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REPORT

Crystalline-rock aquifer system of the Llano Uplift, Central Texas, USA

Neeraja Setlur[1] · John M. Sharp Jr[2] · Brian B. Hunt[3]

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Abstract

The crystalline-rock aquifer system of the Llano Uplift (Central Texas, USA) hosts an important local water resource that has been relatively little studied. The Uplift is a structural dome of Precambrian granitic and metamorphic rocks. Late Paleozoic normal faulting and fractures, decompressive fractures, weathering, lithology, and rock fabric control the aquifer properties. Data from driller reports (over 2,000 wells) show that wells in granites have higher median yields than wells in metamorphic rocks. There is a weak correlation of well yield with regolith thickness, and median regolith thickness is greater over granites than over metamorphic rocks. Fracture permeability, which is very heterogeneous, is the major control. Wells are shallow (generally <100 m depth), but more recent wells have been drilled more deeply. Permeability data imply decreased open-fracture density and aperture with depth, although sample bias is a consideration. Diamond drill cores show that many near-surface fractures with significant aperture are filled by rock fragments from weathered surrounding rocks and that fracture skins are thinner and contain iron oxides in a more reduced state with depth. Fracture skins can be porous, with porosity ranging to over 10%. There is a need to compare crystalline-rock aquifer systems to assess weathering, tectonics, fractures, and mineralogy/petrology to assess the characteristics of these systems, which are critical water resources in large areas of the world.

Keywords Crystalline rocks · Fractured rocks · Aquifer · Permeability · USA

Introduction

Crystalline rocks ("hard rocks") are exposed over large areas (about 20%) of the Earth's continents including the Precambrian shields, massifs, cores of mountain ranges, and other localized areas (Krasny et al. 2014). Crystalline rock aquifers are important in these areas because they are often the only significant local source of groundwater (e.g., most of Africa, Wright 1992). Crystalline rocks also underlie the sedimentary basins of the world. In addition, crystalline rock aquifers have been or are proposed as sites for waste disposal, mining, and geotechnical projects, such as tunnelling. These aquifers share common characteristics (Sharp and Troeger 2015): (1) well yields are variable, but most are relatively small; (2) fractures are critical to the development and permeability of the aquifers; and (3) well productivity is generally greatest in the upper layers of the weathered rock, particularly where the weathered or fissured layer is thick and saturated. Many monographs/compendia, notably including Banks and Banks (1993), Singhal and Gupta (2010), Stober and Bucher (2000), Faybishenko et al. (2000), Krasny and Sharp Jr (2007a), Gudmundsson (2011), and Sharp Jr (2014), have addressed the hydrogeology of crystalline rocks. However, the crystalline rock aquifer system of the Llano Uplift, Central Texas (Fig. 1) has received comparatively little attention with the exception of Hunt (2006, 2008) and Landers and Turk (1973). It is estimated about 6,000 wells produce an estimated pumping of 4.4 million m^3/year of groundwater from this system (Hunt 2006), The Llano Uplft is also under consideration for official recognition as a Texas minor aquifer (George et al. 2011), which is defined as an aquifer suppling large quantities of water in small areas or small quantities of water in large areas. This report re-evaluates the hydrogeologic properties of this crystalline aquifer system by analysis of Texas data sets (TDLR 2016; TWDB 2016), existing diamond drill cores, and of fracture skins in order to update the understanding of this system and provide a basis of comparison for similar aquifer systems elsewhere.

✉ John M. Sharp, Jr
jmsharp@jsg.utexas.edu

[1] Exxon Mobil, 22777 Springwoods Village Parkway,
Spring, TX 77389, USA

[2] Department of Geological Sciences, The University of Texas,
Austin, TX 78712, USA

