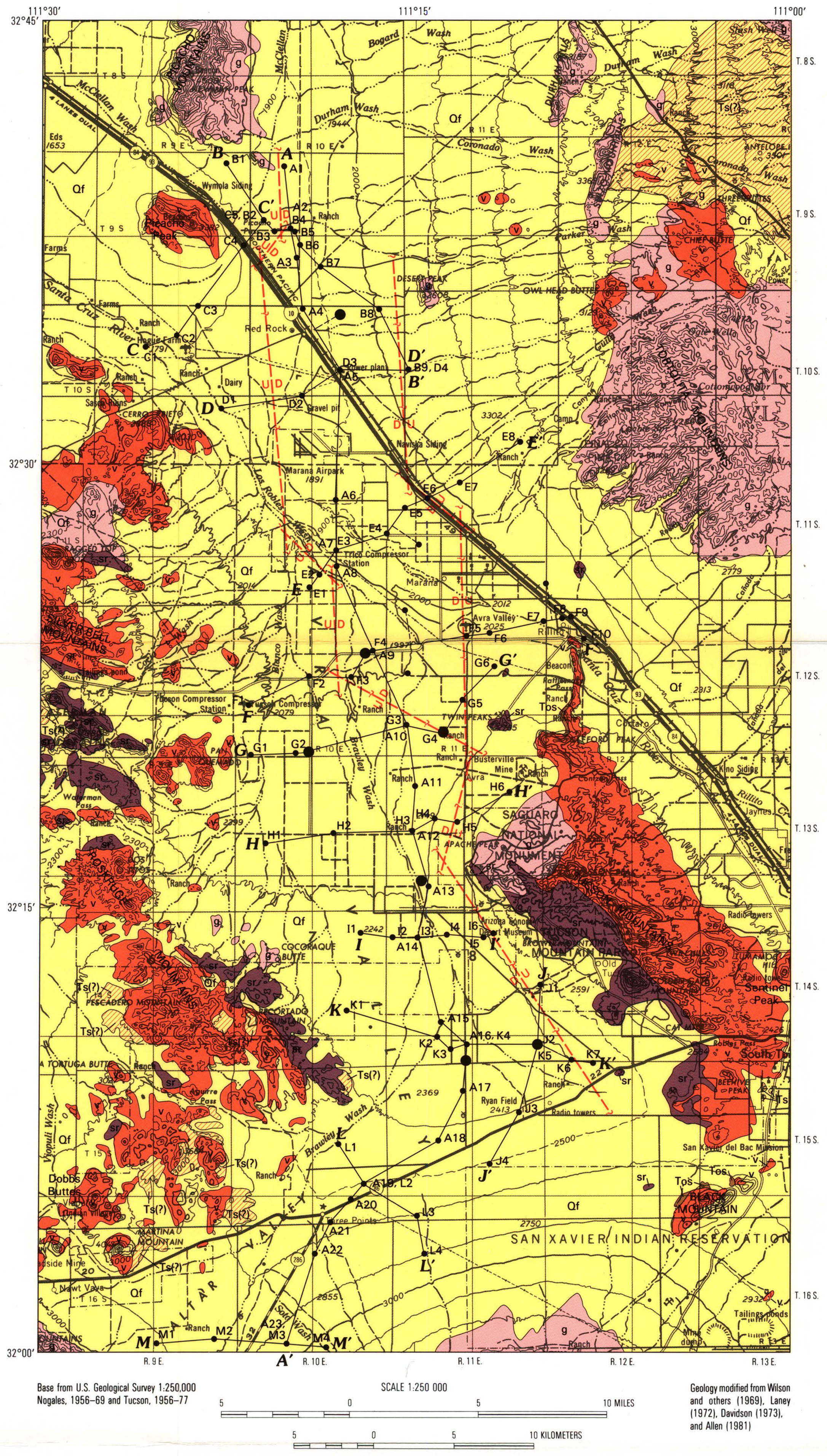

Figure 2.—Generalized distribution of rock types in Avra Valley.

