migrating channel complexes. Mean grain size of channel-related deposits in the axial-fluvial system is typically medium- to coarse-grained sand; sorting is moderate to poor (nomenclature of Folk, 1974). Because of the great lithologic variability of this and other systems in the Santa Fe Group, however, site-specific characterization of hydrogeologic parameters (grain size, sorting, bedding, etc.) may be necessary.

Deposits of the ancestral Rio Grande are the most common constituent of the axial-fluvial depositional system and show evidence for paleoflow subparallel to axes of individual basins. Deposits of major ancestral tributaries to the Rio Grande (Rio San Jose, Rio Puerco, Rio Chama, etc.) are texturally more similar to Rio Grande deposits than to piedmont deposits and thus are included in the axial-fluvial depositional system. These tributary deposits, however, should be mapped separately from ancestral Rio Grande deposits where possible, because of their geologic significance and the possibility that future studies will show them to be hydrologically distinctive. Paleoflow in tributary axial-fluvial rivers ranged from low to high angles relative to basin axes.

The piedmont system is typically composed of alluvial-fan and/or alluvial-slope deposits derived from local basin-margin uplifts. Braided stream deposits constitute most of this depositional system, although other types of fluvial deposits occur locally and debris-flow deposits are common in proximal areas. Where they are voluminous, debris-flow deposits should be mapped separately (see below). Proximal piedmont deposits are commonly conglomeratic and exhibit a dominance of channel-shaped and lenticular bedsapproximately 5-50 m wide that range from approximately 1 m to 5 m thick. There is a general tendency for deposits to become distinctly finer grained and for bedding to become more tabular and thinner (range 0.5-2 m) in distal piedmont areas. Sorting is typically poor to very poor. It may be desirable to separate alluvial-fan from non-fan (alluvial slope) piedmont deposits in future studies, as the presence of fine-grained overbank deposits on alluvial slopes differs from the dominantly coarse sediments that characterize alluvial fans (G. A. Smith, oral comm. 1996). Piedmont deposits are generally better indurated than associated axial-fluvial deposits, probably because of the higher calcite saturations in groundwater in piedmont areas (Mozley et al., 1995).

The transitional piedmont-axial depositional system is a hybrid system that reflects the intimate interfingering between distal piedmont and axial-fluvial environments. The transitional piedmont-axial system is defined as the area where interfingering of axial and piedmont sands and gravels is unresolvable at the map scale. In such areas, the transitional system is defined as the area of overlap between the *mountainward* limit of exposures of axial-fluvial sands and gravels and the *basinward* limit of piedmont deposits. Where the interface between axial-fluvial and piedmont deposits is resolvable at map scale, no transitional system will be present. Mudstone is commonly ambiguous as to its former position within the depositional systems tract (i.e., distal piedmont vs. axial). Thus, although mudstone is a common and hydrologically important part of the transitional piedmont-axial system, it is not a factor in delineating its boundaries. Sorting of sands and gravels in this system ranges from moderate to very poor. Bedding is approximately 0.1-5 m thick.

The eolian system is characterized by crossbedded, well-sorted, medium- to fine-grained sandstones of dune origin and associated interdune deposits. Individual cross-sets are commonly as thick as 2-3 m. The eolian depositional system is common in the lower Santa Fe Group in the northwest Albuquerque Basin (lower part of Zia Formation; Gawne, 1981), locally in the southern Socorro Basin (Popotosa Formation; Davis, 1994), in the subsurface of the Mesilla Basin (Hawley and Lozinsky, 1992), and in the Española Basin (Ojo Caliente Sandstone; Galusha and Blick, 1971; Steinpress, 1981). In the lower Santa Fe Group, eolian sandstones may have aggregate thicknesses of tens to hundreds of meters and areal extents of sub-basinal scale. Mappable eolian units are uncommon in the upper Santa Fe Group where they are typically subsumed as a minor facies within the piedmont or axial-fluvial systems. In areas where the lateral transition between the eolian and other systems is not resolvable at map scale, it may prove necessary to define a transitional eolian system or utilize an arbitrary 50 percentile cut-off in the volumetric abundance of eolian versus other deposits.