[3] Barton Springs/Edwards Aquifer Conservation District,
Austin, TX 78747, USA

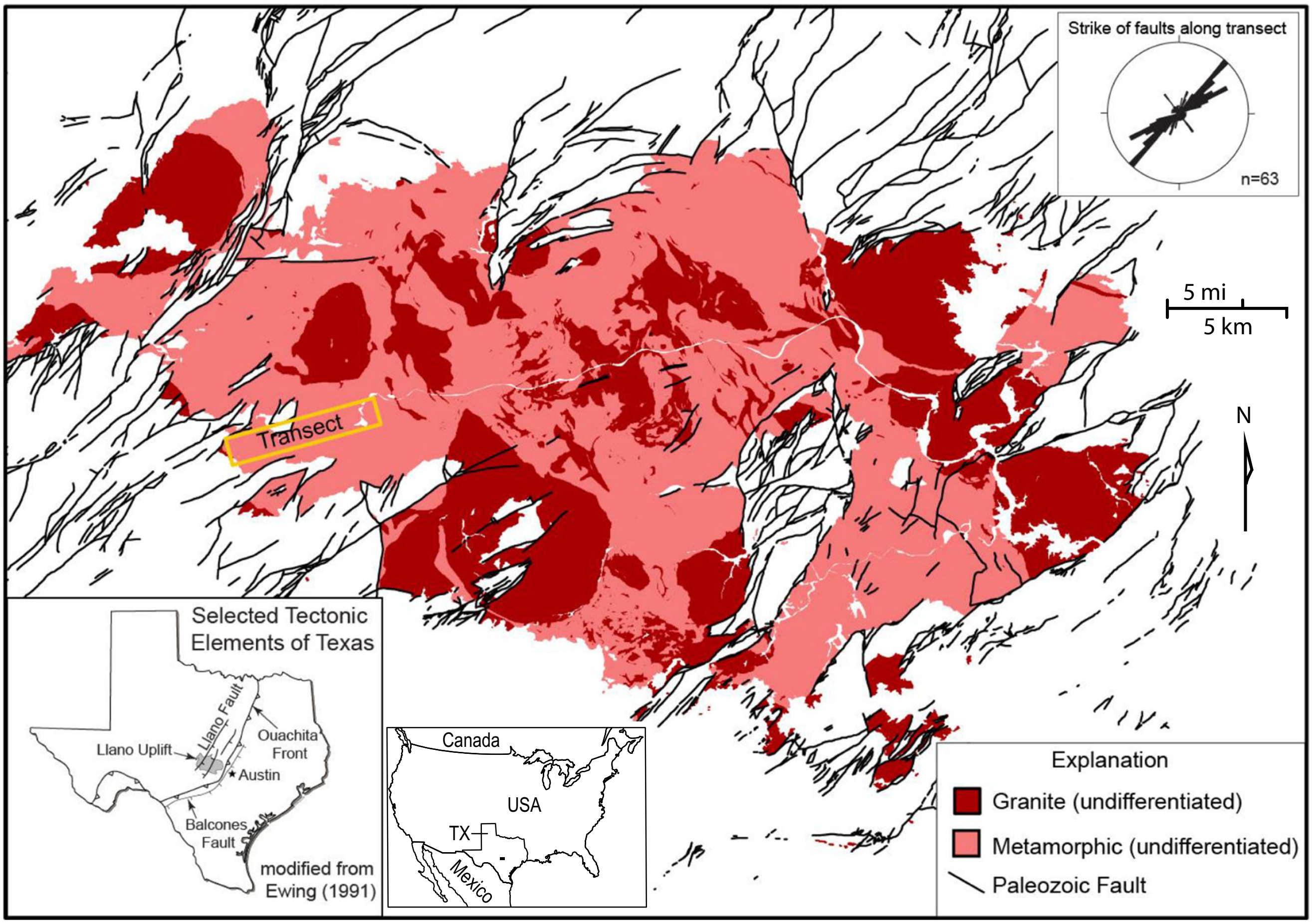


Fig. 1 Study area. Geologic and structure map of the Llano Uplift. Granites (40% of total area) are shown in red, and metamorphic units (60% of total area) are shown in pink. Paleozoic-age faults are shown as black lines (after Barnes 1981). Also shown is a rose diagram showing the strike of faults mapped by Hunt (2000) along the transect shown on the map

Setting

The Llano Uplift (Fig. 1) exposes over 3,400 km^2 of Mesoproterozoic (1.0–1.6 Ga) igneous and metamorphic rocks and is rimmed by Paleozoic and Mesozoic sedimentary rocks. The uplift is northeast of the Edwards Plateau and west of the Balcones Escarpment physiographic regions. The topography is a relatively flat to rolling landscape studded with rounded granite hills or domes up to 180 m high. Some of the hills are fault-bounded grabens of Paleozoic sediments that can be resistant to erosion. The Llano Uplift slopes gradually to the east with elevation ranging from 610 m in the west to 240 m along the Colorado River in the east.

Present-day climate is subtropical subhumid with hot summers and dry winters (Larkin and Bomar 1983). Average annual rainfall is 660–3,760 mm/year increasing from west to east across the study area (Daly 1998). Average surface water evaporation is 1,700−1,800 mm/year (Larkin and Bomar 1983). The Llano River is perennial (except during extreme droughts) and flows west to east through the center of the study area joining the Colorado River to the east. Intermittent streams feed into the Llano River, but these are generally dry or have very low flow during the summer months.

Study area residual soils formed in material weathered from its granite and metamorphic rocks. The soils are moderately deep (50–100 cm) and support grass savannahs scattered with oak trees (Goerdel 1998). McMahan et al. (1984) classify the area as “Live Oak-Mesquite Parks.” Live oak and mesquite are the dominant large woody species, and the term “park” refers to areas where “woody plants grow as clusters or scattered individuals within continuous grass or forbs (11–70% woody canopy overall).” Ranching is the dominant land use; over 80% of the study area is pastureland; and 10% is cropland (Goerdel 1998; USDA 2002). The region has also become a site for country vacation homes in the past several decades.

Geology

The Llano Uplift was formed by the intersection of several arches that formed at different time periods. The geologic and structural development of the uplift involved all the major tectonic cycles that affected Texas, including two major orogenies, a major unconformity, extensional faulting, and erosion (Ewing 2004; Barker and Reed 2010; Ewing 2016). Metamorphic rocks (schists, gneisses, marbles, and metaigneous rocks containing polyphase ductile structures and metamorphic fabrics) cover about 60% of the area and are intruded by syn- to post-tectonic granites comprising about 40% of the exposed Precambrian (Reed 1999; Barker et al. 1996). The rocks record the 300-million-year history of the Grenville Orogeny and formation of the supercontinent Rodinia (Mosher 1998). Following Rodinia's breakup, erosion and uplift occurred during the next 0.6 billion years removing about 10 km of crust in the region. By the Middle- to Late-Cambrian Period, the region was a nearly level plain and began to accumulate early Paleozoic clastic sediments. The Paleozoic Era is represented by marine sedimentation blanketing the Llano Uplift. These rocks dip radially away from the uplift and form the Paleozoic sedimentary minor aquifers (e.g., the Hickory, Marble Falls, and Ellenberger-San Saba aquifers) that surround the uplift (Preston et al. 1996).