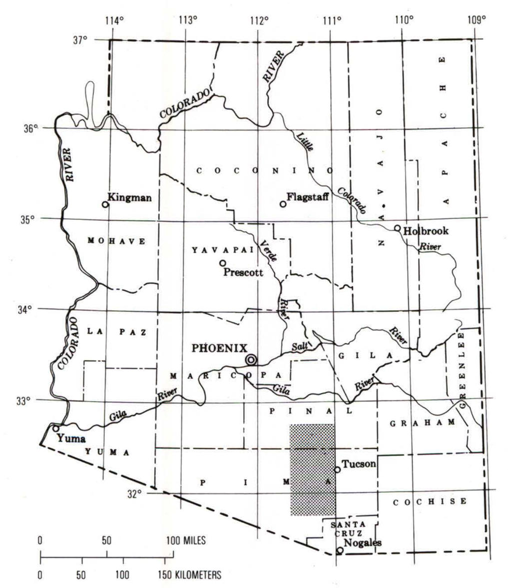

Figure 1.—Area of report (shaded).

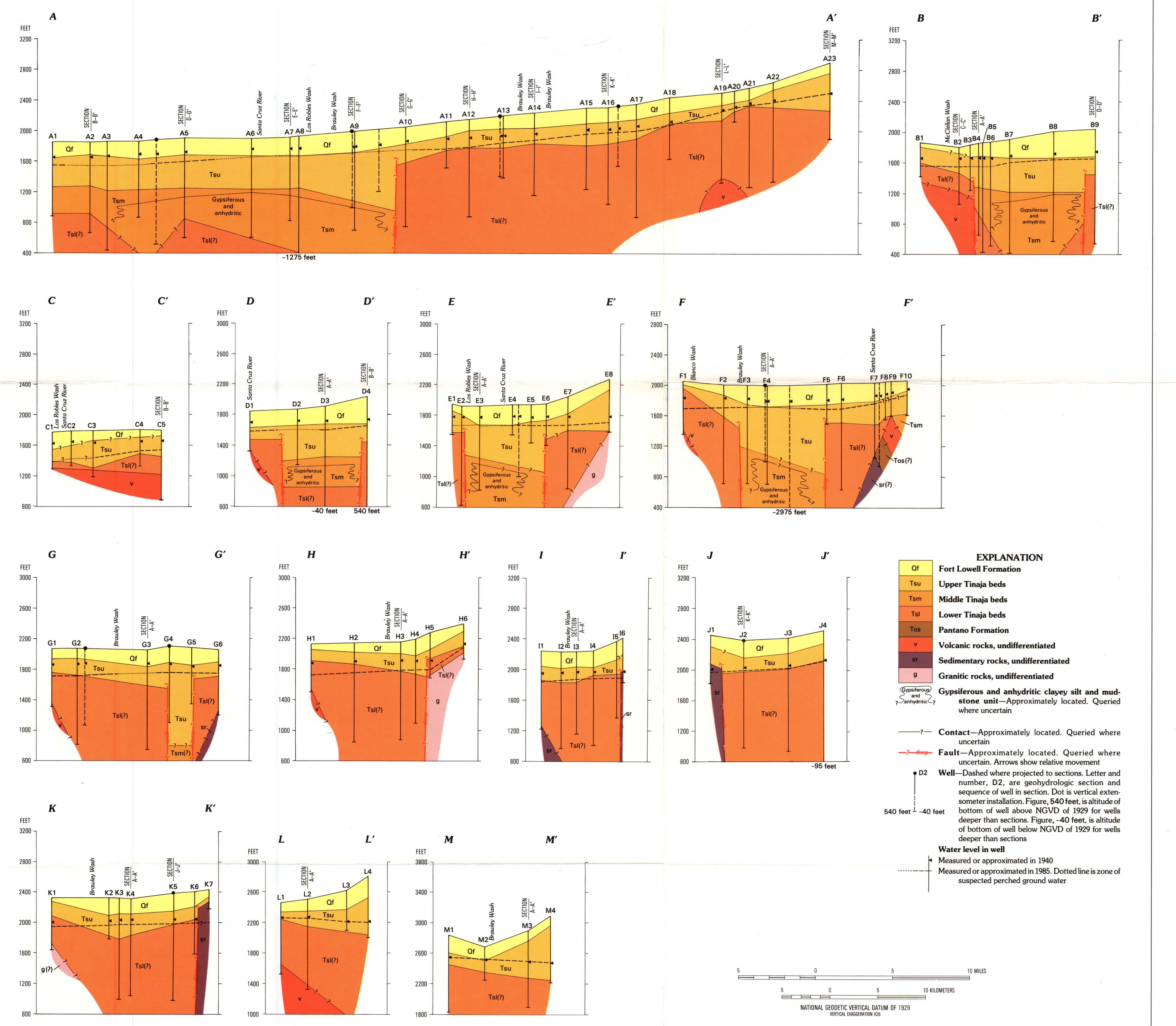

Figure 3.—Geohydrologic sections in Avra Valley.

INTRODUCTION

Avra Valley is a large north-trending alluvial basin about 15 mi west of Tucson in Pima and Pinal Counties, Arizona (fig. 1). The 520-square-mile valley is bounded on the east and west by steep mountain ranges that rise abruptly above a broad and gently sloping valley floor. The climate of Avra Valley is semiarid, and the average annual precipitation ranges from 8 to 12 in (Sellers and Hill, 1974). Two major ephemeral streams, the Santa Cruz River and Brawley Wash, drain the area. These streams and their tributaries provide a source of recharge to an extensive alluvial aquifer that underlies the valley floor. The aquifer consists of interbedded gravel, sand, silt, and clay and contains a vast quantity of ground water.

The physiography, fertile soil, and mild climate of Avra Valley make it an ideal environment for agriculture and urban development. Historically, the valley has been a sparsely populated agricultural area, but in recent years a shift towards urbanization has taken place. Demand for water in the area is high. Streamflow is intermittent and generally of short duration and therefore is not a dependable source of water. Ground water pumped from the aquifer is the main source of water in the valley and is also used to supplement supplies in the adjacent Tucson basin. Although the aquifer is replenished by natural recharge and underflow, rates of recharge and underflow have not kept pace with the rate of pumping. Pumping has