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A DOUBLE-POROSITY MODEL OF GROUND-WATER FLOW IN THE MADERA FORMATION BASED ON SPRING HYDROGRAPHS AND AQUIFER TEST ANALYSES FROM PLACITAS, NEW MEXICO

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Abstract—The Pennsylvanian Madera Formation is a fractured carbonate aquifer of regional significance in the Sandia Mountains east of Albuquerque, New Mexico. Characterization of fractured aquifers is problematic due to the localized nature of ground-water flow. Spring hydrographs and aquifer test data indicate that ground water in the Madera aquifer moves as combined diffuse flow and fracture flow. Aquifer test drawdown data fit a double-porosity model, and show that ground water is primarily transmitted through large fractures, but the majority of aquifer storage is attributable to the limestone matrix. Fracture transmissivity ranges from 1840–2160 ft^2/d. Total storativity, for both fractures and matrix, is 0.20–0.25. The fractures transmitting the bulk of spring discharge are associated with faults in the Madera Formation. Spring hydrographs from fault-controlled springs near the Village of Placitas may provide a potentially valuable source of data on Madera aquifer hydraulic properties, including effective porosity, transmissivity, storage, water budgets, and recharge. Further work is required before the full potential of spring hydrograph data can be utilized as a regional aquifer characterization tool in the Madera Formation.

INTRODUCTION

Carbonate aquifers have long presented a challenge for hydrologists because of the localized nature of ground-water flow, and the difficulty in applying standard aquifer characterization and testing methods. Conceptual models of ground-water flow in carbonate aquifers follow a spectrum stretching from entirely diffuse flow at one extreme to entirely conduit flow at the other (White, 1969, 1977; Ford and Williams, 1989). Most carbonate aquifers fall somewhere in the middle of this spectrum, with both diffuse flow in the matrix and/or pervasive, narrow fractures, as well as conduit flow through solution enlarged fissures, fractures, and bedding planes. These aquifers commonly exhibit a range in aquifer properties of over seven or eight orders of magnitude within tens of meters. Determination of the physical properties of such highly anisotropic and heterogeneous aquifers poses severe practical problems for water resource managers and planners.

The Madera Formation, a carbonate aquifer of regional significance for ground-water development in the Sandia Mountains east of Albuquerque, New Mexico, is currently the focus of a regional hydrogeologic characterization. A comprehensive analysis of carbonate aquifers usually involves complementary approaches that include water balance estimates, borehole analysis, spring hydrograph analysis, and water tracing. Determination of hydraulic properties of carbonate aquifers by analysis of spring hydrographs has been demonstrated by many authors (Atkinson, 1977; Bonacci and Jelin, 1988; Ford and Williams, 1989; Korkmaz, 1990; Bonacci, 1993; and Angelini and Dragoni, 1997). The shape of a spring hydrograph reflects the response of the aquifer to recharge. It is possible to both qualitatively and quantitatively identify ground-water storage, recharge, and transportation properties of an aquifer by the analysis of spring hydrographs. When coupled with water level hydrographs or catchment geometry, spring discharge data can yield good estimates of effective porosity, transmissivity, and water budget components. Furthermore, because spring hydrographs reflect characteristics of the path along which ground water flows from its recharge area to its discharge area, estimates derived from spring hydrographs are representative of the aquifer system as a whole, as opposed to a small area surrounding a single test well. On the other hand, a spring hydrograph will likely represent the non-unique product of several interrelated properties and processes; therefore, interpretation of hydrographs may not be straightforward. This characterization approach can potentially provide valuable input for regional water assessments and ground-water flow models in areas where aquifer data are scarce.

In this analysis, I use aquifer test data from the Madera Formation, and spring hydrographs from three springs near Placitas, New Mexico, to develop a conceptual model of ground-water flow in the Madera aquifer, and to estimate discharge, dynamic storage, recharge, and aquifer properties for the portions of the aquifer contributing to the springs. The study area is located on Cuchilla Lupe, a prominent limestone ridge situated east of the Village of Placitas (Village), and at the northern end of the Sandia Mountains (Fig. 1). Numerous springs discharge along the flanks of Cuchilla Lupe, three of which (Ciruela spring, Placitas spring #3, and El Oso spring) provide most of the

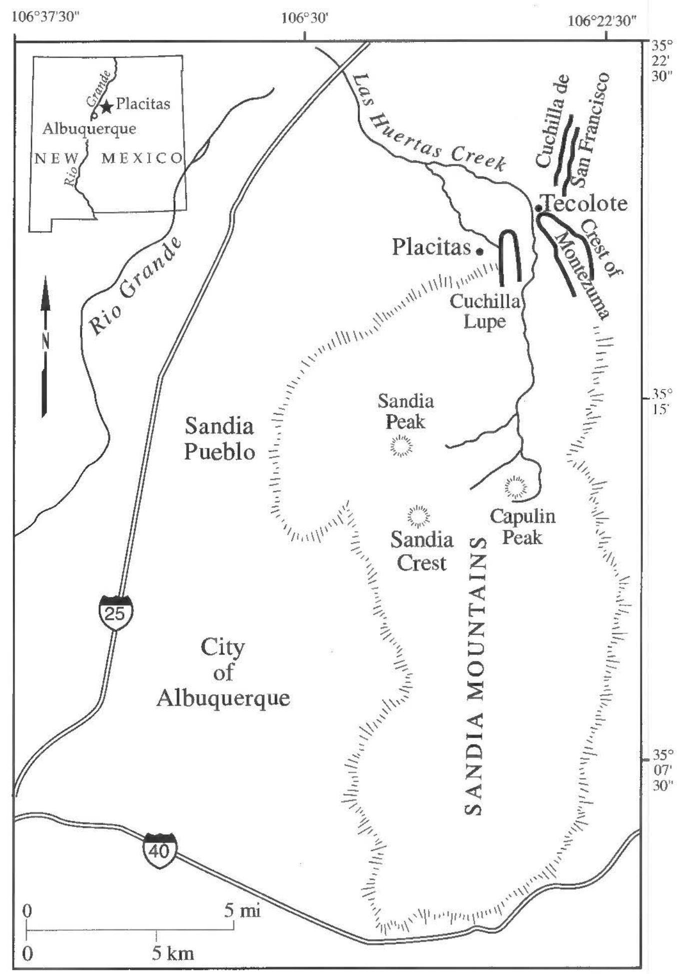

FIGURE 1. Location of Placitas relative to the Sandia Mountains, and the north-trending limestone salients of Cuchilla Lupe, Crest of Montezuma, and Cuchilla de San Francisco.