The late Paleozoic Ouachita Orogeny caused northeast-trending normal faults that cross Precambrian and Paleozoic units in the uplift. These faults contribute to the development of secondary porosity and permeability. During the Mesozoic, the Llano Uplift was a structural high. Cretaceous carbonate and clastic sediments unconformably overlie the Paleozoic sediments and thicken away from the uplift. During the Miocene, the Llano Uplift achieved its present form. The Edwards Plateau region was uplifted and stripped of much of its sedimentary overburden (Ewing 2004).

Faulting and fracturing

Two families of fractures are prevalent in the study area, decompressive and tectonic. Decompressive fractures are typically subhorizontal, diminish with depth, and are related to the uplift of rocks and the release of confining pressures (Folk and Patton 1982). Tectonic fractures tend to be subvertical and concentrated. Paleozoic normal faults crosscut the Precambrian and Paleozoic rocks of the Llano Uplift and generally trend to the northeast (Fig. 1), but can strike in other orientations (Barnes 1981; Johnson 2004). Most faults have a significant normal dip-slip component with moderate throws; however, some faults have throws of greater than 500 m. A number of faults exhibit oblique-slip displacement with left-lateral or right-lateral strike-slip components (Johnson 2004). Moreover, note that faulting within these rocks is more prevalent than shown on published maps (see Appendix)—for example, no mapped faults are shown at the 1:500,000 scale (Barnes 1981), but Hunt (2000) mapped 63 faults within a 16 km transect of crystalline rocks (Fig. 1) in the western Llano Uplift.

Methods

Water-well data from the crystalline rocks of the Llano Uplift, compiled by the Texas Water Development Board (TWDB) and predecessor agencies, were reviewed and reanalyzed. Data collected by Landers and Turk (1973) were compared with the later data from Hunt (2008) to assess well yields as functions of lithology, well depth, and reported depths to fresh bedrock. Field trips to the site area examined the weathering profiles and allowed for sample collection. Eight diamond drill cores stored at the Texas Bureau of Economic Geology (BEG) Core Research Center were logged. These were analyzed for rock quality designation (RQD) and fractures and fracture skins. Samples were taken for scanning electron microscopy (SEM), energy dispersive X-ray spectroscopy (EDS) and optical microscopy. Data collected were compared with previous research on crystalline rock aquifers, particularly in the study area, to provide hydrogeological insights.

Results

Water-well data

Landers and Turk (1973) evaluated TWDB data supplemented with data from local well drillers and interviews with well owners. Hunt (2008) evaluated the entire TWDB well database and included the Texas Department of Licensing and Regulation (TDLR) well drillers logs from 2001 to 2007. This study includes all the data within the TWDB well database and drillers records for all wells from 2001 to 2016. The findings are synopsized in Tables 1 and 2. The data are obtained from databases that contain water well driller's logs, which are variable in quality and accuracy, but analysis from over 2,400 wells shows commonalities.

Landers and Turk (1973) divided well test data by: (1) proximity to reservoirs in the study area and (2) media (granite, grus, fractured granite, schist, and gneiss). They found that wells in grus had the greatest productivity followed by granite, fractured granite), gneiss, and schist. Landers and Turk (1973) noted that wells were more

Table 1 Llano crystalline-rock aquifer median well yields and depths and regolith thicknesses from Texas Water Development Board file data (Landers and Turk 1973[a]; Hunt 2008[b], for wells until 2008; and Sharp et al. 2016[c]), for wells since 2008)

Rock type (No. of wells)	Median well yield [L/m]	Median well depth [m]	Median regolith thickness [m]
Granite (197)[a]	30	22.9	–
Grus (103)[a]	60	12.2	–
Fractured granite (40)[a]	23	25.9	–
Schist (73)[a]	15	15.8	–
Gneiss (48)[a]	15	24.1	–
Granite (559)[b]	57	35.1	11.9
Metamorphic rocks (537)[b]	30	42.7	5.5
Granite (520)[c]	30	48.8	7.0
Metamorphic rocks (246)[c]	26	42.7	6.7

The term ‘metamorphic rocks’ includes undifferentiated schists and gneisses

productive if located close to permanent water reservoirs on the Llano River. Wells close to a reservoir were overall shallower (median depth of 20 m) and more productive (median well yield of 64 L/min) compared to wells at a distance away from the lakeshores which had a median depth of 23 m and a median yield of 38 L/min. The reservoirs were inferred to provide a recharge boundary condition.

Hunt (2008) expanded the database and re-divided all wells into those producing from granites and those from schists/gneisses. Rock types were identified using the Geologic Atlas of Texas and GIS to assign mapped rock types. Driller descriptions of rock cuttings were reviewed to verify assigned rock types and thickness of regolith. The 559 wells located in the granites had a higher median well yields and thicker regoliths than the 537 located in the metamorphic rocks (Table 1). Hunt also found that well drillers reported a higher percentage of “dry” wells (i.e., no significant yield) in the metamorphic rocks than in the granites and that mean salinites are lower in wells in granites (420 mg/L) than in those in metamorphics (500 mg/L). The authors infer that this is caused by slightly higher recharge rates in the granites.

