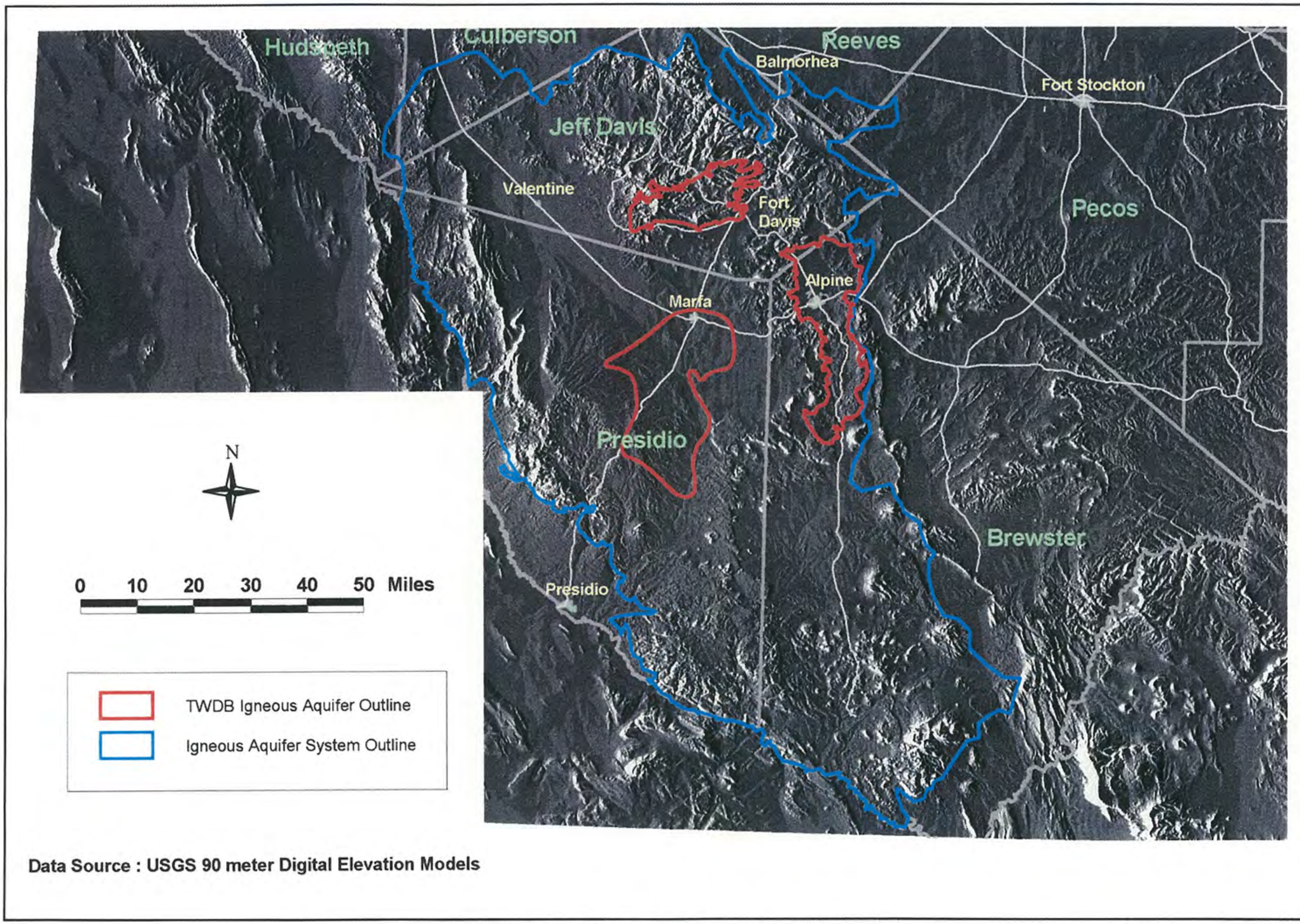

TOPOGRAPHIC RELIEF (HILLSHADE)

FIGURE 7

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The thickness of the igneous rocks has been estimated from geophysical logs and from sample logs of prospective oil wells. In western Jeff Davis County, the thickness of the formations generally ranges from 2,000 ft to as much as 6,000 ft. The Killam oil test well near Valentine encountered 6,032 feet of Igneous formations. In northern Presidio County, the thickness ranges from 1,000 ft to 4,000 ft. Relatively few oil exploration wells have been drilled in Brewster County; however, water well data indicate that the thickness of igneous rocks in the westernmost part of the county is as much as 3,000 ft.

During the latter part of the Tertiary Period, after the cessation of igneous activity, tensional forces caused a series of basins (or bolsons) to form within the complex system of igneous rocks and older rocks. Large sections of the crust moved downward relative to other areas. As these sections of crust subsided, streams draining the structurally higher areas deposited thick sequences of sedimentary material in the resulting basins, such as the Presidio Bolson and Ryan Flat. Although filled with gravel, sand, and silt, the underlying bedrock section of each basin consists of igneous material that was once exposed. The floors of these basins now consist of Quaternary (~1.8 Ma to present) alluvial deposits, the youngest sediments eroded from the surrounding mountains.

HYDROGEOLOGY

The "Igneous aquifer system " is not a single aquifer, but a number of smaller aquifers, with varying degrees of hydrogeologic continuity (or interconnectivity). In a study of the hydrogeology of the Davis Mountains, for example, Hart (1992) reported that groundwater in Jeff Davis County is found in 11 distinct water-bearing units. The faulting and fracturing prevalent in the rocks of this region increase the potential flow between units.