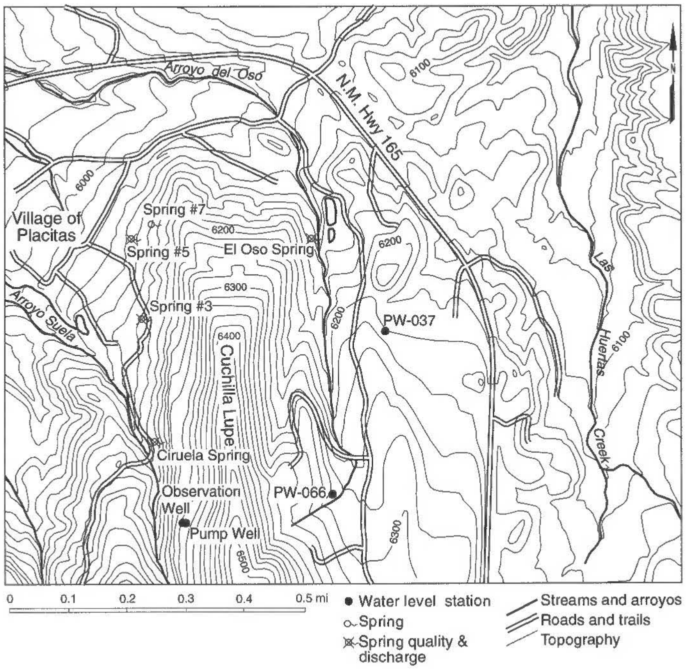

FIGURE 2. The study area showing the vicinity of the Village of Placitas and Cuchilla Lupe.

domestic and irrigation water supply for the Village.

GEOLOGY OF CUCHILLA LUPE

Cuchilla Lupe is a north-trending limestone salient that extends from the northern Sandia Mountains to form a prominent ridge immediately east of the Village of Placitas (Figs. 1, 2). The ridge top is at an elevation of 6500 ft and is composed of the lower limestone member of the Pennsylvanian Madera Formation (Fig. 3). The lower Madera Formation is primarily a thick-bedded limestone, with minor interbeds of variously colored siltstones and shales. The beds generally strike north to northeast with eastward dips ranging from 7 to 20°. Along the toe of the ridge just east of the Village, the limestone beds form a dip slope, with northward dips of approximately 15° (Connell et al., 1995). Stratigraphic thickness of the lower Madera at this location is estimated to be 600–630 ft (Picha, 1982). The stratigraphic units and structures exposed near Placitas are shown on the geologic map in Figure 3, and in cross-section in Figures 4 and 5. Cross-section A–A' (Fig. 4) is constructed west–east through the Village and adjacent to Placitas spring #3. North–south cross-section B–B' (Fig. 5) is constructed though the test wells, Ciruela spring and Placitas spring #3, and illustrates the proximity of the wells and springs to the hydrogeologic boundaries.

Cuchilla Lupe is fault-bounded to the east, west, and north, and forms a horst block in the Las Huertas Creek half-graben (Figs. 3, 4) (Connell et al., 1995). The Suela fault, a major north-trending, down-to-the-west normal fault, forms the western boundary of the Cuchilla Lupe horst, and is located 250 ft west of the test wells. This fault merges with the Placitas fault zone east and northeast of the Village, where it places