Results of studies listed in Table 1 are generally comparable; however, Hunt (2008) and Sharp Jr et al. (2016) grouped all wells into two rock type categories, which include the *grus* (regolith) and fractured categories identified in Landers and Turk (1973). The relatively high yields for the granite in Hunt 2008 include yields of both the granite and grus categories identified in Landers and Turk (1973).

These data imply that, in this study area, granitic rocks are in general slightly more productive than the schists and gneisses, which is most likely because the granitic rocks have some combination of more open fractures and a thicker, more permeable regolith. Note, however, that these general trends do not consider the lithologic differences (see Table 2). Also, the median depth for wells in granites has increased with time. This change in median well depth with time may be a result of the drying up of the aquifer due to the relatively low permeabilities and bedrock recharge rates. In addition, the authors infer that recent population growth, smaller lot sizes, and construction of home

Table 2 Well yields, well depths, and regolith thickness by geologic formations

Geologic formation (No. of wells)	Median well yield [L/m]	Median well depth [m]	Median regolith thickness [m]
Town Mountain Granite (658)	34.0	36.6	9.1
Fine-grained granites (62)	7.6	42.7	3.0
Granite wash (566)	26.5	48.8	7.0
Packsaddle Schist (346)	9.5	36.6	5.6
Valley Spring Gneiss (360)	18.9	48.8	4.0
Big Branch Gneiss (14)	0.19	89.6	7.2
Lost Creek Gneiss (23)	0.0	36.6	5.2
Undifferentiated/unknown (359)	26.5	42.7	4.3

Undifferentiated/unknown were identified by rock type, but the appropriate formation was not identifiable sites have likely influenced the location of wells more than aspects of the topography and geology. For example, houses that seek good views may site more wells on higher ground that would tend to correspond to relatively unfractured or thin regolith terrains.

Table 2 organizes the well yield data by geologic formation and shows that Town Mountain Granite wells have the highest median yield, the thickest median regolith, and the smallest median well depth. The Town Mountain Granite is the name for the coarse-grained granites of the Llano Uplift. The fine-grained granites are less productive as are the Packsaddle Schist and the gneisses. Wells mapped as located in granite wash (grus or alluvium) are also relatively productive, but the data indicate that the wells were generally deeper than the regolith (49 m vs. 7 m). Barker and Reed (2010) subdivided the coarse-grained (Town Mountain) granites into syn-kinematic and post-kinematic and found higher amounts of amphibole and biotite in the coarse-grained granites than in the fine-grained granites. Expansion of biotite with weathering is conducive to creating the weathered zones and increasing permeability and porosity (Lachassagne et al. 2014). Biotite also occurs in the metamorphic rocks, but the well yields and regolith thicknesses are smaller than in the Town Mountain Granite. Folk and Patton (1982) attribute the thick regolith (grus) of the Town Mountain as being caused by buttressed expansion.

Driller reports contain information on well yield, but very few wells have reported drawdowns and times at given pumping rates. Specific capacity data are too few to prepare an equation for estimating site-specific transmissivity as a function of specific capacity as was done by Logan (1964) for Ireland, Rhen et al. (1997) for Sweden, or Robins et al. (2013) for Malawi. However, the few transmissivity estimates derived from the available specific capacity data suggest that the crystalline rocks of the Llano Uplift plot in the intermediary range of the transmissivity data from Krasny et al. (2014, their Fig. 1.1) for all wells drilled in hard rocks. These transmissivities are in the upper 16% for crystalline hard rocks. The Llano crystalline rock aquifer thus appears relatively productive compared to similar aquifers; however, Landers and Turk (1973) noted that well yields as a function of well depth decreased more rapidly in the Llano than in the eastern United States and the Sierra Nevada of California (Davis and Turk 1964). This was attributed to higher weathering rates and thicker regolith (grus) in those other regions.

Well productivity generally decreases with well depth. Figure 2 shows wells yields in granitic and metamorphic rocks as a function of depth. The best fit of the data is a logarithmic regression and the granitic rocks appear more productive than the metamorphic rocks at all depths. These figures show a scatter of data but with generally declining yields in wells that were drilled more deeply. Within this database and according to conversations with local drillers, it is uncommon for drillers to go much beyond 100 m depth. The two wells drilled to over 200 m (Fig. 2) illustrate what drillers recognize—drilling deeper does not generally increase yield in these crystalline aquifers.

The literature suggests fewer wide aperture fractures and decreasing density of permeable fractures in crystalline