exceeded recharge for several decades, resulting in a lowering of ground-water levels throughout most of the valley. In places, water-level declines have resulted in small amounts of aquifer compaction and land subsidence. Earth fissures, some of which may be the result of localized differential subsidence, also have been observed in the valley.

Aquifer compaction, land subsidence, and earth fissures can severely damage or affect the functional capability of manmade features. Aquifer compaction may damage wells, differential land subsidence may adversely affect structures such as sewers and irrigation water-supply systems that are dependent on gravity for their operation, and fissures may damage engineered structures. In addition, compaction and subsidence can seriously reduce the ground-water storage capacity of the aquifer, and fissures may provide a direct path for the rapid movement of contaminants from the land surface to the aquifer.

Damage that results from compaction, subsidence, and fissuring has occurred in the Eloy–Picacho area northwest of Avra Valley (Schumann and Poland, 1970; Davidson, 1973; Laney and others, 1978). Hundreds of square miles in and near the Eloy–Picacho area have been affected by compaction, subsidence, and fissures induced by ground-water withdrawal. Survey data indicate that 120 mi² subsided about 7 to 12.5 ft from 1952 to 1977. Many earth fissures have opened in this area; the fissures commonly are more than 1,000 ft long and generally surround areas of large water-level decline and subsidence. The potential for related damage in Avra Valley was suggested by Caito and Sogge (1982).