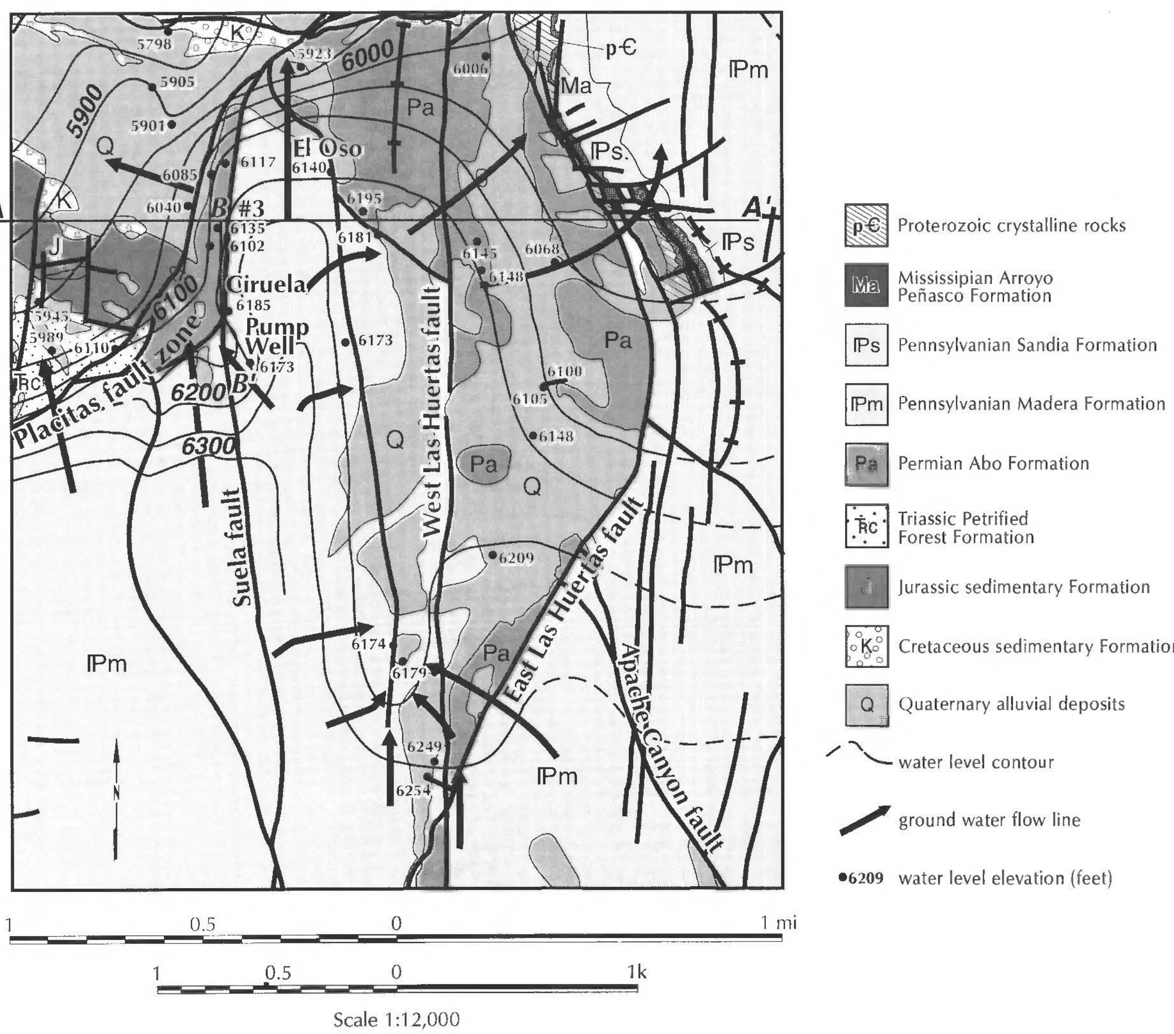

FIGURE 3. Geologic map of the Placitas area (from Connell et al., 1995).

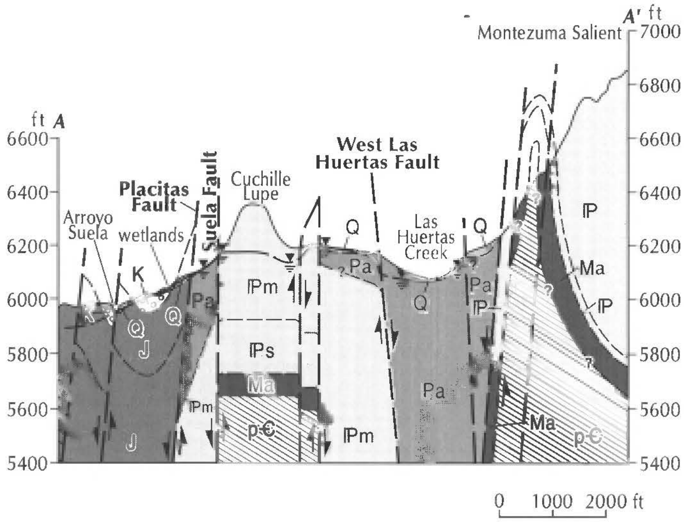

FIGURE 4. Geologic cross-section A–A' through Cuchilla Lupe (see Fig. 3 for unit legend) with five times vertical exaggeration to show shallow water table

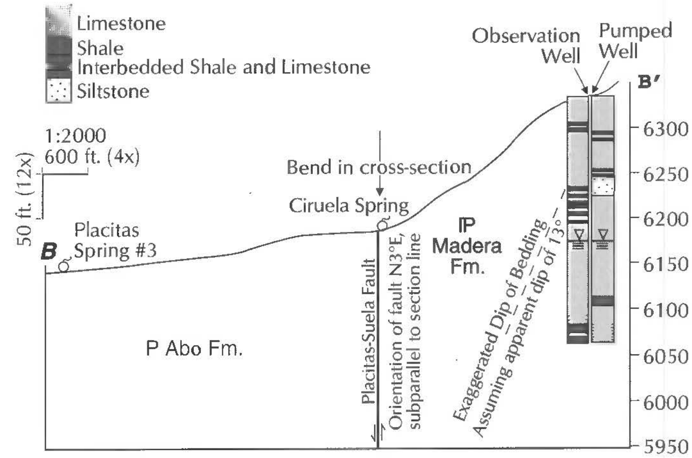

FIGURE 5. Geologic cross-section B–B' through aquifer test wells and springs with 12 times vertical exaggeration to show test well lithology.

Madera limestone against Permian Abo Formation. The Suela fault extends over 5 mi to the south, at least as far as Capulin Peak, where it contributes to a major fault system that forms the upper part of Las Huertas Canyon. Here, the geometry of the fault changes to a west-up orientation. The fault intersects Las Huertas Creek approximately 3.5 mi south-southeast of the test wells. The eastern boundary of the Cuchilla Lupe horst is formed by the West Las Huertas fault, a down-to-the-east normal fault, that also places Madera limestone against Permian Abo Formation. This fault runs roughly coincident with NM-165 south of the Village. A small, local fault, antecedent to the West Las Huertas fault, cuts the center of the horst block and is responsible for most of the relief along the east face of the ridge. Exposures of Abo Formation located west of the Suela fault, north of Cuchille Lupe, and east in Las Huertas Canyon, consist of reddish-brown mudstone and minor interbedded sandstone of relatively low permeability compared with juxtaposed Madera limestone.

Although no data exist concerning fractures along the Suela or West Las Huertas faults, major breccia zones have been mapped along faults that are well exposed elsewhere in the vicinity of Cuchilla Lupe. Examples include the East Las Huertas and Apache Canyon faults located in Madera limestone east of Las Huertas Canyon (Fig. 3), and the Agua Zarca fault in Proterozoic granite to the west (Connell et al., 1995). Breccia zones are commonly associated with well-developed fracture networks, and significant fault-parallel fracture zones up to 10 ft in width have been mapped in the Madera limestone (Picha, 1982). Where the Suela and other faults cut Madera limestone, they are probably paralleled by a pervasive fracture zone that locally and dramatically increases the anisotropy and transmissivity of the Madera aquifer in the vicinity of the faults. However, where faults place lower permeability units adjacent to the highly transmissive Madera limestone, or where a permeability reduction is associated with the core of the fault itself, then the fault may effectively reduce ground-water flow across the structure.