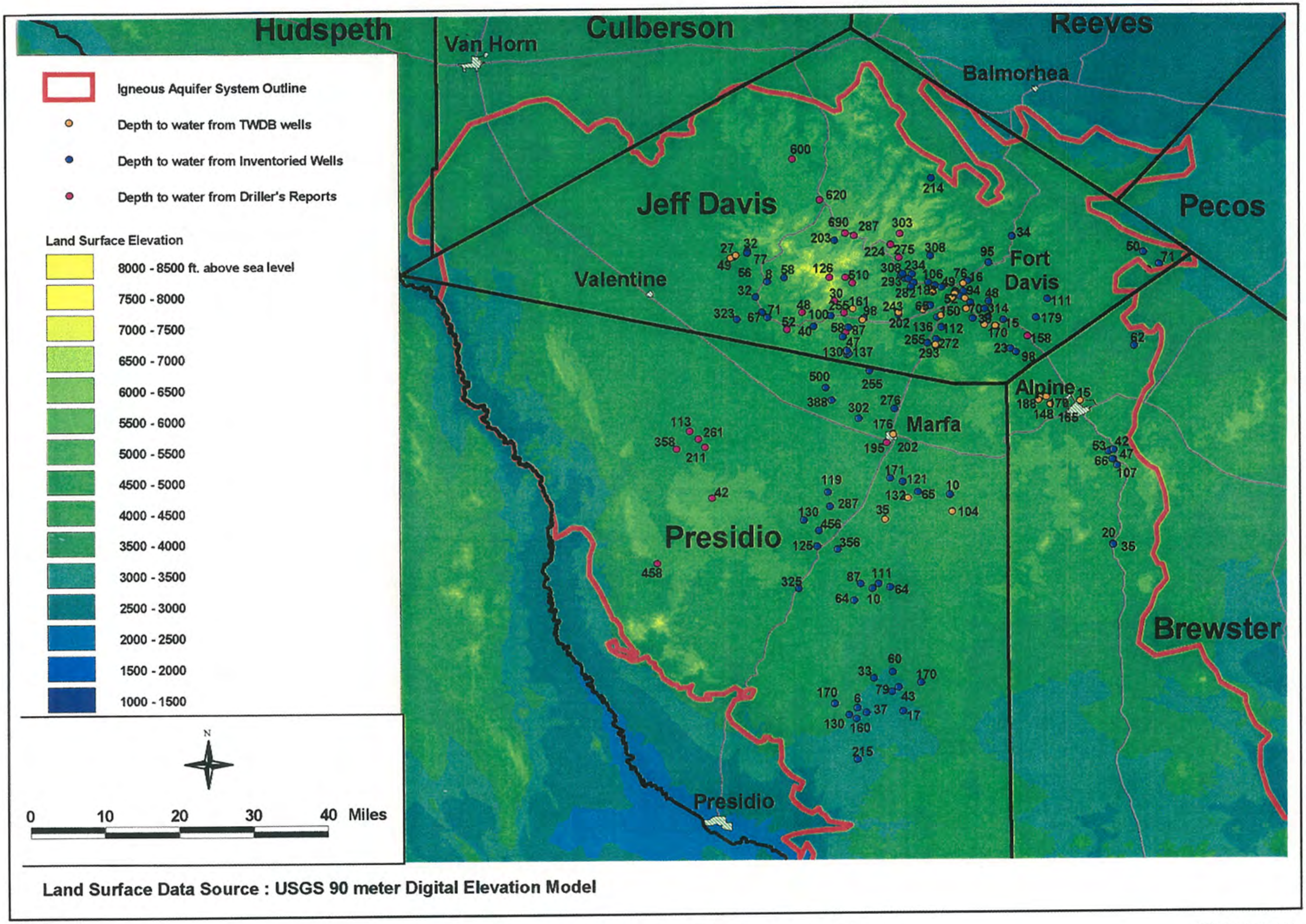
Depth to Groundwater

The depth to groundwater ranges from less than 10 feet to more than 600 ft (Figure 8). Water-level measurements in wells of relative close proximity can vary by several hundred feet. The greatest differences in the depth to groundwater are found in central Jeff Davis County, where the difference may be as much as 500 ft between wells that are less than one mile apart. The difference in depth measurements is related to at least two factors: (1) differences in surface elevations over relative short distances, and (2) the fact that groundwater might not be present in the same stratigraphic horizon in all wells. In the first case, the depth to water in a formation will be greater in wells that are at relatively higher elevations. In the second case, the porosity of a formation might be so low in some areas that the formation might not have the capacity to store appreciable amounts of groundwater. In other areas, porosity might be sufficiently high that the formation might have significant groundwater storage potential. It is difficult to discern which of the two factors above accounts for most of the variations in water depths listed on Figure 8. However, considering the sharp contrasts in topography, especially in Jeff Davis County, it is likely that most of the largest differences in the depth to groundwater between nearby wells are attributable to differences in surface elevation.

Seasonal water-level fluctuations, especially in wells with shallow water levels, may occur as the aquifer responds to changes in precipitation intensity. The water level in six TWDB monitoring wells was measured during the summer months of June and August 2001 and compared to winter measurements taken in December 2000 and January 2001 (Table 2). Of the six wells three had water-level rises from summer to winter, two had declines, and one had virtually no water-level change. Although the survey is not conclusive, the hydrogeologic nature of the aquifer suggests that water-level changes can be expected between wet and dry periods. Additional monitoring with continuous recording equipment is needed to better understand this relationship.

Table 2. Comparison of Winter and Summer Water-level Measurements

Well No.	County	Well Depth	Date Measured	Winter Depth		Date Measured	Summer Depth	Water-Level Change
5122701	Jeff Davis	110	12-01-00	55.5		08-15-01	48.6	-6.9
5132403	Jeff Davis	240	01-19-01	157.2		08-15-01	160.7	+3.5
5225305	Jeff Davis	303	01-10-01	48.5		08-15-01	59.1	+10.6
5225603	Jeff Davis	120	01-09-01	43.2		08-15-01	45.4	+2.4
5226802	Jeff Davis	230	01-09-01	190.5		08-15-01	190.1	-0.4
5249901	Presidio	200	01-23-01	110.2		06-09-01	104.0	-6.2



DEPTH TO WATER FROM LAND SURFACE

FIGURE 8

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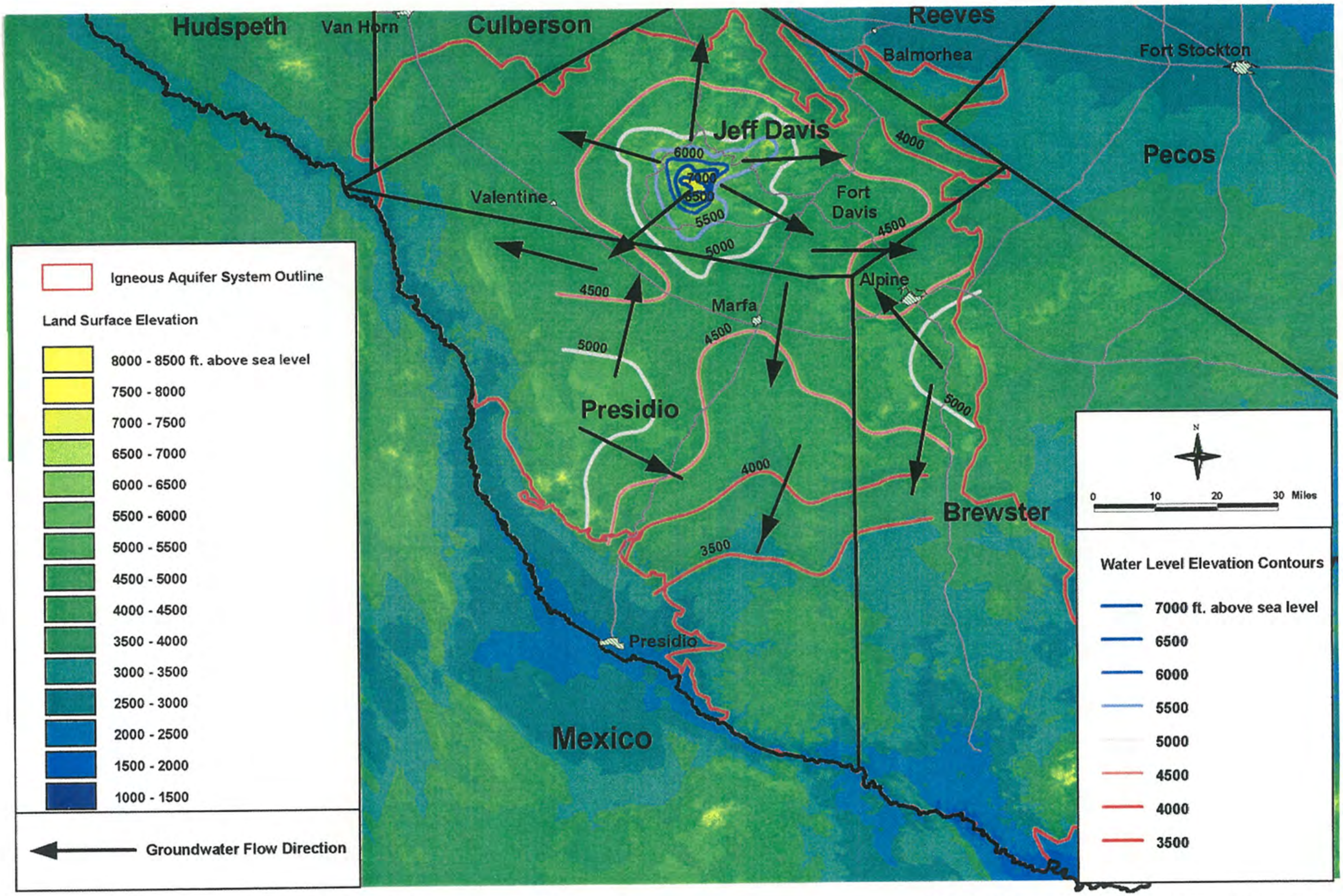
Groundwater Flow Paths

The direction of flow within an aquifer can be discerned by the elevation of the water table relative to a fixed datum. The standard datum for water-level measurements is mean sea level (msl). The elevation of the water table above msl represents the potential energy stored in a column of water. The higher the elevation, the greater the amount of potential energy (or "head") - the driving force behind the flow of groundwater. Groundwater flows in the direction of decreasing head - that is, from high elevations above msl to lower elevations above msl. Because of this, topography is often a reliable guide for tracing the direction of flow.