In 1979 the U.S. Geological Survey, in cooperation with the City of Tucson, began an investigation of aquifer compaction and the effects of land subsidence and earth fissures in the Tucson basin (Anderson, 1987a). In 1983 the investigation was expanded to include Avra Valley. The primary purposes of the investigation are to monitor the amounts of aquifer compaction and land subsidence and to define areas of related potential hazards. This report describes geohydrologic characteristics of Avra Valley that may contribute to potential aquifer compaction, land subsidence, and earth fissures.

The quantitative evaluation of potential land subsidence in this report is presented as an interim land- and water-use planning tool pending acquisition and study of additional data. Cautious interpretation of the results is necessary because only a small amount of compaction and subsidence had occurred in Avra Valley as of 1986. Because of data limitations, the evaluation is made on the assumption that future rates of compaction and subsidence in Avra Valley will be similar to those in the Eloy–Picacho area. The evaluation also assumes that water-level declines in the aquifer will continue. Socio-economic factors that may reduce ground-water withdrawals, and thus the potential for compaction and subsidence in Avra Valley, were not evaluated. These factors include the effects of the 1980 Arizona Ground-Water Management Act that regulates withdrawals of ground water in major agricultural areas, the importation of Colorado River water by the Central Arizona Project, and the probable increased reuse and reclamation of sewage effluent.

Sedimentary units of the aquifer in Avra Valley are, in this report, assigned geologic names derived from a sequence of sedimentary units of similar age in the adjacent Tucson basin (Davidson, 1973; Allen, 1981; Anderson, 1987a; 1987b). Correlation of Avra Valley sedimentary units with their Tucson basin counterparts is based on similar physical characteristics, stratigraphic position, and relation to volcanic rocks of Tertiary age. Some of the stratigraphic and structural relations in this report, which were used to evaluate potential land subsidence and earth fissures, can be interpreted in other ways. Alternative geologic interpretations, however, should have little if any impact on the evaluation because the stratigraphic and structural boundaries presented in this report correspond with the lithologic changes in the sediments of the aquifer that are most likely to affect the magnitude and extent of compaction.

During this investigation, cooperation was received from many employees of the City of Tucson. The author would like to thank R. Bruce Johnson, Chief Hydrologist; Joseph A. Babcock; Gary L. Hix; Gerald J. Huerstal; and Lynn Brumbaugh of the Tucson Water Planning Division and Don H. Madsen, Administrator; Daniel J. Sweet; and Melvin S. Sanderson of the Tucson Water/Water Resources Division. The author is also especially grateful to Herbert H. Schumann, B. L. Wallace, Colleen A. Babcock, and Melinda K. Cuff of the U.S. Geological Survey for their advice and support.

GEOHYDROLOGIC SETTING

The mountains surrounding Avra Valley consist of igneous, metamorphic, and indurated sedimentary rocks of Precambrian to Tertiary age (fig. 2) that generally yield only small to moderate quantities of water to wells and springs along the margins of the basin. Withdrawal of water from the rocks of the mountains probably will result in little or no compaction. The valley floor is underlain by unconsolidated to indurated sedimentary deposits of Tertiary and Quaternary age (figs. 2 and 3) that yield small to large quantities of water to wells within the basin. Withdrawal of water from some of these deposits may result in moderate to large amounts of aquifer compaction.

Major sedimentary units in Avra Valley are the Pantano Formation of Oligocene age, the Tinaja beds (informal usage) of Miocene and Pliocene age, and the Fort Lowell Formation of Pleistocene age (Davidson, 1973; Allen, 1981; Anderson, 1987a; 1987b). The Pantano Formation consists of conglomerate, sandstone, mudstone, and gypsiferous mudstone. The Tinaja beds consist of deposits ranging from gravel and conglomerate to gypsiferous and anhydritic clayey silt and mudstone. The Fort Lowell Formation is made up of gravel, sand, and clayey silt. The Tinaja beds are subdivided into lower, middle, and upper units in the subsurface (Anderson, 1987a; 1987b). Data from well cuttings and cores indicate that the lower unit consists mainly of silty sand, gravel, and conglomerate, the middle unit mainly of gypsiferous and anhydritic clayey silt and mudstone, and the upper unit of gravel to clayey silt.