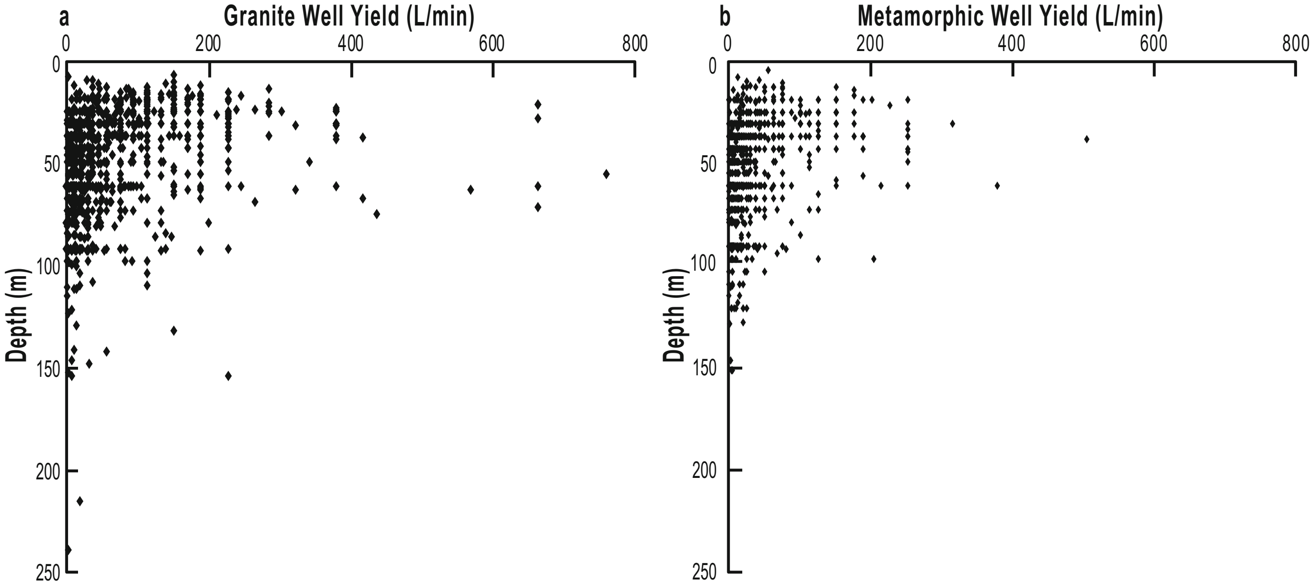


Fig. 2 Well yields in **a** granites and **b** metamorphic rocks versus depth. Regressions in Table in the section 'Discussion and conclusions'. L/min = 26.4 gallons per minute (gpm); 100 m = 328 ft. Original data (TDLR 2016; TWDB 2016) are in gpm and feet

rocks with increasing depth (e.g., Snow 1968; Carlsson et al. 1983; Gonzalez-Yelamos et al. 1993; Wladis et al. (1997), Zhao 1998; Normani et al. 2007; Jiang et al. 2010; Krasny et al. 2014). As an exception, Huntley et al. (1991) did not find this; however, they speculated that statistics showing decrease in the fracture frequency or the frequency of "water-bearing" fractures with depth are questionable because wells in crystalline rock aquifers are only drilled to a depth sufficient to produce the target well yield. This can create a sampling bias as noted by Huntley et al. (1991) and Wladis et al. (1997); however, although significant variations can occur, the general trend of decreasing fracture permeability with depth in crystalline rocks (below the weathered shallow horizons) is well documented. Decreased fracture density and permeability with depth is a key contributor to the decreasing yield with increasing well depth.

The data (Landers and Turk 1973; Hunt 2008; Sharp Jr et al. 2016) show that more deeper wells were drilled in recent years. The authors infer that the greater depth for more recent wells is the result of better well-drilling technology and the rise of vacation home sites that often have good views and are thus located on topographic highs where the water table lies at greater depth. In addition, the highs tend to be located in zones of limited fracturing and thinner weathered zones.

Permeability

In these crystalline rock systems, permeability is controlled by fracture density, connectivity, and hydraulic apertures and by weathering—e.g., Wright 1992; Krasny and Sharp Jr 2007b; Lachassagne et al. 2011, 2014. Lithology and rock textures affect the distribution and character of fractures and weathering. Shallow weathered and/or fissured zones (regolith), where saturated, generally provide the highest well yields due to higher porosity and permeability compared with the underlying crystalline bedrock (e.g., Deere and Patton 1971; Wyns et al. 2004; Lachassagne et al. (2011). The characteristics of the soil overlying the hard rock aquifer (also a function of the underlying bedrock) affect recharge, so soil properties must also be considered. Where only fractures provide the only significant permeability, this can vary by orders of magnitude over short distances (e.g., Dewandel et al. 2006; Stober and Bucher 2007), and transmissivity estimates from specific capacity tests are limited because of highly variable storativity and limits on well depth (Huntley et al. 1991); however, higher well yields generally correspond to greater permeability.

Regolith zones

In the study area, well drillers generally identify the total thickness of materials above bedrock. As shown in Table 2, regolith was generally the thinnest over gneisses, slightly thicker over schists, and thickest over granites (regolith is shown in the Appendix). Regolith permeability in these crystalline-rock systems is commonly high and is typically is the most hydrodynamically active part of these systems (Krasny and Sharp Jr 2007b). The weathered rock zone (Deere and Patton 1971), corresponding to the fissured layer of Lachassagne et al. (2011, 2014) and Wyns et al. (2004) and to Acworth's zone D (Acworth 1987), is expected to have the greatest permeability (Fig. 3).

Deere and Patton (1971) used the RQD from diamond drill cores to constrain the location of the transition zone (IIa) from soil to partly weathered rock, and found it was characterized by a variable, but low (<50%) RQD. Deere and Patton (1971) stated that the transition zone (IIa) typically has the highest permeability, which corresponds to the upper fissured layer of Wyns et al. (2004). The partly weathered rock zone (IIb) is characterized by RQDs generally ranging from 50 to 75%.