Lacustrine (playa) mudstones are widespread in the lower Santa Fe Group and reflect a period of rapid tectonism and development of closed basins in many areas of the Rio Grande rift during the middle to late Miocene (Cather et al., 1994). Bedding in lacustrine deposits, although commonly obscure, ranges from approximately 0.1 m to 1 m and has tabular geometry. Lacustrine mudstones in the lower Santa Fe Group were typically deposited under semiarid conditions in shallow ephemeral playas, as is attested by the red coloration of mudstones, lack of associated deep-water delta deposits, and the common occurrence of evaporites (mostly gypsum).

It is my experience that the finely intercalated interface between the piedmont and lacustrine systems of the lower Santa Fe Group is invariably unresolvable at a map scale of 1:24,000. This poses a nomenclatural problem: for the purposes of mapping, where do piedmont deposits end and playa deposits begin? Machette (1978) described transitional facies between piedmont and playa systems. I initially adopted this nomenclature, but abandoned it after realizing that distal piedmont beds in some open basins (e.g. distal facies of the Tesuque Formation in the central Española Basin) are lithologically quite similar to true transitional piedmont-playa beds in closed basins to the south. I now use the simple textural criteria of greater than two-thirds lacustrine mudstone content to arbitrarily delimit the lacustrine system (Fig. 1). Although it is certainly reasonable to describe the adjacent sandstone-mudstone lithofacies of the piedmont system as a separate transitional system, it is probably simpler to note the transitional nature of these beds elsewhere in the text of the map. This then avoids the mislabeling of sandstone-mudstone piedmont deposits in open basins as "transitional playa" beds.

Lacustrine deposits in the upper Santa Fe Group occur primarily in association with the axial-fluvial depositional system. These deposits represent sedimentation in small ox-bow lakes and in ponds on the floodplain. Because of their limited thickness and lateral extent, lacustrine mudstones in the upper Santa Fe Group are commonly subsumed within the axial-fluvial system. Wherever possible, however, they should be mapped separately because of their hydrologic significance.

A debris-flow-dominated variant of the piedmont system is widespread in the basal Popotosa Formation in the Socorro and La Jencia Basins (Chamberlin, 1982; Cather et al., 1994). It consists of >50% matrix-supported, very poorly sorted, crudely stratified debris-flow deposits that are typically much better indurated and presumably less permeable than associated alluvial piedmont deposits. Bedding is commonly lenticular, with widths as much as 100 m and thicknesses ranging from approximately 1 m to 5 m. In the upper Santa Fe Group, debris-flow deposits are rarely widespread or voluminous enough to warrant mapping as a separate unit; in most cases the debris-flow deposits represent a minor and unmappable facies within the more voluminous alluvial deposits of the piedmont system. Where mappable debris-flow deposits interfinger with alluvial deposits, I use an arbitrary 50 percentile criteria to divide them. This 50 percentile cut-off may be applied to both vertical stratigraphic successions and to lateral transitions and reflects the volumetric dominance of alluvial vs. debris-flow components within gradational sequences that are not resolvable at map scale.

Textural lithofacies

Each of the depositional systems above is divided into textural lithofacies on thebasis of grain size, partly because of the demonstrable correlation between mean grain size and permeability for shallowly buried axial-fluvial and piedmont deposits (Detmer, 1995a, b). The map distribution of lithofacies also provides useful information for stratigraphic analysis, such as textural trends within piedmont deposits and evidence for facies control by intrabasin faulting. A ternary diagram divided into seven arbitrary fields (Fig. 1) is used to subdivide each system. The architectural elements of Miall (1985) compose small, homogeneous elements within the larger textural lithofacies designated in this report. Unlike the architectural elements of Miall, however, the lithofacies recognized in this study are mappable at a scale of 1:24,000.

Three of the depositional systems (axial-fluvial, piedmont, and transitional piedmont-axial) exhibit broad ranges of textural lithofacies (Table 2); two systems (eolian and debris-flow-dominated piedmont) show limited textural variation primarily related to their lateral gradation with other deposits. The remaining lacustrine system, unlike the others, is not independent of textural lithofacies. As noted above, as an arbitrary simplification I have opted to apply the term lacustrine system only to rocks of the mudstone lithofacies (m). Of course, nonlacustrine mudstone does occur in other systems, such as the axial-fluvial, piedmont, and transitional piedmont-axial (Table 2). In the absence of petrographic or other laboratory constraints, field classification of mudstone exposures among these depositional systems commonly depends upon local facies associations.