The Pantano Formation, lower Tinaja beds, and middle Tinaja beds consist largely of moderately indurated to indurated deposits that may be generally resistant to deformation related to ground-water withdrawal. The deposits may, in places, be susceptible to compaction; however, their lithologic properties indicate that they are far less prone to compaction than the overlying deposits of the upper Tinaja beds and Fort Lowell Formation. The upper Tinaja beds and Fort Lowell Formation consist largely of unconsolidated to poorly indurated deposits that may, in places, be greatly susceptible to compaction where saturated. The potential for aquifer compaction and its effects in the valley, therefore, is dependent mainly on the characteristics of the upper Tinaja beds and Fort Lowell Formation and the relation between these units and bedrock. As used here, bedrock includes the rocks of the mountains and the deposits of the Pantano Formation, lower Tinaja beds, and middle Tinaja beds.

The aquifer consists of the Pantano Formation, the Tinaja beds, and the Fort Lowell Formation as shown in figure 3. The Pantano Formation yields small to moderate quantities of water to wells but is deeply buried in most parts of the valley. The Tinaja beds yield small to large quantities of water to wells and are the most important source of ground water in the valley. The Fort Lowell Formation is the most permeable unit in the aquifer and yields moderate to large quantities of water to wells but generally is unsaturated throughout most areas of the valley as of 1986. Coarse-grained deposits of the upper Tinaja beds and Fort Lowell Formation commonly yield more than 1,000 gal/min of water to properly constructed wells.

In general, the water-bearing alluvial deposits of Avra Valley are interconnected hydraulically at least to a depth of 700 ft and form a single unconfined aquifer (Moosburner, 1972). In parts of the valley, water below a depth of about 1,100 ft is confined below clay and silt layers and may rise above the regional water table (Moosburner, 1972). Perched ground water may lie above the regional water table in some interior parts of the basin (figs. 3 and 7) on the basis of anomalously shallow ground-water levels and cascading water in wells (Reeter and Cady, 1982; Whallon, 1983; Cuff and Anderson, 1987). The zone of suspected perched ground water in the central and northern parts of the basin occurs where the saturated deposits of the upper Tinaja beds and Fort Lowell Formation consist largely of fine-grained sediments. Fine-grained sediments of the upper Tinaja beds and Fort Lowell Formation in the central and northern parts of the valley contain a large percentage of the volume of water that is stored in the aquifer. Because the sediments generally are much more compressible than their coarse-grained counterparts elsewhere in the basin, the potential for aquifer compaction in these areas is high.

The potential for aquifer compaction in Avra Valley is greatly dependent on the thickness and clay-silt content of the saturated sediments of the upper Tinaja beds and Fort Lowell Formation. Major variations in thickness of the upper Tinaja beds that are related to the structural deformation of underlying bedrock may profoundly affect the amount of compaction and subsidence and the formation of fissures in parts of the valley as water levels decline (fig. 3). Potential effects of these variations may be greatest in areas where the upper Tinaja beds are also rich in clay and silt. Areal distributions of clay- and silt-size particles—diameters of less than 0.0625 mm—contained in the upper Tinaja beds and Fort Lowell Formation are shown in figures 4 and 5 (see sheet 2). Montmorillonite clay is the dominant interstitial clay in the adjacent Tucson basin (Laney, 1972) and is probably a major constituent of the fine-grained sediments in Avra Valley. Overall, montmorillonite probably accounts for about 90 to 95 percent of clay minerals in the sediments on the basis of local and regional sampling (F. N. Robertson, Hydrologist, U.S. Geological Survey, oral commun., 1984). Montmorillonite clay is more compressible than other clay minerals and more susceptible to compaction (Meade, 1968). The percentage of clay and silt in well cuttings, by weight, was averaged over the thickness of the formation penetrated by each sampled well (figs. 4 and 5). Well cuttings generally were sampled every 5 to 10 ft of well depth. Most wells fully penetrate the Fort Lowell Formation; however, many wells only partially penetrate the upper Tinaja beds. In the central and northern interior parts of Avra Valley, the sediments of the upper Tinaja beds and Fort Lowell Formation are about 500 to 1,000 ft thick (fig. 3). Sediments of these units consist of 40 to 80 percent clay and silt in about a quarter of the basin (figs. 4 and 5). The potential for aquifer compaction and land subsidence is greatest where the saturated deposits of these units are both thick and rich in clay and silt.