Water-level elevation contours are shown on Figure 9. The highest elevations, of course, are in the mountains and along the fronts of the mountains. The lowest elevations are from wells in the valleys between the broad exposures of igneous rocks. Although water levels within a localized area may vary considerably, more recognizable flow trends can be observed on a regional scale. The general flow pattern, as indicated by the colored water-level contours of Figure 9 in Jeff Davis County is radial – that is, from the higher elevations in the central areas of the county toward lower-lying areas of Jeff Davis County and surrounding counties. The contours within the boundaries of Presidio County indicate that groundwater flow systems originate in the higher elevations of mountain watersheds along the Alamito Valley. The flow systems converge beneath the northward-oriented valley. From there, the direction of flow is toward the south.



Land Surface Elevation Data Source : USGS 90 meter Digital Elevation Model

Water elevation control points are shown in Figure 8

REGIONAL WATER-LEVEL ELEVATIONS AND GROUNDWATER FLOW PATHS

FIGURE 9

LBG-GUYTON ASSOCIATES

Springs

In a survey of the springs of Texas, Brune (1981) counted more than 150 springs, in Brewster, Jeff Davis and Presidio Counties. Many of the springs of these counties discharge along bedding planes and fractures from intrusive or extrusive igneous rocks. A small number of springs discharge from the alluvial deposits along the margins of the basins. The springs of Presidio and Brewster Counties appear to be more evenly distributed across the different extrusive igneous formations compared to Jeff Davis County, where the Huelster, Star Mountain and Barrel Springs formations account for most of the springflow. The discharge of many of the springs is highly variable, and Brune (1981) noted that many springs in this area were not flowing at the time of his survey. Long periods of drought reduce the amount of recharge in the watersheds that provide the source water for springs. Depending on the amount of water in storage, springflow might decrease if an adequate amount of recharge is not available to sustain flow to springs. Pumpage from nearby wells might also affect springflow by lowering the water level below the orifice of a spring. Brune (1981) reported that discharge of springs in this area ranges from less than 0.5 gallons per minute (gpm) to as much as 200 gpm. Most springs, however, were listed in the "small" to "very small" categories, with discharges of less than 5 gpm. Hart (1992) estimated that total daily discharge from springs in Jeff Davis County is 1.1 million gallons per day.

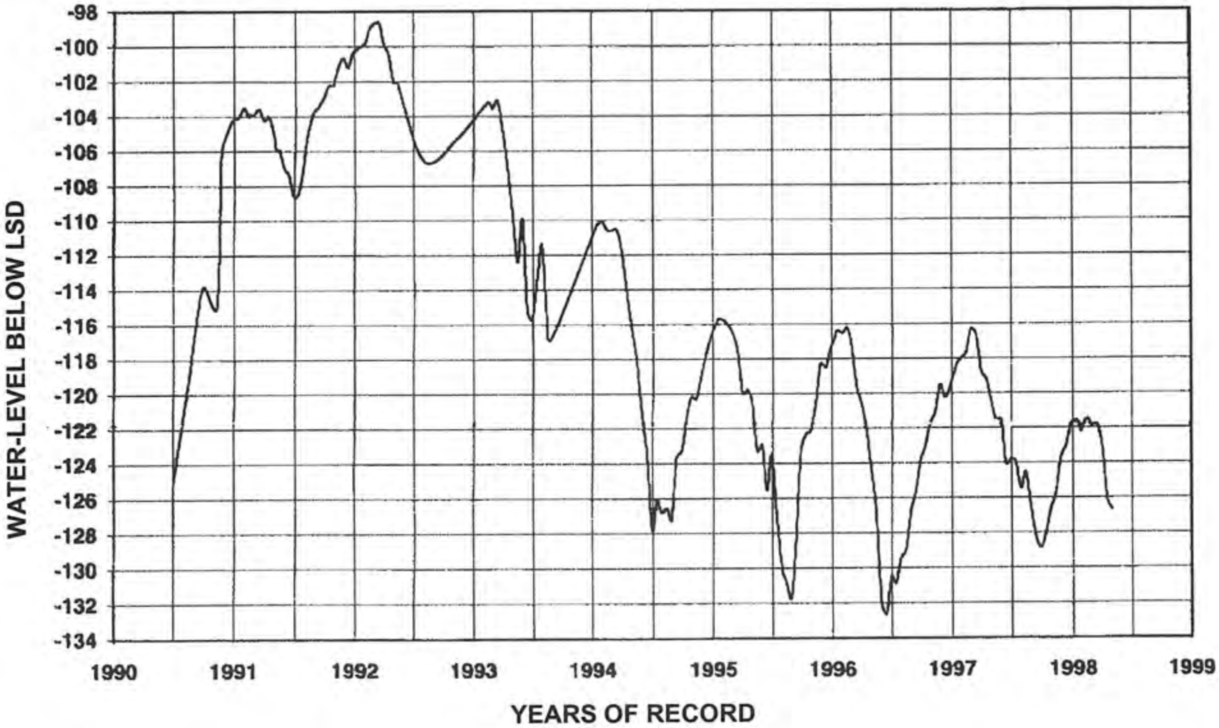
Springs issuing from the Igneous aquifer system are adequate to provide water for domestic use, and the watering of livestock and game. There is no municipal use reported for spring water in the study area.

Recharge

Precipitation recharge is defined as the amount of rainfall that infiltrates through soil and rock to reach the saturated zone of the aquifer. Four significant factors that control recharge in the study area include amount of precipitation, location of drainages that concentrate surface-water runoff, location and density of exposed fractured rock, and soil infiltration potential. Based on these factors, recharge is most favorable in areas of higher elevation where precipitation rates are at their greatest and fractured rock is exposed, and in lower elevation valleys containing porous soils. The estimated volume of recharge that occurs based only on precipitation is discussed in the Availability and Demand section of this report.