The shaded patterns in Fig. 1 depict the most-common grain-size associations for both narrow and broad piedmont systems and for lacustrine systems. For narrow piedmont systems in narrow basins, such as the Sierra Ladrones Formation piedmont system in the eastern Socorro Basin (Cather 1995a, b), the range of mappable lithofacies is typically quite limited. It is common for only the conglomerate (c) and conglomerate-sandstone (cs) lithofacies to be present. In broad piedmont systems in open basins, such as is represented by the Tesuque Formation in the Española Basin, the fine-grained distal portions are well developed. In closed-basin piedmont systems the textural variation is commonly complete; bouldery piedmont deposits near the mountains grade basinward into finer conglomerates and sandstones that ultimately interfinger with mudstones of the lacustrine system (Groat, 1972). In contrast to those of the piedmont system, deposits of the axial-fluvial and transitional piedmont-axial systems would be plotted in a broad area of Fig. 1; only the conglomerate-mudstone (cm) lithofacies is poorly represented in these systems (Table 2).

TABLE 2—Estimated volumetric importance and mean permeabilities (darcys) of textural lithofacies in depositional systems of Santa Fe Group. **A**, abundant; **C**, common; **M**, minor; —, rare or absent; **n.d.**, no permeability data.

Textural lithofacies (see Fig. 1)	Depositional system					
	axial-fluvial	transitional piedmont-axial	piedmont	lacustrine	debris-flow piedmont	eolian
c	C n.d.	M n.d.	A n.d.	—	A n.d.	—
cs	A 20.9[a]	M n.d.	A n.d.	—	C n.d.	M n.d.
s	A 22–69[b]; 6.9[a]; 15–19[c]; 26.6[d]	C n.d.	C n.d.	—	—	A 6.8[e]
csm	C n.d.	C n.d.	—	—	—	M n.d.
sm	C n.d.	A n.d.	C n.d.	—	—	M n.d.
cm	—	—	—	—	—	—
m	M 10^{-6} [a]	C n.d.	M n.d.	A n.d.	—	—

[a]Davis, 1994. Means from log-transformed data from ancestral Rio San Jose-Rio Puerco tributary axial-fluvial deposits, Sierra Ladrones Fm.
[b]Detmer, 1995a. Means from recalculated log-transformed data (D. Detmer, written comm. 1996) from ancestral Rio Grande axial-fluvial deposits, Sierra Ladrones Fm.
[c]Gotkowitz, 1993. Means from log-transformed data from ancestral Rio San Jose–Rio Puerco tributary axial-fluvial deposits, Sierra Ladrones Fm.
[d]Gotkowitz, 1993. Mean from log-transformed data from ancestral Rio Grande axial-fluvial deposits, Sierra Ladrones Fm.
[e]Davis, 1994. Mean from log-transformed data from eolian deposits, Popotosa Fm.

Optional parameter

The fifth part of the classification is an unspecified, optional parameter that is intended to lend flexibility to the system. Where used in map-unit designations, the letter designation of the fifth parameter is parenthetically enclosed to avoid potential confusion with the other standardized parameters (Table 1). In mapping the Santa Fe Group in the Mesa del Yeso quadrangle, I used this category to distinguish between volcaniclastic and siliciclastic parts of the Sierra Ladrones Formation (Cather, 1995a). Another possible use would be to denote variation in cementation within the Santa Fe. In my experience, however, cementation commonly co-varies with both depositional system and textural lithofacies (cf. Mozley et al., 1995), thus obviating the need for a separate cementation parameter. In such cases, system- or lithofacies-specific modes of cementation may be described in the "Description of Units." In some instances, however, cementation patterns do not co-vary with depositional systems or textural lithofacies and must be mapped separately.

Note that while the first four classification parameters form a nested hierarchy, the fifth optional parameter may not necessarily be a nested subset of either lithofacies or depositional systems. This may result in complex contact relationships. For example, the contact between the volcaniclastic and siliciclastic petrosomes in the Sierra Ladrones Formation crosses several lithofacies contacts within the piedmont system (Gather, 1995a). Depending on the nature of the optional fifth parameter, such crosscutting relations may greatly complicate the resulting map.

Methodology and discussion

The proposed classification involves four parts and an optional fifth. The resulting map-unit designations have the following form: Age / Unit / Depositional system / Textural lithofacies / (Optional parameter).