The potential for localized differential land subsidence and earth fissures is greatest where saturated fine-grained deposits of the upper Tinaja beds and Fort Lowell Formation overlie shallowly buried faults or convex irregularities in the bedrock. The potential also may be great where the saturated sediments of the upper Tinaja beds and Fort Lowell Formation change abruptly from mainly coarse grained to fine grained in composition across a short distance in the aquifer. The compressibility of the deposits, amount and distribution of ground-water pumpage, and resultant water-level declines will ultimately control the magnitude and extent of these effects in the valley.

CONVERSION FACTORS

For readers who prefer to use metric units, conversion factors for the terms used in this report are listed below:

MULTIPLY	BY	TO OBTAIN
inch (in)	25.4	milimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
square mile (mi²)	2.590	square kilometer (km²)
acre-foot (acre-ft)	0.001233	cubic hectometer (hm³)
gallon per minute (gal/min)	0.06309	liter per second (L/s)

National Geodetic Vertical Datum of 1929 (NGVD of 1929): A geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929.

EXPLANATION OF TERMS AND PROCESSES

In this report, an *aquifer* is defined as a body of sedimentary materials that is sufficiently permeable to conduct ground water and to yield economically significant quantities of water to wells and springs (Bates and Jackson, 1980). *Aquifer compaction* is the decrease in thickness of an aquifer that is caused by the withdrawal of water and resultant reduction in size of intergranular spaces within compressible aquifer deposits (Poland and Davis, 1969). Aquifer compaction results in *land subsidence*, which is the sinking or settlement of the land surface (Poland and others, 1972). Unequal sinking or settlement of the land surface between adjacent areas is called *differential land subsidence* and may be localized or regional in nature. *Earth fissures* are narrow, vertical tensional breaks that form in alluvial deposits; those that form as a result of localized differential land subsidence are referred to as *subsidence fissures* (Schumann and Poland, 1970; Jachens and Holzer, 1979). Subsidence fissures that show vertical offset have been referred to as *faults* (Jachens and Holzer, 1979). Fissures that are eroded by flowing water form wide gully-like depressions called *fissure gullies* (Kam, 1965).

Unconsolidated to poorly indurated sediments undergo compaction as a result of a variety of natural phenomena. *Natural compaction* results mainly from the weight of overlying sediments; however, other natural phenomena that press on or shake the sediments, such as earth tides and occasional stress from seismic activity, may also cause compaction. Natural compaction of such sedimentary materials is greatly accelerated by the withdrawal of ground water. The lowering of the ground-water table or a decrease in artesian head results in the rearrangement and closer packing of the coarse and essentially incompressible aquifer grains and the compression and partial dewatering of compressible fine-grained aquifer materials (Davidson, 1973). An aquifer is most susceptible to compaction where it is rich in clay but permeable enough so that substantial quantities of water can be withdrawn (Davidson, 1973).