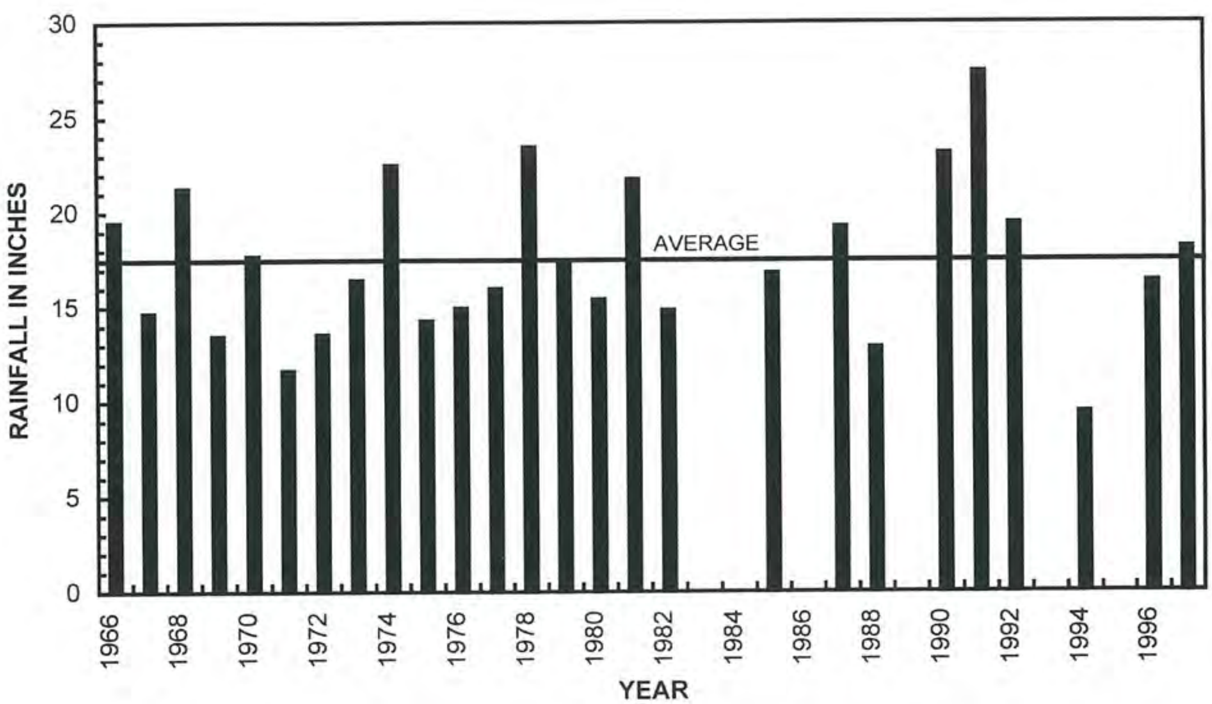
The freshness of Igneous aquifer system water quality, as exhibited by its typically low total dissolved solids content, indicates water is transmitted (recharged) relatively rapidly from the surface to the aquifer. A water-level hydrograph of City of Alpine's Musquiz Well No.11 (Figure 10a) also demonstrates the aquifer's rapid response to recharge derived from precipitation events. Higher water levels are evident in the early 1990s during a period of higher rainfall (Figure 10b) and decline in following years as less rainfall occurred.

Recharge is enhanced in areas with high fracture densities. Fracturing can be caused by (1) the cooling of molten rock, (2) the erosion of rocks and the release of compressive stresses from the removal of the overburden, (3) regional crustal flexing or subsidence, and (4) faulting. Areas with relatively little fracturing are likely to have higher amounts of surface runoff and, thus, lower degrees of recharge potential. Hart (1992) observed that fault zones that intersect stream courses are channels for the direct infiltration of water. In these areas, streams carrying water from higher elevations of mountain watersheds lose a portion of their flow to the fractures. These "losing" streams can be identified on the basis of reductions in flow downstream of known fractures and fault zones. The geologic map (Figure 6) offers a glimpse of where the major fault-controlled recharge areas are located in the study area. The areas with the greatest density of faults exposed at land surface are in the middle to higher elevations of the watersheds of the Davis Mountains in Jeff Davis County (McCutchin fault zone) and in the igneous rocks that border the Alamito Valley (drained by Alamito Creek) of Presidio County. Other significant recharge areas are likely to be located along the coarse-grained alluvial fans of the mountains that border the valleys of the Marfa and Alpine basins.



HYDROGRAPH OF CITY OF ALPINE MUSQUIZ WELL NO. 11 (52-34-303)

FIGURE 10a



CITY OF ALPINE ANNUAL RAINFALL

FIGURE 10b

Discharge and Well Yields

Discharge from the Igneous aquifer system occurs by flow to springs and by municipal, domestic and livestock wells. Except for local stream segments, there is no major stream in the area to which groundwater discharges continually from shallow saturated sediments. The major centers of discharge from the aquifer system are the municipal wellfields of Alpine, Fort Davis and Marfa; agricultural use by Village Farms, Powell Plant Farm, and Antelope Valley Farm; and possibly from relatively closely spaced domestic wells.

A list of municipal water supply wells producing from the Igneous aquifer system, including information on the depths of the wells and their estimated discharge rates, is found in Table 3.

Table 3. Selected Public Water Supply Wells [Source: TWDB]

Owner	Well Name or Number	State Well Number	Year Completed	Well Depth (Ft)	Reported Yield (gpm)
Fort Davis WSC	Well #1	52-25-304	1929	90	
"	Well #2	52-25-305	1971	303	300
"	Well #3	52-25-311	1991	300	200
Davis Mtn State Park	Well #1	52-25-204	1966	250	300
"	Well #2	52-25-303	1966	275	110
McDonald Observatory	Well #1	51-24-901	1973	525	19 gpm with 4 ft drawdown
"	Well #2	51-24-902	1973	550	19 gpm with 85 ft drawdown
Prude Ranch Resort	Football Field	52-25-207	1972	186	20
High Frontier School		52-26-701	1990	450	23 gpm with 105 ft drawdown
"		52-26-702	1964	125	
City of Alpine	Musquiz #6	52-35-104	1972	540	325
"	Musquiz #7	52-34-301	1972	408	325
"	Musquiz #8	52-34-106	1972	350	120
"	Musquiz #9	52-34-107	1972	400	
"	Musquiz #10	52-34-302	1984	450	500
"	Musquiz #11	52-34-303	1984	400	225 gpm with 45 ft drawdown
"	Meriwether #1	52-35-402	-	-	40
"	Meriwether #2	52-35-401	1960	485	80
"	Golf Course Well	52-43-312	1950	350	135
"	East Well	52-43-308	1927	580	75
"	Railroad Well	52-43-307	1923	320	50
"	Lower Hill Well	52-43-310	1949	443	215
"	Upper Hill Well	52-43-311	1929	703	210
"	Roberts #1	52-35-704	1957	451	55
"	Roberts #2	52-35-705	1957	400	133
"	Roberts #3	52-35-706	1954	400	45
"	Roberts #4	52-35-702	1971	798	98
"	Roberts #5	52-35-703	1977	905	160
"	Miles Well	52-35-707	1925	212	43
"	Gardner Well	52-35-708	1959	390	145 gpm with 6 ft drawdown
"	Cartwright Well	52-35-709	1958	400	175 gpm with 128 ft drawdown
"	Daugherty	52-35-710	1965	345	
"	Terry #2	52-43-110	1954	540	31
"	Lewis Well	52-35-716	1999	885	270 gpm with 94 ft drawdown
City of Marfa	Well #2	51-48-603	1945	1,100	375
"	Well #3	51-48-601	1936	841	1,000
"	Well #4	51-48-602	1928	881	700
"	Well #5	51-48-604	1983	882	180 gpm with 151 ft drawdown

Hart (1992) estimated the producing ranges of individual igneous formations in Jeff Davis County (Table 4).

Table 4. Well Depths and Yields of Igneous Formations of Jeff Davis County (Hart, 1992)

Formation	Well Depths (ft)	Well Yields (gpm)
Intrusives	150 - 730	5
Wild Cherry	Springs	-
Mount Locke	Springs	-
Barrel Springs	72 - 320	3 – 250
Merrill	Springs	-
Sheep Pasture	135	10 – 25
Sleeping Lion	100 - 439	35
Frazier Canyon	48 - 846	2 – 190
Adobe Canyon	100 - 915	5 – 25
Limpia	106 - 600	2 – 55
Gomez	32 - 600	5 – 18
Star Mountain	63 - 630	1 – 325
Huelster	52 - 250	6

LBG-Guyton (1999) conducted an evaluation of the groundwater resources in the vicinity of the McDonald Observatory. Groundwater production from this area is primarily from the Barrel Springs formation. Two wells were examined as part of the investigation. The wells, located about 2 miles south of the observatory, supply all of the water for the observatory. Although located fairly close to each other, the wells have very different characteristics. One well exhibited significant drawdown when pumped at a rate of 19 gpm. The transmissivity was 195 gallons per day per foot (gpd/ft). The second well had only 4 ft of drawdown at the same pumping rate and a transmissivity of 1,930 to 2,280 gpd/ft. The different performances of the wells and the results of the pumping tests underscore the variability of well yields expected of fractured-rock aquifers.