The determination of the first two parameters (age, unit) are based on regional stratigraphic considerations and are beyond the scope of this report. The third parameter, depositional systems, represents an interpretive category whose determination requires some experiencein paleoenvironmental analysis. The categories utilized in the present classification (axial-fluvial, piedmont, transitional piedmont-axial, eolian, lacustrine, and debris-flow-dominated piedmont systems), however, are sufficiently broad that only a modicum of field experience is necessary. Paleocurrent indicators within depositional systems should be routinely recorded. Not only are such indicators useful in constraining sediment-dispersal patterns, but paleoflow direction appears to correlate with the orientation of permeability anisotropy (Davis et al., 1993).

Unlike depositional systems, the fourth parameter (textural lithofacies) is descriptively determined (Fig. 1). However, because of the inherently transitional boundaries between many textural lithofacies, precise placement of contacts between lithofacies can be problematic and will be a source of imprecision in mapping. To reduce the error caused by variation of technique between mappers, the following is a summary of some methods I have found useful in delineating textural lithofacies.

(1) Because *mappability* is an underlying rationale for delineation of all the above textural lithofacies, it is important to think in terms of packages of rock whose size (thickness, areal extent) is depictable at the scale of interest. This will not only be a function of map scale, but of local relief and exposure quality. I find it useful to keep a mental running average of textures for packages of strata that are approximately 10 m minimum thickness (for map scales of 1:24,000) and that have mappable lateral extents. For example, a local conglomeratic piedmont-channel deposit, although perhaps unique and sedimentologically informative, if not of mappable size might simply be subsumed within an enclosing map unit dominated by piedmont sandstones. Geologically or hydrologically important features that are not of mappable size should be noted in the "Description of Units" of the map.

(2) Classification of textural lithofacies can be accomplished by visual estimation of conglomerate, sandstone, and mud-stone ratios. Although greater precision would result from measurement and detailed description of numerous closely spaced stratigraphic sections, such an approach is rarely feasible during quadrangle-scale mapping. I have found that visual estimation of textures is reasonably precise if one takes the time to occasionally recalibrate the eye by close visual inspection of outcrops using a grain-size chart.

(3) Mapping of textural lithofacies is, of course, easiest in areas of good exposure and high relief. In areas of poor exposure, I make lithofacies assignments to isolated and often widely separated outcrops, and then later use these control points to estimate the location of contacts (usually

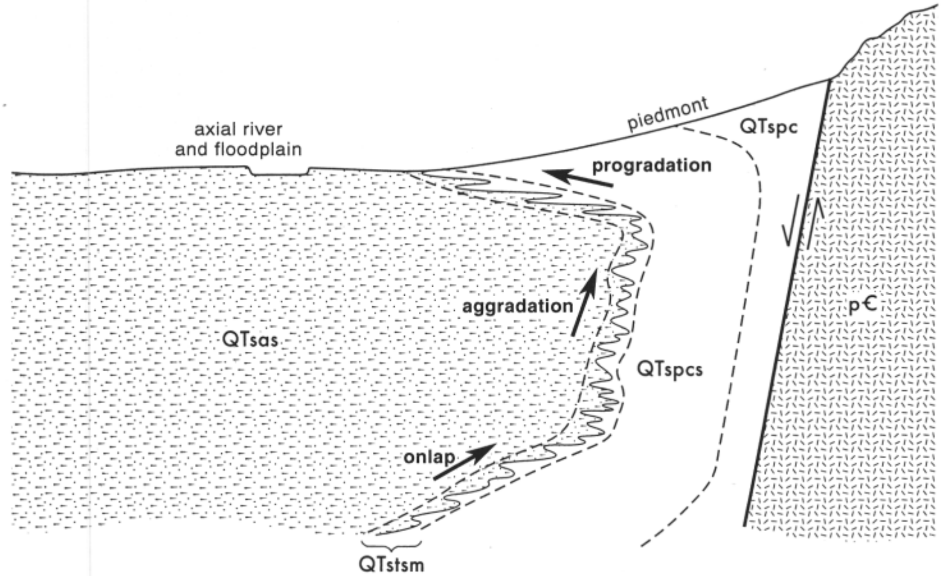

FIGURE 2—Hypothetical cross section of upper Santa Fe Group basin-fill showing contact relations between sandstone lithofacies of the axial-river system (**QTsas**), sandstone-mudstone lithofacies of the transitional piedmont-axial system (**QTstsm**), conglomerate-sandstone lithofacies of the piedmont system (**QTspcs**), and conglomerate lithofacies of the piedmont system (**QTspc**). **pЄ**, Precambrian bedrock. Note interfingering of axial-fluvial and piedmont deposits that defines the transitional axial-piedmont system and the subvertical orientation of lithofacies contacts except during episodes of onlap (retrogradation) and progradation.