The numerous faults bounding Cuchilla Lupe influence the local hydrology of the Madera aquifer and the Village springs. Water level contours (Fig. 3) show ground-water converging near Suela fault, the small antecedent fault along the east-face of Cuchilla Lupe, and/or their associated and parallel damage zones, indicating that high permeability along the faults causes them to act as drains. Water level data across portions of the Placitas fault zone show declines in hydraulic head, suggesting restriction of flow where lower permeability units, such as the Permian Abo, or Cretaceous Mancos formations, are placed adjacent to Madera limestone. Openings associated with bedding planes, and fractures become enlarged over time by dissolution of the limestone in ground water, and contribute to a conduit component of ground-water flow within the Madera aquifer. Two large springs, Ciruela spring and El Oso spring, are located along separate faults in the Madera Formation, where the limestone abuts lower permeability units. Ciruela spring discharges from enlarged fractures within the Suela fault. El Oso spring discharges at the termination of the small antecedent fault on the east side of Cuchilla Lupe. Numerous other smaller springs, including Placitas springs #3, #5, and #7, emerge from the Abo Formation between the Suela and Placitas faults.

DATA COLLECTION

Beginning in April, 1998, the U.S. Bureau of Reclamation (USBOR) and the Las Acequias de las Placitas (Las Acequias) undertook a drought relief project for the Village. The project was designed to gather information on the Madera Formation aquifer in the vicinity of Cuchilla Lupe and the Village, through the installation of two exploratory wells, a borehole aquifer test, and the collection of spring discharge data. The springs, test wells, and other features are shown in Figure 2. The wells were drilled and installed in April and May, 1998. Beginning on 23 May 1998 and continuing for almost five months, discharge from four springs in the vicinity of the Village (Ciruela spring, El Oso spring, and Placitas springs #3 and #5) was monitored on an hourly to daily basis. Discharge from springs #3 and #5 was measured with two 0.45 cfs (202 gal/min) ramp flumes with an accuracy of ±3%. Ciruela discharge was measured by combining a flow meter and totalizer in the system delivery line with a 0.45 cfs ramp flume on an overflow ditch. Discharge from El Oso spring was measured using a 2 cfs (898 gal/min) ramp flume, also with an accuracy of ±3%. On 28 September, a three-day aquifer test was undertaken, during which water levels in the pumping and observation wells and discharge from the four springs were monitored. Spring monitoring has continued to the present, and is ongoing. Spring and aquifer test data were collected by the USBOR and volunteers of Las Acequias as part of the drought relief project. Analysis of the aquifer test and spring discharge data was completed by the New Mexico Bureau of Mines and Mineral Resources (NMBMMR) and is the subject of this paper.

SPRING HYDROGRAPH ANALYSIS

The forms of discharge hydrographs are varied, complex, and governed by factors including lithology, aquifer storage characteristics, aquifer geometry, and the nature of the recharge. Most discharge hydrographs have three common features: (1) a lag time between a recharge input and the spring's response, (2) a rise to peak discharge (rising limb), and (3) a decline as discharge returns to normal (recession). The shape of these features reflects the response of the aquifer to recharge,

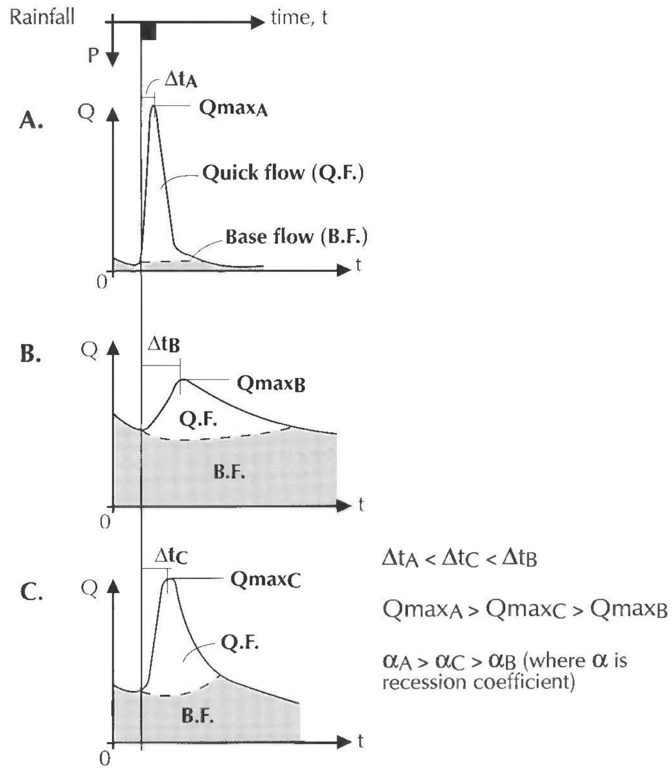

FIGURE 6. Various forms of discharge hydrographs for: **A,** conduit flow, **B,** diffuse flow, and C, combined flow (modified from Bonacci, 1993).

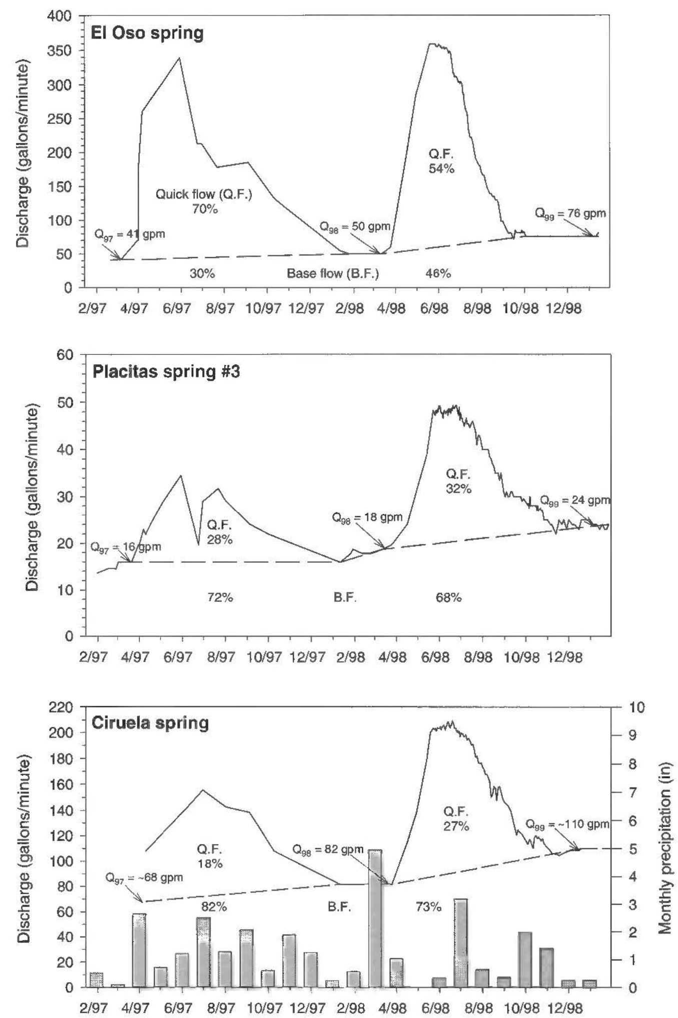

FIGURE 7. Spring hydrographs for El Oso spring, Placitas spring #3, and Ciruela spring for water years 1998 and 1999.