Water Quality

Groundwater in the study area is relatively low in total dissolved solids (TDS). The term "TDS" refers to the concentration of dissolved constituents derived primarily from the interaction of groundwater with the rocks through which water flows. Other dissolved solids are contributed by fertilizers and leaking septic tanks (among other factors). Water is considered to be a "universal solvent". Typically the longer water is in contact with rocks, the higher its TDS concentration will become. The concentration of dissolved solids, however, is largely dependent on the types of rocks through which groundwater flows. Because the mineralogy components of many igneous rocks are not highly soluble, groundwater flowing through the rocks of the Davis Mountains typically does not have high TDS concentrations or the same concentration ratios of constituents that are typical of groundwater that has been in contact with more soluble rocks, such as limestone or gypsum. This is significant because the TDS concentration is one factor that determines whether or not water is potable (that is, suitable for drinking), or requires special treatment, such as blending or filtering. The U.S. Environmental Protection Agency (EPA) has recommended 1,000 milligrams per liter (mg/l) as the upper limit of TDS for the short-term consumption of water by humans. Livestock can tolerate water with concentrations as high as 5,000 mg/l. Water with a TDS concentration less than 1,000 mg/l is considered to be "fresh"; between 1,000 and 3,000 mg/l, water is considered to be slightly saline (or brackish); and between 3,000 and 10,000 mg/l, water is regarded as saline.

The TWDB groundwater database currently contains water-quality analyses on samples from 131 (110 ionically balanced) Igneous aquifer wells. The minimum, median and maximum concentration levels of specified constituents determined from the 110 balanced analyses are shown in Table 5. Of 59 Jeff Davis County wells with balanced chemical analyses listed in the TWDB's water-quality database, the TDS concentration ranges from 83 to 603 mg/l. The median is 223 mg/l. Thirty-eight wells are listed in Brewster County. The TDS for these wells ranges from 136 to 766 mg/l. The median concentration is 286 mg/l. Balanced analyses are available for 13 wells producing groundwater from the igneous rocks of Presidio County. The TDS concentration range for these wells is smaller than the ranges in Jeff Davis and Brewster Counties. The low concentration is 247 mg/l, and the high concentration is 531 mg/l.

Chloride and sulfate (Table 5) are specific dissolved constituents for which maximum concentration levels (MCL's) have been recommended by the EPA. The MCL of each constituent has been set at 250 mg/l. The maximum concentration of chloride is 87 mg/l in Brewster County, 31 mg/l in Jeff Davis County, and 72 mg/l in Presidio County. The maximum concentration of sulfate is 142 mg/l in Brewster County, 156 mg/l in Jeff Davis County, and 94 mg/l in Presidio County. Neither constituent exceeds its recommended MCL. However, concentrations of fluoride often exceed primary standard MCL's of 2 mg/l.

Additional water-quality data were gathered in the form of specific conductance measurements of water samples collected from 21 wells in the study area (Table 1). Specific conductance is a measure of the ability of water to conduct electricity and is directly proportional to the amount of dissolved minerals that are in the water (TDS $\simeq$ 65% Spec. Cond.). The specific conductance of the 21 samples ranged from a high of 898 micromhos per centimeter (mmhos/cm) in Jeff Davis County to a low of 232 mmhos/cm also in Jeff Davis County. Average specific conductance of water samples taken from wells in the three counties is: Brewster 460 mmhos/cm (2 wells), Jeff Davis 413 mmhos/cm (13 wells), and Presidio 443 mmhos/cm (6 wells).

Table 5. Igneous Aquifer System Water Quality (mg/l)

	SiO2	Ca	Mg	Na	K	HCO3	SO4	Cl	F	NO3	pH	Total hard.	TDS
Minimum	20	17	2	15	3	78	3	6	1	6	8	80	247
Median	65	35	5	63	8	210	31	26	2	13	8	107	354
Maximum	87	105	9	120	9	322	94	72	3	30	8	294	531

GROUNDWATER AVAILABILITY AND DEMAND

A major component of this study and its significance to the regional water planning process is the estimation of water-supply availability from the Igneous aquifer system and its potential to meet current and long-term water-supply needs.

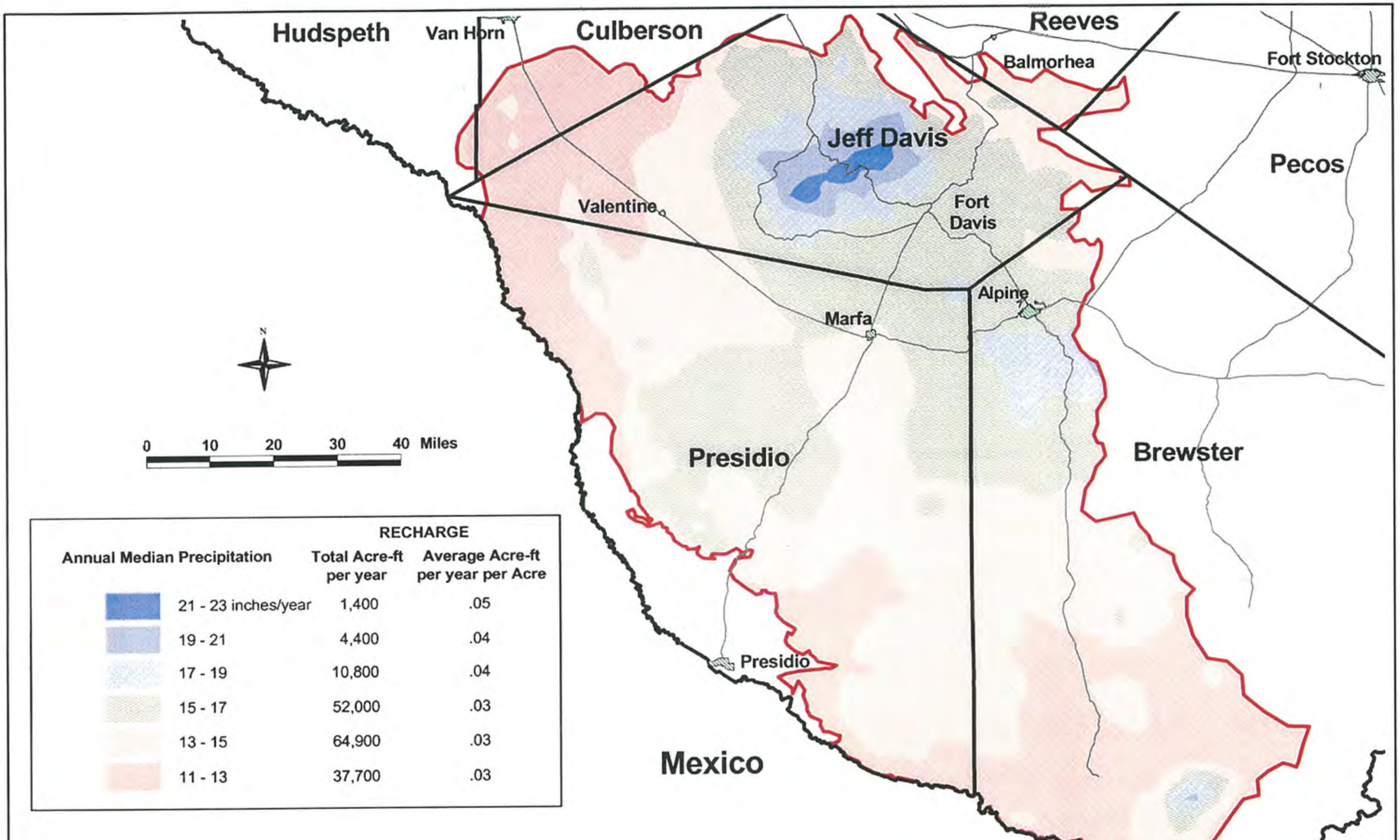
Recharge

The amount of recharge previously estimated by the TWDB for each of the three Igneous aquifer areas delineated by the TWDB is: 5,800 acre-ft in Brewster County; 2,500 acre-ft in Jeff Davis County; and 8,500 acre-ft in Presidio County. These estimates were based on the assumption that 2.5 percent of average annual rainfall (16 inches) is converted to recharge over the 785 mi^2 delineated by the TWDB.