dashed or dotted) through the map area. Wherever possible, I also extrapolate the approximate location of buried contacts (dotted) beneath post-Santa Fe cover. Except for faults, this is not normally done on geological maps. Estimation of the location of buried contacts will be necessary for the ultimate goal of basin-scale hydrogeologic modeling; this is best done by the mapper in the field.

(4) It is important to note that map patterns and cross-section geometries of lithofacies may differ significantly from those of traditional geologic maps in that contacts between textural lithofacies are commonly at a high angle to bedding. In other words, in simple aggradational sequences, contacts between lithofacies will be *subvertical* (Fig. 2). Only during episodes of rapid progradation or retrogradation (onlap) will lithofacies contacts be subparallel to bedding.

(5) Wherever possible, contacts between textural lithofacies should be placed at natural boundaries within depositional systems. These boundaries are analogous to those utilized in sequence stratigraphy (unconformities, surfaces of rapid progradation or retrogradation, flooding surfaces along margins of lacustrine systems, etc.) and, although some generalization may be necessitated by map-scale requirements, are highly reproducible between workers. Placement of other lithofacies contacts, however, such as between laterally equivalent conglomerate and conglomerate-sandstone lithofacies of the piedmont system in simple aggradational sequences, may be somewhat subjective.

Use of the optional fifth parameter may vary between areas and workers, without compromising the utility of the remainder of the classification.

Despite the unavoidable imprecision of some aspects of the proposed classification, I believe it is preferable to the lumping together of deposits of drastically variable lithologic and hydrogeologic characteristics that occurs when mapping only depositional systems. Much work remains before the present classification will be of much value to hydrologists. It should be emphasized that the individual architectural elements analyzed by Gotkowitz (1993), Davis (1990, 1994), Planert (1995), Davis et al. (1993) and Detmer (1995a, b) represent only small components of the textural lithofacies described herein. For example, the axial-fluvial column in Table 2 contains permeability measurements by Gotkowitz (1993) and Davis (1994) that are from meter-scale architectural elements of the tributary axial-fluvial system exposed at the Bosque site approximately 17 km south-southwest of Belen in the southern Albuquerque Basin. Their permeability measurements were taken from architectural elements that, when considered individually, would be classified as lithofacies cs, s, or m (Fig. 1) of the tributary axial-fluvial system. It is important to note, however, that these architectural elements are not mappable at a scale of 1:24,000. Because of this, map-scale considerations would require that the entire studied interval at the Bosque site be texturally averaged and mapped as a single sandstone-mudstone lithofacies of the tributary axial-fluvial system (QTsasm), bounded above and below by sandstone lithofacies of the tributary axial-fluvial system (QTsas). This will necessitate the calculation of hydrologic characteristics (magnitude and spatial correlation structure of permeability) for the entire thickness of the studied unit (-15 m). Such modeling of composite hydrostratigraphic sequences has not yet been attempted in the Santa Fe Group, but it will be necessary in order to bridge the gap in scale between current hydrologic studies and ongoing geologic mapping. Conversely, if mapping at a scale of 1:24,000 is not adequate to address local hydrogeological issues such as modelling of contaminant transport, additional mapping at larger scales will be required.

The hydrologic characteristics of many textural lithofacies in Table 2 remain unstudied. This is particularly true of the conglomeratic portions of the facies tract that are not readily amenable to characterization by either field or laboratory techniques. The potential value of this classification system will be fully realized only when average hydrologic characteristics have been determined for *all* of the volumetrically important textural lithofacies listed in Table 2 for *each* formation of the Santa Fe Group in a given basin.

ACKNOWLEDGMENTS—Field work for this report was supported by the New Mexico Bureau of Mines and Mineral Resources (C. E. Chapin, Director) and by matching-funds grants provided by the National Geologic Mapping Act via the U.S. Geological Survey. The paper was improved by NMG reviewers W. C. Haneberg and G. A. Smith. Additional helpful reviews were by B. D. Allen, R. M. Chamberlin, C. E. Chapin, S. D. Connell, D. M. Detmer, J. W. Hawley, P. Johnson, D. W. Love, S. G. Lucas, G. H. Mack, F. Phillips, and W. R. Seager.