and provides information about the nature of ground-water flow contributing to the spring. Forms of discharge hydrographs reflecting conduit, diffuse, and combined flow are shown in Figure 6. A steep rising limb, short response time, sharp peak, and steep recession indicate conduit flow. A broad peak with a gently sloping rising limb and recession indicates a dominant component of diffuse flow.

Hydrographs of the Placitas springs (Fig. 7) indicate that ground water in the Madera aquifer moves as combined diffuse flow and fracture flow. Spring discharge fluctuates with a strong seasonal response to spring snowmelt. More detailed analyses of local precipitation and spring discharge for Summer and Fall of 1998 have shown no response to local summer thunderstorms. Discharge rates rise rapidly in mid April, maintain a relatively constant discharge for 4–8 weeks, then decrease slowly to a relatively constant winter base flow by mid September to late October. The hydrograph from El Oso spring has a steep rising limb and relatively short response time, a narrow peak, and a moderate recession to a very constant winter base flow. During the rising limb of the April 1997 hydrograph, discharge increased from 70 to 184 gal/min (163%) in just one day, and to over 260 gal/min (370%) in six days. This curve reflects a large component of fracture or conduit flow. Spring #3 and Ciruela spring hydrographs exhibit more moderate spring-time discharge peaks and are nearly identical in form. Discharge during the rising limbs of the two hydrographs increases 140% over the same seven-week period (from April 1 to May 20), and the recession curves have comparable shapes. The hydrograph form indicates a system dominated by diffuse flow with minor input from fracture flow (Figs. 6, 7). Spring #3 and Ciruela spring clearly discharge from the same, diffuse-flow dominated catchment. Discharge from El Oso spring originates from a different portion of the Madera aquifer dominated by fracture flow.

TABLE 1. Discharge estimates for Placitas Village springs for water years 1998 and 1999 derived from spring hydrograph separation (see Fig. 7).

Spring	Water year[1]	Quick flow discharge ac-ft	Quick flow discharge % of total	Base flow discharge ac-ft	Base flow discharge % of total	Total discharge ac-ft
El Oso	1998	174	70	75	30	250
	1999	129	54	111	46	240
#3	1998	10	28	27	72	37
	1999	15	32	33	68	49
Ciruela	1998	32	18	151	82	183
	1999	60	27	159	73	219

[1]From March 1 of previous year; discharge values for water year 1999 are projected based on base flow measurements taken January 26, 1999.

Spring hydrographs can be separated into components of quick flow and base flow in a manner analogous to separation of stream-flow hydrographs. Ground-water flow during a hydrograph rise and peak derives from quick flow, which is rapidly percolating water moving through well-developed networks of conduits, fissures, and large fractures. During hydrograph recession and base flow, discharge derives predominantly from diffuse flow through pervasive fractures and smaller openings. Hydrograph separation is approximate because all methods are partly subjective. The simplest hydrograph separation technique, and the one applied here, is to draw a line connecting the point at the beginning of the rising limb with the point at the base of the recession curve (Viessman and Lewis, 1996; Atkinson, 1977). Hydrographs of the Placitas springs (Fig. 7) are separated into quick flow and base flow components, and the volume of each component is obtained by computing the area beneath each curve (Table 1). Hydrograph separation suggests that over half of the annual discharge

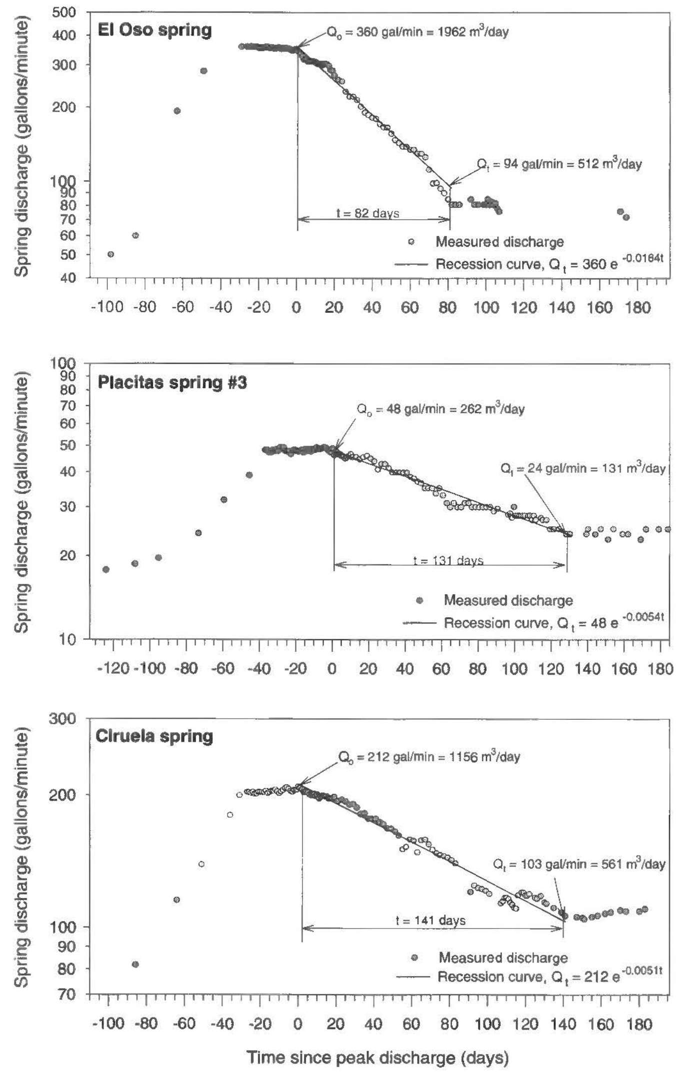

FIGURE 8. Recession curve analysis for Placitas Village springs for water year 1999.