Eight diamond drill cores, documented in Saucier and Buck (1970) and stored in the core repository of the Texas BEG, were logged including RQDs. Fracture features were noted, specifically the fracture skins, and samples were taken for laboratory analyses.

Referring to the RQD values at each depth for each core, the thicknesses of the weathered/fissured zone can be estimated. Cores 10, 19, and 25 have thin weathered/fissured zones, while cores 8, 32, 34, and 39 have thicker weathered/fissured zones. Core 39 is also highly fractured below the weathered zone, whereas cores 10, 19, and 25 are in areas with poor prospects for pumping from the weathered zone. The RQDs reflect the heterogeneity in both fracture intensity and weathered/fissured zone thicknesses can be expected in these terrains. RQD in these settings is an efficient method for determining the depth and thickness of the weathered/fissured zones. This dependence of crystalline rock aquifer permeability on the fissured layer or weathered rock zone is supported by the fact that four of the highest yielding wells are in thick regolith (Fig. 5). It is noted, however, that in the zones of fresh or unweathered rock, RQD is not a good predictor of permeability as RQD estimates fracture density and neither fracture aperture nor connectivity (Piscopo et al. 2017).

As a proxy for the relationship between permeability and regolith thickness, the relationship between well

	Krasny & Sharp (2007b)	Deere & Patton (1971)				Acworth (1987)		Lachassagne et al. (2011)		Wyns et al. (2004)
Common Zone	Hydrodynamical zone	Zone		RQD	k	Zone	k	Zone	k	Zone
Regolith	Upper / local (intensive & shallow)	Residual soil	Ia -O & A horizons	-	medium to high	Soil - A horizon	high	Soil not classified		
			Ib - B horizon	-	LOW	Soil - B horizon	low to medium			
			Ic - C horizon (saprolite)	0	medium	Zone a - Soil zone C	low	Clayey saprolite	low	Clayey saprolite
						Zone b	low	Sandy saprolite	low to medium	Sandy saprolite
						Zone c	low to medium			
		Weathered rock	IIa - Transition (residual soil to partly weathered rock)	variable (0 to 50%)	HIGH	Zone d - fractured and fissured rock	high to medium	Fissured layer	medium to HIGH	Upper fissured layer
Bedrock			IIb - Partly weathered rock)	generally 50 to 75 %	medium to high					Lower fissured layer
	Middle / regional (intermediate)	Unweathered rock	III	> 75%	low to medium	Fresh rock	low	Fresh basement	low	Fresh basement
	Lower / retarded (slow, deep, negligible to stagnant)									
	Global (often insignificant)									

Fig. 3 Vertical zonation classifications in the crystalline-rock aquifer systems (modified from Sharp et al. 2016))

yield and depth to bedrock (regolith thickness) was analyzed from Texas databases (Fig. 4). Well yields for regolith thicknesses of 50–80 m are relatively high; however, it is inferred that the five well logs reporting over 80 m to reach unweathered bedrock may be recording errors. The authors observed that such thick weathered zones do not exist in the study area. Given average water tables of 11–12 m (Hunt 2008), 80+ m of saturated sediments should have greater yields. Lachassagne et al. (2011 and 2014) found that weathering was a very important control on crystalline rock permeability at sites in France and India, but the weak dependence on well yield as a function of regolith thickness (Fig. 4; Table 5) in the Llano Uplift indicates that fracture transmissivity (hydraulic aperture and connectedness) is the major factor controlling well yields (Fig. 5).

Soils

Study area soils are either residual (see Appendix) or transported (developed on alluvium or colluvium). There are no significant aeolian or lacustrine deposits and the area is unglaciated. Soils developed on the granitic and metamorphic rocks (Table 3) are the Castell, Katemcy, Keese, Ligon, Lou and Voca soils (McCormick 2016; Goerdel 1998). The Katemcy and Ligin soils developed on schists and tend to be lower in permeability (measured by infiltration tests). This is an expected result because the micas in the schists weather preferentially to clays, a process that limits permeability, recharge, and consequently weathering, thereby limiting development of the soil, including regolith thickness. The Keese and Lou soils overlying granite and grus have higher rates of infiltration, with the exception of the Voca soil, which is thick and clay-rich, allowing for a more developed B horizon (Ib in Fig. 3) causing the low permeability.

Faults and fractures

There are several regional fracture/joint sets in the study area. Strikes of NE, N, and NW were reported by Alnes (1984). Boyer et al. (1961) documented four sets on a gneiss in Llano County, with the NE and NW sets being more prominent. Faulting within the basement rocks is therefore much more prevalent than shown on published maps (e.g., Barnes 1981; Hunt 2000).