References

Anderson, M. P., 1989, Hydrogeologic facies models to delineate large-scale spatial trends in glacial and glaciofluvial sediments: Geological Society of America, Bulletin, v. 101, pp. 501-511.

Baldwin, B., and Butler, C. 0., 1985, Compaction curves: American Association of Petroleum Geologists, Bulletin, v. 69, no. 4, pp. 622-626.

Bryan, K., 1938, Geology and ground-water conditions of the Rio Grande depression in Colorado and New Mexico: [U.S.] Natural Resources Planning Board, Washington, The Rio Grande Joint Investigations in the Upper Rio Grande Basin, v. 1, pt. 2, pp. 196-225.

Cather, S. M., 1995a, Geologic map of upper Cenozoic deposits of the Mesa del Yeso 7.5-minute quadrangle, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Open-file Report 417a, scale 1:24,000.

Cather, S. M., 1995b, Geologic map of upper Cenozoic deposits of the Loma de las Cañas 7.5-minute quadrangle, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Open-file Report 417b, scale 1:24,000.

Cather, S. M., Chamberlin, R. M., Chapin, C. E., and McIntosh, W. C., 1994, Stratigraphic consequences of episodic extension in the Lemitar Mountains, central Rio Grande rift; *in* Keller, G. R., and Cather, S. M. (eds.), Basins of the Rio Grande rift: Structure, stratigraphy, and tectonic setting: Geological Society of America, Special Publication 291, pp. 157-170.

Chamberlin, R. M., 1982, Geologic map, cross sections, and map units of the Lemitar Mountains, Socorro County, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Open-file Report 169, 3 plates, scale 1:12,000.

Darton, N. H., 1922, Geologic structure of parts of New Mexico: U.S. Geological Survey, Bulletin 726, pp. 173-275.

Davis, J. M., 1990, An approach for the characterization of spatial variability of permeability in the Sierra Ladrones Formation, Albuquerque Basin, New Mexico: Unpublished MS thesis, New Mexico Institute of Mining and Technology, Socorro, 137 pp.

Davis, J. M., 1994, A conceptual sedimentological-geostatistical model of aquifer heterogeneity based on outcrop studies: Unpublished PhD dissertation, New Mexico Institute of Mining and Technology, Socorro, 234 pp.

Davis, J. M., Lohman, R. C., Phillips, F. M., Wilson, J. L., and Love, D. W., 1993, Architecture of the Sierra Ladrones Formation, central New Mexico: Depositional controls on the permeability correlation structure: Geological Society of America, Bulletin, v. 105, pp. 998-1007.

Davis, R. A., 1992, Depositional systems: An introduction to sedimentology and stratigraphy: Prentice Hall, New Jersey, 604 pp.

Detmer, D. M., 1995a, Permeability, porosity, and grain-size distribution of selected Pliocene and Quaternary sediments in the Albuquerque Basin, central New Mexico: Unpublished MS thesis, New Mexico Institute of Mining and Technology, Socorro, 115 pp.

Detmer, D. M., 1995b, Permeability, porosity, and grain-size distribution of selected Pliocene and Quaternary sediments of the Albuquerque Basin: New Mexico Geology, v. 17, no. 4, pp. 79-87.

Fisher, W. L., and Brown, L. F., Jr., 1972, Clastic depositional systems-a genetic approach to facies analysis: Bureau of Economic Geology, University of Texas at Austin, Annotated Outline and Bibliography, 211 pp.

Fisher, W. L., and McGowen, J. H., 1967, Depositional systems in the Wilcox Group of Texas and their relationship to the occurrence of oil and gas: American Association of Petroleum Geologists, Bulletin, v. 53, pp. 30-54.

Folk, R. L., 1974, Petrology of sedimentary rocks: Hemphill, Austin, 182 pp.

Galusha, T., and Blick, J. C., 1971, Stratigraphy of the Santa Fe Group, New Mexico: American Museum of Natural History, Bulletin, v. 144, pp. 1-127.

Gawne, C. E., 1981, Sedimentology and stratigraphy of the Miocene Zia Sand of New Mexico: Geological Society of America, Bulletin, v. 92, pp. 999-1007.