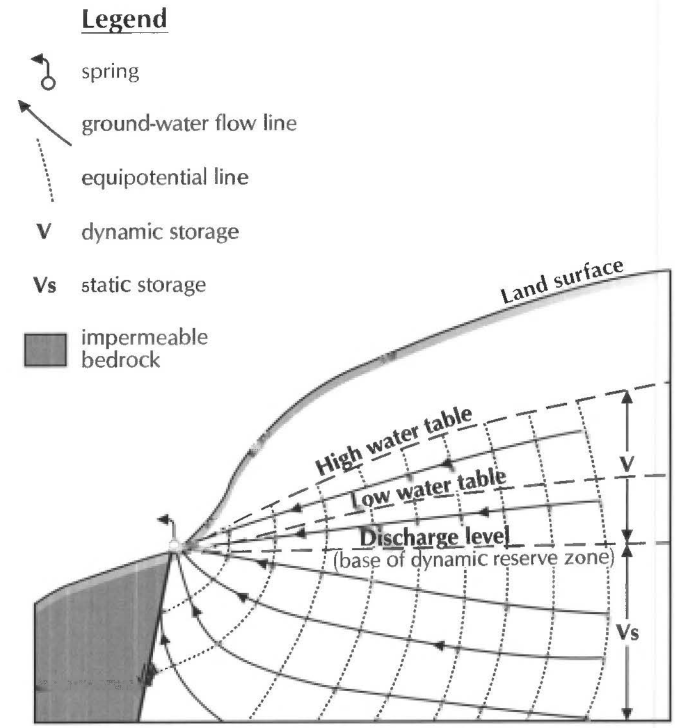

FIGURE 9. Schematic illustration of aquifer storage zones depicting concept of dynamic and static storage.

of El Oso spring is composed of quick flow, whereas 70–80% of annual discharge from spring #3 and Ciruela spring is comprised of base flow.

Quantitative analysis of hydrograph recession follows the simple exponential relation (Maillet, 1905): $Q_t = Q_o e^{-\alpha \cdot t}$, where Q_t is the discharge at time t, Q_o is the discharge at the start of recession, t is the time elapsed (in days) between Q_t and Q_o, and α is a recession coefficient (in days^{-1}), which depends on the geometry and hydrologic characteristics of the spring's catchment. In a semi-logarithmic plot, the recession curve is represented as a straight line with a slope of $-\alpha$. Recession curve analysis of the Placitas spring hydrographs is shown in Figure 8. Parameter values for each spring, including recession coefficients and Q_t calculated for the end of the recession period, are compiled in Table 2. The value of the recession coefficient α is a function of the aquifer

TABLE 2. Recession curve analysis for Placitas Village springs based on water year 1999 hydrograph (see Fig. 8).

Spring	Recession Interval, t (d)	Q_o gal/min	Q_t gal/min	Recession coefficient, α (d^{-1})
El Oso	82	360	94	0.0164
#3	131	48	24	0.0054
Ciruela	141	212	103	0.0051

effective porosity and transmissivity, and describes the rate of withdrawal of water from storage. When α is large, recession is steep, indicating a rapid drainage of fractures and fissures, and limited aquifer storage capacity. Conversely, a small α value indicates slow drainage from an extensive network of fractures or pores with a large storage capacity. Ciruela and spring #3 have very similar recession coefficients, which are much smaller in value than the coefficient for El Oso spring.

Estimates of dynamic storage can be derived by integration of the previous equation:

$$V = \int_0^t Q_o e^{-\alpha \cdot t} = \frac{Q_o}{\alpha}(1 - e^{-\alpha \cdot t}) = \frac{Q_o - Q_t}{\alpha}$$

Here, V is termed the dynamic storage, dynamic volume, or dynamic reserve, and represents the volume of water in storage above the level of the outflow spring. Figure 9 illustrates that only the upper part of the aquifer is dynamically involved in active ground-water circulation. A deeper, static storage zone may have a high permeability and storage capacity, but zero discharge if there is no hydraulic head to drive the flow. This equation determines the volume of water added to or released from ground-water storage over any given time period ($\Delta t = t_o - t_t$) between two discharges of interest. When applied to winter base flow between consecutive years, one can quantify aquifer recharge and changes in aquifer storage over cycles of wet and dry years and in response to ground-water development. Changes in dynamic storage in the portion of aquifer contributing to spring discharge can be calculated for the water year using a water balance approach (Korkmaz, 1990):

$$V_t = V_o + R - Q$$

where Vt is the dynamic storage at the end of the water year (t_t), Vo is the dynamic storage at the beginning of the water year (t_o), R is the ground-water recharge volume during the water year (time period, (Δt), and Q is the total volume of ground-water discharge during the water year. This simple water balance approach is used to estimate recharge and dynamic storage for the Placitas springs catchments. Results for

TABLE 3. Estimates of dynamic storage and recharge for Placitas Village springs for water years 1998 and 1999 (see Fig. 7 and Table 1).

Spring	Water year[1]	Winter base flow, gal/min	Dynamic storage ac-ft $V_o(Q_o/\alpha)$	ac-ft $V_t(Q_t/\alpha)$	Change in storage $\Delta V=V_t-V_o$ ac-ft	Total annual discharge, Q_T ac-ft	Recharge $R=Q_T\pm\Delta V$ ac-ft
El Oso	1997	41	—	11.0	—	—	—
	1998	50	11.0	13.5	+2.5	250	252
	1999	76	13.5	20.5	+7.0	240	247
#3	1997	16	—	13.1	—	—	—
	1998	18	13.1	14.8	+1.7	37	39
	1999	24	14.8	19.6	+4.8	49	54
Ciruela	1997	68	—	58.9	—	—	—
	1998	82	58.9	71.0	+12.1	183	195
	1999	110	71.0	95.3	+24.3	219	243

[1]From March 1 of previous year; discharge values for water year 1999 are projected using base flow measurements taken January 26, 1999.

each water year are shown in Table 3. It must be cautioned that application of these results is limited until the catchment area contributing to each spring is better defined. Further, the approach assumes that all aquifer outflow occurs through the springs, and that no other outflow components exist, such as leakage or flow across catchment boundaries. These problems are not trivial. However, the technique is a potentially significant approach to regional aquifer characterization and may prove useful in a region cursed by serious complexity and scarce data.