Aquifer compaction consists of *elastic* and *inelastic components* (Poland and others, 1972). The elastic component is recoverable and results in aquifer expansion when a rise in water level or an increase in artesian head occurs. The inelastic component is nonrecoverable and results in permanent compaction of the aquifer. In clay- and silt-rich—fine-grained—aquifer materials, the inelastic component commonly is many times larger than the elastic component. In sand- and gravel-rich—coarse-grained—materials, however, the inelastic component may be small compared to the elastic component. The elastic component occurs simultaneously with water-level decline, whereas the inelastic component may occur at a slow rate (Poland and others, 1972). Inelastic compaction of an aquifer may lag the water-level decline or decrease in artesian head by as much as several years (Helm, 1978). The time lag is caused by slow drainage of water from fine- to coarse-grained beds. The nature of the time lag is dependent on clay-bed thickness, permeability, and pore pressure.

Compaction of aquifer deposits occurs when the upward pressure or buoyancy of the ground-water reservoir is reduced as a result of a decrease in artesian head or a decline in water level. A reduction of upward pressure or buoyancy increases the *vertical effective stress* exerted on the aquifer deposits. The resulting compaction is dependent on the *preconsolidation stress*, which is the maximum vertical effective stress to which the aquifer sediments have been previously subjected (Casagrande, 1936; Holzer, 1981). Water-level decline will be accompanied by *elastic compaction* if the resulting increase of vertical effective stress is less than the preconsolidation stress. Elastic compaction occurs in the preconsolidation range but may include a small inelastic component (Poland and others, 1972; Holzer, 1981). Water-level decline will be accompanied by *virgin compaction* if the resulting increase of vertical effective stress is greater than the preconsolidation stress. Virgin compaction consists of elastic and inelastic components (Poland and others, 1972). The inelastic component of virgin compaction typically is much larger than the elastic component, especially if the aquifer is rich in clay and silt. In general, virgin compaction causes a much greater magnitude of volumetric strain in the aquifer than does elastic compaction and, therefore, may be much more damaging.

The magnitude of water-level decline that is necessary to initially induce virgin compaction of aquifer materials has a wide range and is related, in part, to the degree to which the materials are naturally consolidated in relation to overburden pressure. A lowering of the water level or a decrease in artesian head may soon lead to virgin compaction in normally consolidated aquifer materials. Commonly, however, aquifer sediments are naturally overconsolidated and compact elastically until tens or hundreds of feet of water-level decline have occurred. *Overconsolidation* is defined as the consolidation of sedimentary material greater than that normal for the existing overburden (Bates and Jackson, 1980). The magnitude of the water-level decline where compaction of overconsolidated aquifer materials initially changes from elastic to virgin in nature is referred to in this report as the *threshold water-level decline* (Holzer, 1981).

Specific unit compaction, aquifer compaction per unit of water-level decline, and *land subsidence per unit of water-level decline* are useful ratios for contrasting elastic compaction with virgin compaction. Specific unit compaction is the compaction of deposits per unit of thickness per unit of increase in applied stress during a specified time period (Poland and others, 1972). The transition from elastic compaction to virgin compaction of aquifer materials may result in an order-of-magnitude increase in the measured amounts of specific unit compaction, aquifer compaction per unit of water-level decline, and land subsidence per unit of water-level decline (Riley, 1969; Meyer and Carr, 1979; Holzer, 1981).

The difference between aquifer compaction and land subsidence can be clarified by briefly describing how they are measured. Aquifer compaction is determined by measuring the distance between the land surface and the bottom of a well that may only partially penetrate the aquifer; compaction below the bottom of the well is unmeasured. Land subsidence is measured by resurveying land-surface points of established elevations; subsidence equals the amount of all compaction underlying a given point. Thus, a measurement of aquifer compaction will be less than a measurement of land subsidence for a given point and time unless the well in which it is measured fully penetrates all compressible deposits of the aquifer.