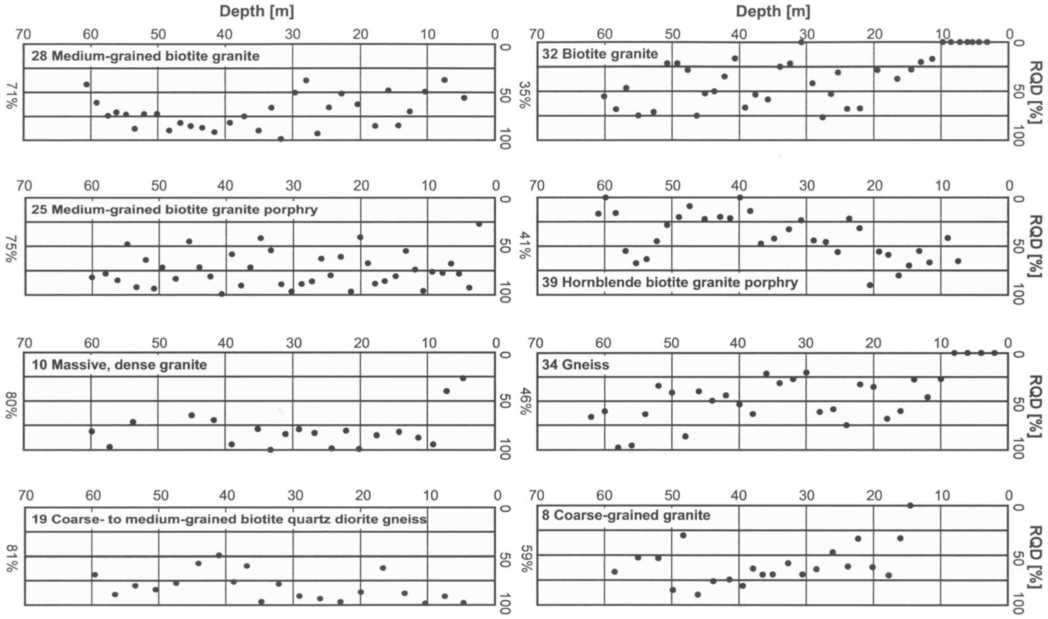


Fig. 4 Rock quality designation (RQD) in ascending order for eight diamond drill cores from the Llano Uplift with lithologic descriptions of Saucier and Buck (1970). Total borehole RQD is given below each log

Metamorphic rocks are faulted and fractured pervasively in the vicinity of closely spaced, small throw faults, whereas granitic rocks tend to have more widely spaced, large throw faults (Schmittle 1987; Johnson 2004). Thus, the fabric within the metamorphic rocks appears to have influenced the structural style, and possibly the permeability, within the crystalline rocks. The predominant fault direction corresponds to the NE set (Orr 1962; Hunt 2008) as depicted in Fig. 1. The faulted zones commonly serve as sites for deeper weathering thus offering greater fracture intensity and thus permeability, even where the faults are not always mapped.

Fracture skins and fills

Fracture skins are “zones of altered rock abutting a fracture surface and the coatings of the fracture surface by infiltered debris, precipitated minerals, and organic matter” (Robinson and Sharp Jr 1997). These zones are important because they can, to some extent, either retard or enhance flow through a medium (Robinson et al. 1998). The transport properties of these skins can be characterized by chemical composition and physical properties such as thickness and porosity. Studies focusing on the characterization of these transport properties for the Town Mountain Granite are listed in Garner (2007).

Porosity and pore diameter

Of the samples taken from the eight cores in Fig. 4, only three had fracture fills large enough to analyze using Hg-injection porosimetry. Table 4 below summarizes the data from three fracture fills and two fracture skins including one from Australia for comparison. These data show that fracture skin and fracture fill porosity are significant. In addition, the small pores allow for a large specific surface. The higher porosities ranging from 6 to 15% are characteristic of the thick white weathering rinds found in near-surface fractures.

Thickness and aperture

In all eight cores, fracture aperture and skin thickness vary with depth, but follow general trends. Near-surface fractures have larger apertures and are more likely to have fracture fills made up of thick weathering rinds with high porosities. With depth, both fracture aperture and skin thickness decrease with more fractures appearing completely filled. Representative fracture skins are shown

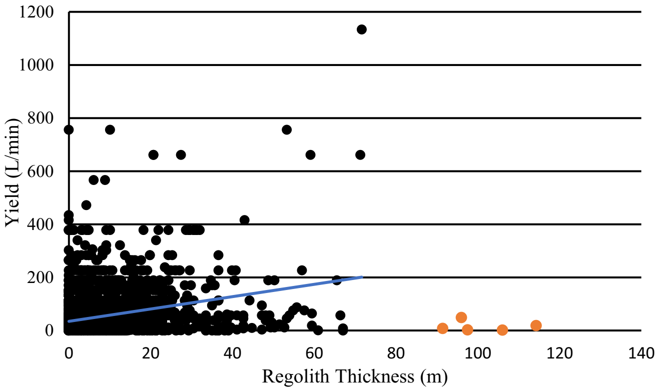


Fig. 5 Well yield (>2,400 wells) with driller regolith thickness (reported depth to fresh bedrock). Wells in thick (>50 m) regolith tend to have high yields, but the scatter of value demonstrates the importance of fracture permeability as some wells with minimal regolith have high yields. Drillers logs indicating wells with more than 80 m of regolith (orange data) are questionable for the study area. Original data (TDLR 2016; TWDB 2016) are in gpm and feet

in Fig. 6 in granitic rocks. Similar trends are observed for skins in metamorphic rocks.

Composition

Fracture skins and fills were analyzed using SEM, EDS, and X-ray diffraction (XRD), in addition to optical microscopy. SEM samples were taken of fracture faces and cross sections of the fractures as shown in Fig. 6. The samples were not coated prior to imaging. Images were taken at various magnifications, and EDS analysis was conducted using different sized areas.