AQUIFER TEST DATA AND ANALYSIS

A three-day aquifer test was conducted in the USBOR drought relief exploration well in September, 1998. Water level measurements were taken in both pumping and observation wells during three days of pumping and through a three-day recovery period. Drawdown and recovery data from the test are presented in Figures 10 and 11.

Semi-log plots of drawdown data are consistent with a double porosity model developed by Barenblatt et al (1960) and described by Kruseman and deRidder (1990). This model views a fractured rock formation as consisting of two different media, both having their own characteristic hydraulic properties: (1) the fractures with high permeability and low storage capacity, and (2) the matrix blocks with low permeability and high storage capacity. The ground-water flow mechanism entails re-equalization of the pressure differential between the fractures and matrix by water flowing from the matrix blocks into the fractures. Flow towards a pumping well in this double-porosity system occurs entirely through the fractures, is radial, and in an unsteady state. Flow from the matrix to the fractures is assumed to be in pseudo-steady state.

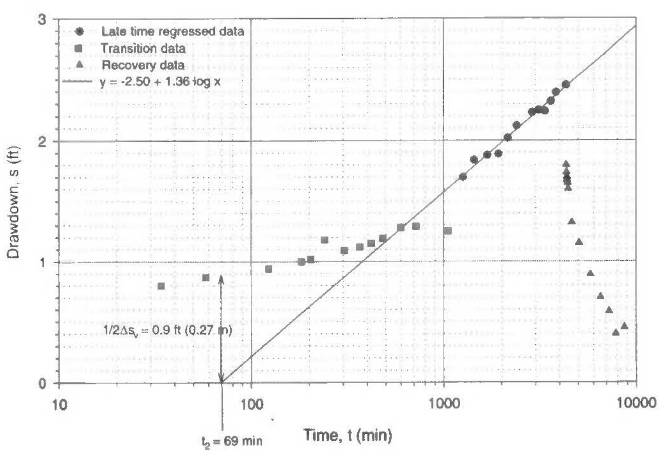

FIGURE 11. Drawdown vs. log time for observation well, and Warren-Root straight line analysis.

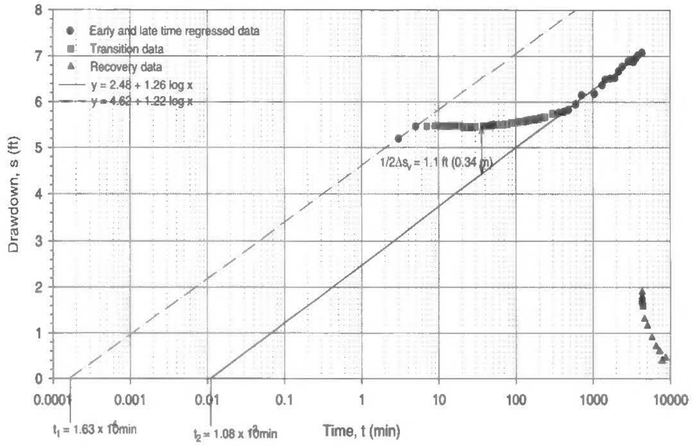

FIGURE 10. Drawdown vs. log time for pumping well, and Warren-Root straight line analysis.

The primary characteristic of drawdown in this model is a partitioning of data into three distinct time periods: (1) early pumping time, when all the flow comes from the fractures; (2) intermediate pumping time, a transition period during which the matrix blocks feed water at an increasing rate to the fractures, resulting in a partially stabilized drawdown; and (3) late pumping time, when the pumped water comes from storage in both the fractures and the matrix. Semi-log time-drawdown plots from a fractured, double-porosity system reflect these three time periods with a characteristic pattern of two parallel lines, representing early and late time drawdown, connected by a transitional curve representing the partially stabilized drawdown of intermediate time.

The drawdown data taken from the pumping and observation wells during the USBOR aquifer test generally fit this model (Figs. 10, 11). There are insufficient early time data to establish definitively the early-time straight line in the pumping well drawdown curve, but the data do show that an early time straight segment exists. The intermediate time transition and the late-time straight line are clearly defined in both wells. No early time data were gathered from the observation well. Three double-porosity methods were employed to evaluate the aquifer test data (Kruseman and deRidder, 1990): (1) the Warren-Root straight line method for analysis of early-time and late-time drawdown data from the pumping well (Fig. 10); (2) the Warren-Root straight line method for analysis of late-time drawdown data from the observation well (Fig. 11); and (3) the Bourdet-Gringarten curve fitting method for analysis of late-time drawdown data from the observation well. Results of computation of aquifer hydraulic properties are presented in Table 4, including the transmissivity of the fractures and storativity for both

TABLE 4. Aquifer hydraulic properties for the Madera Formation estimated from aquifer test data (see Figs. 10, 11).

Data Analyzed	Test Method	Tf[1] (ft^2/d)	Kf[2] (ft/d)	$(S_f+S_m)^3$	S_f^3	S_m^3
Pumping well late time	Warren-Root	197	32	0.20	0.003	0.197
Pumping well early time	Warren-Root	201	33	0.20	0.003	0.197
Observation well late time	Warren-Root	183	20	0.24	0.012	0.228
Observation well late time	Bourdet-Gringarten	171	19	0.26	nd	nd

[1]Transmissivity of fractures
[2]Hydraulic conductivity of fractures, assuming aquifer thickness, b = 20 ft for pumping well, and b = 30 ft for observation well
[3]S_f = storativity of fractures; S_m = storativity of matrix
nd = no data

fractures and matrix. Only drawdown data provide a separate quantification of fracture and matrix properties. Aquifer test results confirm the double porosity character of the Madera carbonate aquifer. The results indicate that fracture transmissivity is on the order of 1840–2160 ft^2/day, and that aquifer storativity, approximately 0.25, is almost entirely attributable to the matrix.