The rate and magnitude of aquifer compaction and land subsidence commonly vary considerably from place to place. Localized differential compaction and subsidence may be accompanied by the formation of fissures and faults. Localized differential subsidence, fissures, and faults are most likely to occur near the edges of a basin where compaction may be greatly influenced by the depth and geometry of bedrock. Bedrock as defined in this report includes all rocks and deposits of the mountains and subsurface that are generally resistant to deformation related to ground-water withdrawal. Differential compaction of the aquifer in such places may cause the land surface to bend across prominent bedrock features; the accompanying tensile strain may result in fissuring. Subsidence fissures commonly overlie shallowly buried fault scarps or convex irregularities in the bedrock; those that form above buried fault scarps may show vertical offset (Feth, 1951; Schumann and Poland, 1970; Holzer and others, 1979; Jachens and Holzer, 1979). Some localized differential subsidence and fissures occur in the central parts of a basin where bedrock is deeply buried. Subsidence and fissures such as these probably are the result of differential compaction across abrupt lateral depositional features that affect the compressibility and (or) water-bearing characteristics of the aquifer.

Although land subsidence and earth fissures commonly result from compaction of the aquifer, they may result also from other processes. Land subsidence and fissures, for example, commonly occur as a result of *hydrocompaction,* which is the vertical compaction or collapse of near-surface low-density sediments following a sudden or unusually large application of water to the land surface (Pashley, 1961; Poland and others, 1972; Davidson, 1973). Fissures also form in response to *desiccation,* which is the drying of near-surface fine-grained sediments by evapotranspiration (Neal and Motts, 1967). Desiccation of sediments may occur in the unsaturated zone or in the zone drained by shallow water-level declines (Anderson, 1978). Earth fissures have also been attributed to horizontal-seepage forces (Lofgren, 1971) and horizontal contraction caused by capillary stresses in the zone drained by water-level declines (Holzer and Davis, 1976; Holzer, 1977). Some fissures may be the result of natural compaction or seismic activity.

Some earth fissures appear to form near the land surface and deepen with time. Others may initially form at depth and propagate upward (Neal, 1972; Holzer, 1977). Fissures initially appear at the land surface as segmented arcuate to linear narrow cracks, and segments commonly form en echelon or polygonal patterns (Holzer, 1977). Fissures that accompany hydrocompaction and desiccation generally form arcuate to polygonal shapes that are tens to hundreds of feet across; fissure segments are generally tens of feet deep (Pashley, 1961; Neal and Motts, 1967; Anderson, 1978). Fissures that accompany water-level decline, aquifer compaction, and land subsidence generally form arcuate to linear en echelon patterns that are hundreds to thousands of feet in length; fissure segments may be hundreds of feet deep (Holzer and Davis, 1976; Holzer, 1977; Anderson, 1978).

Subsequent erosion and enlargement of earth fissures by flowing water result in the formation of fissure gullies; gullying is often dramatic after periods of heavy precipitation. Sediment that is eroded from near the land surface travels downward and is deposited at depth in fissure cavities (Holzer, 1977). Thus, the ultimate size of a fissure gully is dependent on the initial sediment-storage capacity of the underlying fissure. The sediment-storage capacity of fissures that accompany water-level decline, aquifer compaction, and land subsidence generally is large. Some resultant fissure gullies are more than 1,000 ft long and as much as 10 ft wide and 10 ft deep (Laney and others, 1978). Fissure gullies that result from hydrocompaction and desiccation, however, generally are small because the initial fissures are shallow and have limited sediment-storage capacity. Gullying may continue until earth fissures are filled completely with sediment. In arid environments, fissures may not fill for tens of years (Anderson, 1978). In areas of active land subsidence, new fissures may form from time to time and existing fissures may occasionally reopen; therefore, gullying may be a persistent problem.

POTENTIAL FOR AQUIFER COMPACTION, LAND SUBSIDENCE, AND EARTH FISSURES IN AVRA VALLEY, PIMA AND PINAL COUNTIES, ARIZONA

By

S.R. Anderson

1989