For the purpose of this report, 2.5 percent of median annual rainfall was assumed for the entire 8,200-mi^2 aquifer area. However, rather than assuming an entire area average rainfall, the 2.5 percent was applied separately to each median rainfall polygon shown in Figure 4 and then summed. This allows for a higher volume of recharge per unit surface area in areas experiencing higher rainfall rates. Based on this methodology, average annual recharge to the Igneous aquifer system is 171,200 acre-feet per year (Figure 11). As explained previously in the Hydrogeology section of this report, the actual rate of recharge at any specific location is also a factor of concentration of rock fracturing, surface drainage patterns, and soil infiltration potential.

Recoverable Groundwater in Storage

The assumptions used to derive estimates of the volume of recoverable groundwater within each of the three areas delineated by the TWDB were: (1) that the average saturated thickness of the igneous rocks is 600 ft, (2) that porosity is 10 percent, and (3) that 30 percent of groundwater in storage is potentially recoverable. Based on these assumptions, the following estimates were made: 3.1 million acre-ft in Brewster County; 1.3 million acre-ft in Jeff Davis County; 4.6 million acre-ft in Presidio County; for a total of 9.0 million acre-ft. If these assumptions are extended across the 8,200 mi^2



Annual Median Precipitation	RECHARGE Total Acre-ft per year	Average Acre-ft per year per Acre
21 - 23 inches/year	1,400	.05
19 - 21	4,400	.04
17 - 19	10,800	.04
15 - 17	52,000	.03
13 - 15	64,900	.03
11 - 13	37,700	.03

Precipitation Data Source: Natural Resources Conservation Service

Estimated recharge is based on 2.5 percent of annual precipitation ranges.

ESTIMATED AVERAGE ANNUAL RECHARGE
(Based Only on Precipitation)

FIGURE 11

LBG-GUYTON ASSOCIATES

of land within the newly designated boundary, and the fracture porosity is more appropriately set at 5 percent, then the volume of groundwater that is potentially recoverable might be as much as 47 million acre-ft. However, due to the hydrologically disconnected nature of the aquifer, the actual amount of water that might be expected to be recoverable is most likely much less.

It is important to note, however, that the concept of "potential recoverability" is based on the unrealistic assumption that a sufficiently large number of wells spread throughout the aquifer extent can be installed to extract all of the potentially recoverable groundwater. The concept is also based on the assumption that the aquifer is sufficiently homogeneous to permit the pumpage of the potentially recoverable groundwater. There are, however, significant engineering and economic limitations to the amount of groundwater that can be pumped from an aquifer.

The concept of availability does not suggest that all of the potentially recoverable water within an aquifer is either accessible to or producible by all users. In the narrowest sense of the term, then, availability should be regarded as an estimate of the volume of groundwater that a specific user or group of users might reasonably expect to pump from a designated part of an aquifer, based on limitations imposed by financial resources, the depth to water, the cost of pumping, the efficiency of production and distribution systems, and water quality.

Further work will be required to address this issue, so the above estimate should be regarded only as preliminary. For example, it will be necessary to conduct more detailed geophysical evaluations and pumping tests of the igneous rocks to derive better estimates of porosity, saturated thickness, and yield. It will also be important to investigate the extent of hydrogeologic communication between different water-bearing zones.

Demand

Water demand projections, as listed in the 2001 Far West Texas Regional Water Plan (Table 6), show that water demand in Alpine is expected to increase from 1,524 acre-ft in the year 2000 to 2,461 acre-ft in by the year 2050. In Fort Davis, the demand will decrease from 236 acre-ft in 2000 to 225 acre-ft by 2050. Marfa's demand for groundwater is projected to increase from 977 acre-ft in 2000 to 1,189 acre-ft in 2050. Some increase in rural-domestic water demand is expected, while no increase is expected for irrigation, livestock, or other non-human drinking water use. Groundwater availability from the aquifer system appears to be more than adequate to satisfy the expected demands not only of the above cities, but also of other water users (FWTRWP, 2001).

Table 6. Projected Municipal Water Demand (in acre-feet/year)

	YEAR					
	2000	**2010**	**2020**	**2030**	**2040**	**2050**
Alpine	1,524	1,668	1,891	2,055	2,243	2,461
Fort Davis	236	241	240	236	230	225
Marfa	977	1,067	1,175	1,282	1,228	1,189

Source: 2001 Far West Texas Regional Water Plan.

AQUIFER MANAGEMENT

Groundwater conservation districts have been established in Brewster, Jeff Davis and Presidio Counties to ensure the orderly development and management of groundwater resources. In general, the District's management goals strive to:

- Improve understanding of groundwater conditions
- Provide for efficient use of groundwater
- Protect and enhance the quantity and quality of groundwater by controlling and preventing waste
- Regulate the development and production of groundwater to ensure adequate supplies for the future.

The Districts will play an important role in the development of best management practices by providing basic geologic and hydrogeologic information to the public, by conducting public education programs on water use and conservation, and by promulgating reasonable and fair policies to guide the development of groundwater.

The Districts, as well as the communities of Alpine, Fort Davis and Marfa, might further consider the following management issues:

1. Because the Igneous aquifer system is the only source of water for the cities of Alpine, Fort Davis and Marfa, it will be important to monitor water levels in and around the municipal wellfields. Where possible, municipal groundwater production should be distributed over as wide an area as possible. This strategy would reduce the amount of localized drawdown by minimizing the stress within the aquifer system.
2. Plans for housing developments that are not expected to be supplied by municipal water systems should first demonstrate that adequate groundwater is available to meet the needs of residents. This should include an assessment of the maximum amount of water usage expected from a development, along with estimates of the number of wells, expected depths of the wells, and expected yields.
3. Water quality should be monitored regularly, especially where there is a high concentration of underground storage tanks or septic tanks.

4. Drought-contingency plans should be reviewed regularly to ascertain whether elements of the plans should be fine-tuned or changed completely. This is especially important in case population growth exceeds projections, or if some of a city's infrastructure must either be replaced or expanded.
5. The flow of many springs in the Igneous aquifer system area is sensitive to the amount of precipitation. As such, diminished springflow, especially sharply diminished springflow, may be regarded as an early indicator of the onset of drought conditions. Landowners might consider monitoring the flow of springs on their property as a means of helping the groundwater conservation districts and cities decide when to implement the first stages of drought contingency plans.

CONCLUSIONS

The Igneous aquifer system covers 8,200 mi^2 of Brewster, Jeff Davis and Presidio Counties and is the only source of water for the residents of this mountainous region of Texas. The aquifer system is made up of a series of water-bearing stacked lava flows, ash-flows, and basinfill sediments that are in varying degrees of hydrologic communication.