Gotkowitz, M., 1993, A study of the relationship between permeability distributions and small-scale sedimentary features in a fluvial formation: Unpublished MS thesis, New Mexico Institute of Mining and Technology, Socorro, 78 pp.

Groat, C. G., 1972, Presidio Bolson, Trans-Pecos Texas and adjacent Mexico: Geology of a desert basin aquifer system: Bureau of Economic Geology, University of Texas at Austin, Report of Investigations No. 76, 46 pp.

Haneberg, W. C., 1995, Depth-porosity relationships and virgin specific storage estimates for the upper Santa Fe Group aquifer system, central Albuquerque Basin, New Mexico: New Mexico Geology, v. 17, no. 4, pp. 62-71.

Hawley, J. W., and Haase, C. S., compilers, 1992, Hydrogeologic framework of the northern Albuquerque Basin: New Mexico Bureau of Mines and Mineral Resources, Open-file Report 387, 74 pp.

Hawley, J. W., and Lozinsky, R. P., 1992, Hydrogeologic framework of the Mesilla Basin in New Mexico and western Texas: New Mexico Bureau of Mines and Mineral Resources, Open-file Report 323, 66 pp.

Hawley, J. W., Haase, C. S., and Lozinsky, R. P., 1995, An underground view of the Albuquerque Basin; *in* Ortega-Klett, C. T. (ed.), The Water Future of Albuquerque and the Middle Rio Grande Basin: New Mexico Water Resources Institute, Proceedings of the 39th Annual Water Conference, pp. 37-55.

Hayden, F. V., 1869, Preliminary report of the U.S. Geological Survey of Colorado and New Mexico: U.S. Geological Survey, Third Annual Report, 155 pp.

Ingersoll, R. V., Cavazza, W., Baldridge, W. S., and Shafiqullah, M., 1990, Cenozoic sedimentation and paleotectonics of north-central New Mexico: Implications for initiation and evolution of the Rio Grande rift: Geological Society of America, Bulletin, v. 102, pp. 1280-1296.

Keaton, J. R., 1984, Genesis-lithology-qualifier (GLQ) system of engineering geology mapping symbols: Bulletin of the Association of Engineering Geologists, v. 21, pp. 335-364.

Machette, M. N., 1978, Geologic map of the San Acacia quadrangle, Socorro County, New Mexico: U.S. Geological Survey, Geologic Quadrangle Map GQ 1415, scale 1:24,000.

Miall, A. D., 1985, Architectural element analysis: A new method of facies analysis applied to fluvial deposits: Earth Science Reviews, v. 22, pp. 261-308.

Mozley, P., Beckner, J., and Whitworth, T. M., 1995, Spatial distribution of calcite cement in the Santa Fe Group, Albuquerque Basin, NM: Implications for ground-water resources: New Mexico Geology, v. 17, no. 4, pp. 88-93.

NACSN (North American Commission on Stratigraphic Nomenclature), 1983, North American stratigraphic code: American Association of Petroleum Geologists, Bulletin, v. 67, pp. 841-875.

Planert, C. S., 1995, Determination of hydraulic conductivities of low permeability materials in the Sierra Ladrones Formation, Albuquerque Basin: New Mexico Institute of Mining and Technology, Socorro, Hydrology Program Open-file Report, 60 pp.

Seager, W. R., Hawley, J. W., Kottlowski, F. E., and Kelley, S. A., 1987, Geology of the east half of the Las Cruces and northeast El Paso 1° x 2° sheets, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Geologic Map 57, scale 1:125,000.

Shepard, R. G., 1989, Correlations of permeability and grain size: Ground Water, v. 27, pp. 633-638.

Spiegel, Z., and Baldwin, B., 1963, Geology and water resources of the Santa Fe Area, New Mexico: U.S. Geological Survey, Water-supply Paper 1525, 258 pp.

Steinpress, M. G., 1981, Neogene stratigraphy and structure of the Dixon area, Espanola Basin, north-central New Mexico: Summary: Geological Society of America, Bulletin, v. 92, pp. 1023-1026.

Vukovic, M., and Soro, A., 1992, Determination of hydraulic conductivity of porous media from grain-size composition: Water Resources Publications, Littleton, CO, 83 pp.

Wentworth, C. K., 1922, A scale of grade and class terms for clastic sediments: Journal of Geology, v. 30, pp. 377-392.