CONCLUSIONS AND DISCUSSION

The Madera Formation carbonate aquifer is a two-component system, in which ground water is primarily transmitted through large fractures, but the majority of ground-water storage is attributable to the limestone matrix and a network of fine fractures. In the vicinity of Cuchilla Lupe near Placitas, New Mexico, the fractures transmitting the bulk of aquifer discharge are associated with faults in the Madera Formation. Numerous springs discharge along major north–south faults as they terminate against the Placitas fault zone, immediately east of the Village of Placitas. Discharge hydrographs from three of these springs indicate that ground water moves through the Madera Formation as both conduit or fracture flow and as diffuse flow. Hydrograph separation indicates that over 50%, and possibly as much as 70%, of annual discharge from El Oso spring is quick flow, which originates from rapidly percolating water moving through a well-developed network of conduits, fissures, and large fractures. In contrast, 70–80% of annual discharge from Ciruela spring and Placitas spring #3 is base flow, which originates entirely as diffuse flow of ground water through limestone matrix and small fractures and openings. The double-porosity character of the Madera Formation is also reflected in aquifer test data. Semi-log drawdown plots of water level drawdown over time fit the theoretical double porosity model of Barenblatt et al. (1960). Analyses of drawdown data indicate a fracture transmissivity of 1840–2160 ft^2/day, and an aquifer storativity of 0.20 to 0.25 that is almost entirely attributable to the matrix. Spring hydrographs also provide a potentially valuable source of data on Madera aquifer properties including effective porosity, transmissivity, storage, water budget, and recharge. Estimates of dynamic storage and recharge for the portion of Madera aquifer contributing to the springs are developed from spring hydrographs. Further work is required before the full potential of spring hydrograph data can be utilized as a regional aquifer characterization tool in the Madera Formation.

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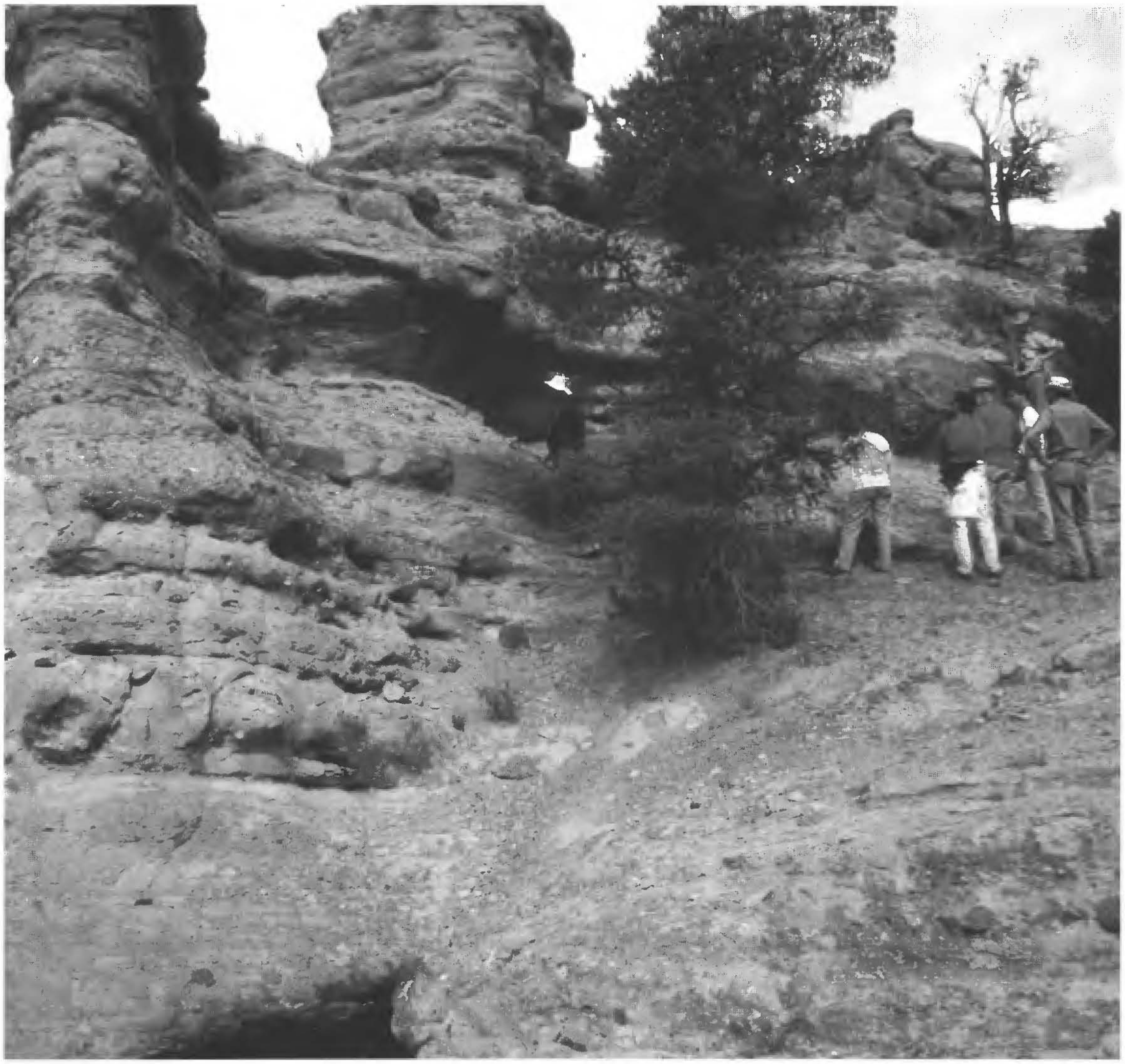

Eroding volcanoclastics of the Gila Formation with particles ranging in size from dust to large boulders at third-day stop 1A of the 1994 NMGS trip to the Mogollon slope of west-central New Mexico and east-central Arizona. The rocks may be flat-lying here, but the geology certainly is not simple (photograph courtesy of George Austin).