The depth to groundwater varies from less than 100 ft to nearly 600 ft. The highest water-level elevations are in central Jeff Davis County, and the lowest are in southern Presidio County. Water-level measurements in closely-spaced wells can vary by several hundred feet. Large differences in depth measurements between closely-spaced wells are probably related to sharp variations in topography over relatively short distances and to low porosity and storage capacity of many of the individual igneous flows.

Groundwater flow directions in Jeff Davis County are radial. The systems originate in the upper elevations of the mountain watersheds and then flow outward toward the topographically lower areas of Jeff Davis County and surrounding counties. In Presidio County, the flow systems originate in the mountains that border the Alamito Valley. The systems converge beneath the valley and flow toward the south. Other than discharge to springs and wells, there are no major perennial streams to which groundwater discharges in the study area.

Groundwater is stored primarily in fractures and rubble zones along bedding planes. Much of the recharge to the aquifers is by the infiltration of water through fractures – especially in areas where fractures intersect streams that drain mountain watersheds. Recharge also occurs by the infiltration of rainfall through the coarse-grained alluvial fans that border the mountains. Total recharge within the 8,200-mi^2 study area might be as much as 171,200 acre-ft per year. The volume of potentially recoverable water in storage within the fractured igneous rocks and the pore spaces of rubble zones might be as much as 47 million acre-ft. However, due to the hydrologically disconnected nature of the aquifer, the actual amount of water that might be expected to be recoverable is most likely much less. Sufficient groundwater exists within the Igneous aquifer system to meet future water-supply needs of the local area. However, expanded and improved infrastructure may be required.

A principal management issue is the need to avoid excessive pumpage from the municipal wellfields of Alpine, Fort Davis and Marfa. Wells should be spread over as wide an area as possible in order to minimize drawdowns in the wellfields. Plans for new developments outside of municipal supply systems should include assessments of the availability of groundwater. Finally, landowners might consider monitoring springflow as an early indicator of the onset of drought conditions in the region.

REFERENCES

Alcott, J.V., 1998, Characterization of Hydrologic Parameters at an "Arid Exempt" Landfill in Big Bend National Park: Unpublished MS Thesis, Sul Ross State University.

Ashworth, J.B., and Hopkins, J., 1995, Aquifers of Texas: Texas Water Development Board Report 345.

Back, W., Rosenshein, J.S., Seaber, P.R., 1988, The Geology Of North America, Hydrogeology: The Geological Society of America, V. O-2.

Baker, C.L., & Bacon C.S., 1939, Report on Underground Water Prospects in the Vicinity of Alpine, Texas: Agricultural and Mechanical College of Texas, unpublished report.

Baker, Lynda O/Brian, 1988, A Hydrogeochemical Comparison Study; The Influence of Igneous Versus Sedimentary Drainage Basin Lithology in Surface Water Composition in the Trans-Pecos Region, Southwest Texas: Unpublished MS Thesis, Sul Ross State University.

Bomar, George, 1995, Texas Weather: The University of Texas at Austin Press, 2nd ed.

Bowden, A.C., & Collie, W.M., 1954, City of Alpine, Texas; Report on Proposed Water Supply Explorations: Unpublished Report prepared for the City of Alpine.

Brune, Gunnar, 1975, Major and Historical Springs of Texas: Texas Water Development Board Report 189.

Brune, Gunnar, 1981, Springs of Texas (Brewster County, pp. 84-95; Jeff Davis County, pp. 256-263; Presidio County, pp. 368-376): Branch-Smith, Inc., Fort Worth, Texas.

Chastain-Howley, A., 2001, Igneous Aquifers of Far West Texas: *in* Aquifers of West Texas: Texas Water development Board Report 356, p. 175-189.

Davis, M.E., 1961, Ground-Water Reconnaissance of the Marfa Area, Presidio County, Texas: Texas Board of Water Engineers Bull. 6110.

Deal, Dwight, 1979, Musquiz Water Field, Preliminary Report to the Alpine City Council: Unpublished report prepared for the City of Alpine.

DeCook, K.J., 1961, A Reconnaissance of the Ground Water Resources of the Marathon Area, Brewster County, Texas: Unpublished report prepared in cooperation with the United States Geological Survey.

Far West Texas Regional Water Plan, 2001.

Follett, C.R., 1954, Records of Water-Level Measurements in Culberson, Hudspeth, and Jeff Davis Counties, Texas: Unpublished report prepared in cooperation with the U.S. Geological Survey, United States Department of the Interior.

Glen, Jean, 1981, Geology and Petrology of a Portion of the Southern Davis Mountains, Brewster County, Texas: Unpublished MS Thesis, Sul Ross State University.

Goldich, S.S., & Elms, M.A., 1949, Stratigraphy and Petrology of Buck Hill Quadrangle, Texas: Geological Society of America Bull, Vol. 60, No. 7, p. 1133-1182.

Gorski, D.E., 1970, Geology and Trace Transition Element Variation of the Mitre Peak Area, Trans-Pecos Texas: Unpublished MA Thesis, University of Texas Austin.

Hart, M.A., 1992, The Hydrogeology of the Davis Mountains, Trans-Pecos Texas: Unpublished MA thesis, The University of Texas at Austin.

Lang, J.W., & White, W.N., 1947, Ground Water in the Vicinity of Alpine, Brewster County, Texas: Unpublished report prepared for the City of Alpine.

Lang, J.W., 1949, Ground Water in the Alpine Area and Adjacent Territory, Brewster County, Texas: Unpublished Report prepared in cooperation between the U.S. Geological Survey, U.S. Department of the Interior and the Texas State Board of Water Engineers.

LBG-Guyton Associates, 1996, Ground-Water Resources Evaluation for Proposed Greenhouse Site Near Fort Davis, Texas: Unpublished report prepared for AgroPower Development, Inc.

LBG-Guyton Associates, 1997, Ground-Water Resources Evaluation for the Proposed Greenhouse Site Near Marfa, Texas: Unpublished report prepared for AgroPower Development, Inc. and Village Farms of Texas.

LBG-Guyton Associates, 1998, Preliminary Evaluation of Potential Ground-Water Supply Development for the City of Alpine, Texas: Unpublished report prepared for the City of Alpine.

LBG-Guyton Associates, 1999, Lewis No. 1 Test Hole Evaluation, Alpine, Texas: Unpublished report prepared for the City of Alpine.

LBG-Guyton Associates, 1999, Sunny Glen Well Field Evaluation: Unpublished report prepared for the City of Alpine.

LBG-Guyton Associates, 1999, Evaluation of Water Resources for the McDonald Observatory, Davis Mountains, Texas: Unpublished report prepared for The University of Texas at Austin.

Lewis, Jean, 1949, Geology of Barillos Dome, Jeff Davis County, Trans-Pecos Texas: MA Thesis, University of Texas, Austin.

Leverette, Mitchell, 1989, The Stratigraphy, Petrography, and Geochemistry of Volcanic Rocks I the Area of Overlap Between the Paisano and Davis Mountains Volcanic Centers: Unpublished MS Thesis, Sul Ross State University.

Littleton, R.T. & Audsley, G.L., 1957, Ground Water Geology of the Alpine, Area, Brewster, Jeff Davis, and Presidio Counties, Texas: Texas Board of Water Engineers Bull. 5712.

McAnulty, W.N., et al, 1950, Geology and Ground-Water Resources of Alpine and Adjacent Territory, Brewster County, Texas: Unpublished Report prepared for the City of Alpine.

McAnulty, W.N., 1955, Geology of Cathedral Mountain Quadrangle, Brewster County, Texas: Geological Society of America Bull, Vol. 66, No. 5, p. 531-578.

Muse, R.W., 1966, Water Level Data From Observation Wells in Culberson, Jeff Davis, Presidio and Brewster Counties: Texas Water Development Board Report 16.

Reed, E.L., 1966, A Study of Ground Water Resources in the Vicinity of Alpine, Texas: Unpublished report prepared for the City of Alpine.

Reed, E.L and Associates, 1973, A Study of Ground Water Resources in the Vicinity of McDonald Observatory, Mt. Locke, Jeff Davis County, Texas: Unpublished report prepared for The University of Texas, Austin, Texas.

Palczynsky, C.E., 2001, Groundwater in the Tertiary Volcanic Sequence of the Eastern Davis Mountains, Trans-Pecos Texas: Unpublished MS Thesis, Sul Ross State University.

Parker, D.F., 1979, The Paisano Volcano: Stratigraphy, Age, and Petrogenesis: *in* Guidebook 19, The University of Texas at Austin Bureau of Economic Geology, p. 97-105 (also PhD Thesis, UT-Austin, 1976)

Schmidt, R.H. 1995, The Climate of Trans-Pecos Texas: *in* The Changing Climate of Texas: Predictability and Implications for the Future: Texas A&M GeoBooks, pp. 122-137.

Smith, M.A., 1975, Geology and Trace Element Geochemistry of the Fort Davis Area, Trans-Pecos Texas: Unpublished Ph.D. Thesis, University of Texas, Austin.

Stemsel, N.B., 1935, Report on the Water Supply of Alpine, Brewster County, Texas: Bureau of Economic Geology, The University of Texas, unpublished report.

SUPPLEMENTAL INFORMATION

GEOLOGIC TIME SCALE

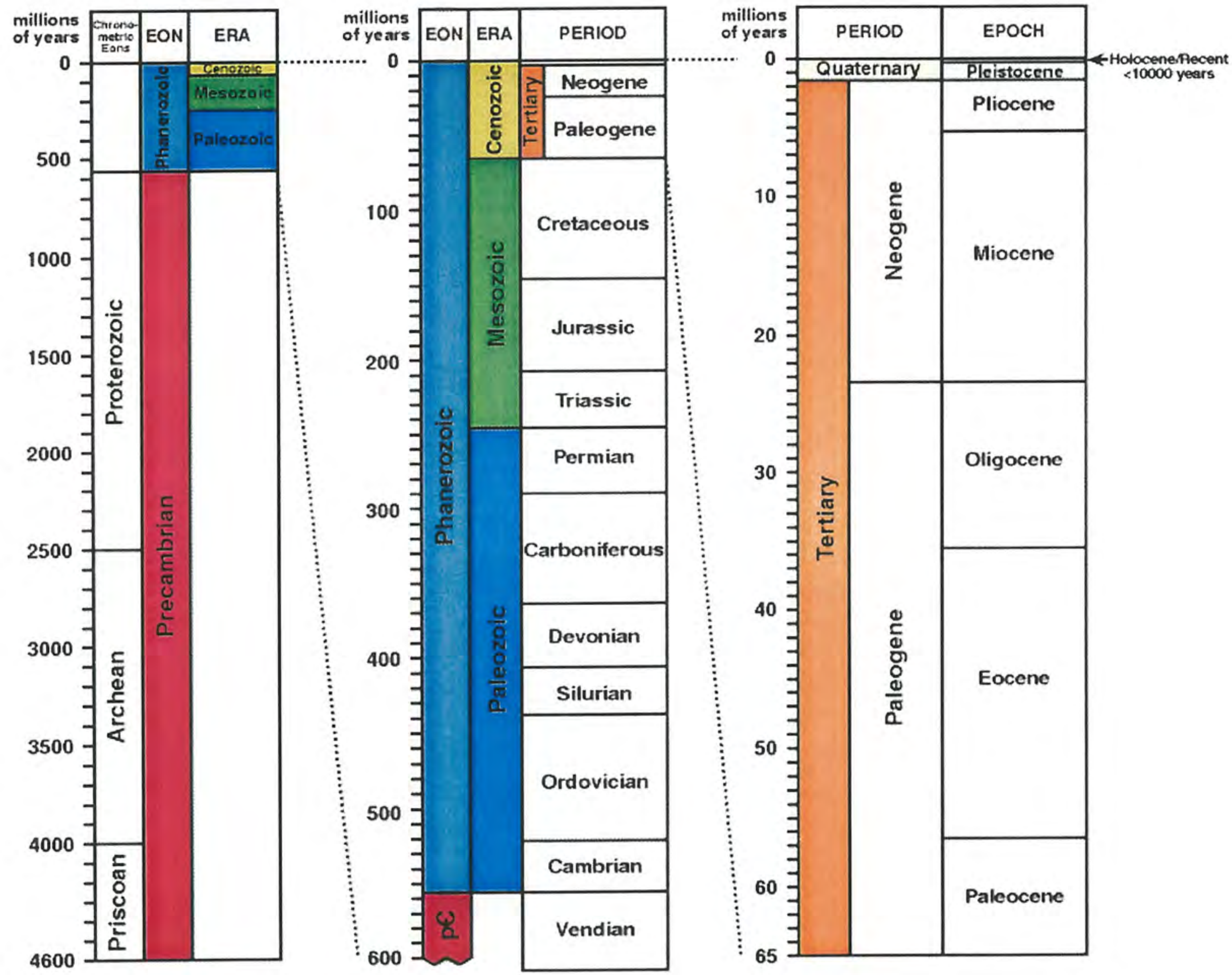
Few discussions about geology of the Trans-Pecos make sense without reference to the geologic time scale. Geologic time can be referred to either as "relative time" or as "absolute time."

- **Relative time** -- subdivisions of Earth's geology in a specific order based on relative age relationships (most commonly, stratigraphic position). These subdivisions are given names, most of which can be recognized globally, usually on the basis of fossils.
- **Absolute time** -- numerical ages in "millions of years" or some other measurement. These are most commonly obtained by radiometric dating methods performed on appropriate rock types.

Relative time represents the physical subdivisions of the Earth's stratigraphy, and absolute time represents the measurements made upon those strata to determine the actual time that has transpired since the rocks were formed. Absolute time measurements can be used to assign ages to the relative time scale.

The following scale shows the major divisions of geologic time. The time scale is depicted in its traditional form, with oldest at the bottom and youngest at the top. The column on the left shows the complete sequence of time from the estimated origin of the Earth (4.6 billion years ago) to the present day. All time up to about 550 million years ago (Ma) is referred to as the Precambrian Eon. All time from 550 Ma to the present is referred to as the Phanerozoic (or visible life) Eon. The second column is an expansion of the Phanerozoic Eon from Column 1. The Phanerozoic Eon is divided into three eras: the Paleozoic (550 Ma to 250 Ma), the Mesozoic (250 Ma to 65 Ma), and the Cenozoic (65 Ma to present). Each Era is further subdivided into smaller spans of time referred to as "Periods". The third column is expansion of the Cenozoic time scale to show its division into the Tertiary and Quaternary Periods. The Tertiary Period (which includes the igneous rocks of the Trans-Pecos region) is split into five epochs, and the Quaternary Period into two epochs.

Geologists date rocks based on their relative position in the stratigraphic column, the occurrence of specific fossils found in the rocks, and also by radiometric methods which allow "absolute" ages to be estimated. Thus, based on stratigraphic position relative to other rocks, paleontological data, and radiometric age calculations, rocks can be assigned to their respective periods and epochs within the Geologic Time Scale.



MAJOR DIVISIONS OF GEOLOGIC TIME

LBG-GUYTON ASSOCIATES