Analysis for fracture skin composition was done on cores 8, 10, 19, 32, and 34. Fracture skins in the dark colored metamorphic parent rocks are thinner and more difficult to distinguish from the host. EDS analysis of the fracture skins yielded element amounts in weight percent. Figure 7 compares the expected weight percent in Llano Uplift granites for total iron (3.4% as Fe_2O_3 from Johnson et al. 1976) to the weight percents collected from the core samples. All of the skins show increased amounts of iron compared to the expected average of 3.4%. Variations in the amount of iron in the skin, especially values below 3.4%, are due to non-uniform skin coatings. The weight percent of total iron decreases with depth, which is consistent with the decrease in skin thickness with depth. EDS analysis was used to compare directly the composition differences between the parent rock and fracture skin of a specific sample. This confirmed that there is indeed a significant increase in the amount of iron in the skin versus the fresh rock.

Powders were created from grinding fracture skins in X-ray diffraction. Dremmel diamond drill bits were used for the grinding. Powders were prepped with the addition of 10%

Table 3 Soil data from Goerdel (1998) and McCormick (2016) giving the soil name, underlying rock type, and soil permeability and thickness

Soil name	Underlying rock type	Soil permeability	Soil depth
Castell	Gneiss	Slow/moderate	Moderate
Katemcy	Schist	Slow	Moderate
Keese	Gneiss or granite	Moderately rapid/moderate	Shallow
Ligon	Schist	Slow/moderate	Moderate
Lou	Granite grus	Moderate/rapid	Moderate
Voca	Granite grus	Slow	Very deep

Notes: Slow permeability is defined as infiltration rates of 2–5 mm/h; moderately slow is 5–15 mm/h; moderate is 15–51 mm/h; moderately rapid is 51–152 mm/h; rapid is 150–508 mm/h. Conversion 1 in./h = 25.4 mm/h

Table 4 Summary of Hg-injection porosimetry data

Sample	Porosity [%]	Median/mean pore diameter [µm]
Core No. 10 granite fracture fill	9.9	0.2884/0.1563
Fredericksburg Town Mountain Granite skin	6.1	8.569/–
Core No. 9 gneiss fracture fill	2.0	7.392/–
Core No. 34 gneiss fracture fill	15.5	0.204/0.0861
Australian Calca (green) Granite skin	5.6	0.0339/0.10014

Fracture skin data from Garner (2007)

by mass of pure analysis grade corundum powder. Due to the thinness of the skins used to make the powder, XRD scans of the powders produced scans typical of granite parent rock. It is surmised that a significant amount of the granite parent rock was ground into the powder of the skins causing the parent rock minerals to overpower the minerals of the very thin fracture skins. Preliminary data suggest that certain trace elements (e.g., Ce, La, Ti, and Nd) may be relatively more prominent on skins at greater depths (Setlur et al. 2017), but more analyses are needed.

Fracture skins at shallow depths are ferruginous and are mainly red to yellow in color. Some skins and fills close to the surface can be an off-white color. With depth the skins are more greenish. This may represent the oxidation state of the iron oxides present in the skins (P. Bennett, personal communication, 2018), but further chemical analysis of the skins must be done to confirm.

Optical microscopy thin sections were a standard size, and imaging was done at 5×, 10×, and 20× magnifications. Very shallow microfractures are commonly filled with shards of surrounding minerals (Fig. 8); however, it was not possible to identify all the minerals included in the shards due to limits regarding magnification and lack of crystal structure. Nonetheless, quartz and feldspar crystals probably are from weathering of the parent rock. In addition, it was found that fracture fills tend to follow grain boundaries and fill in scratches (indentations) on the grains (Fig. 9). The greater weathering, thicker fracture skins, and greater secondary iron content in the shallower portions of the aquifer is consistent with the greater permeability and more intensive flow in this zone.

Discussion and conclusions

The hydrogeological properties of the crystalline rock aquifer system of the Llano Uplift are generally consistent with other crystalline (hard rock) aquifer systems. Faulting and fractures (notably decompressive fractures) and weathering control aquifer properties, and wells are

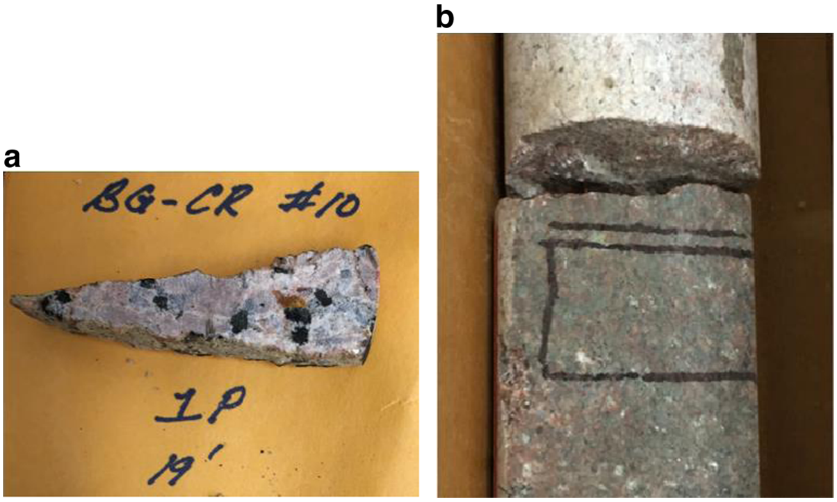
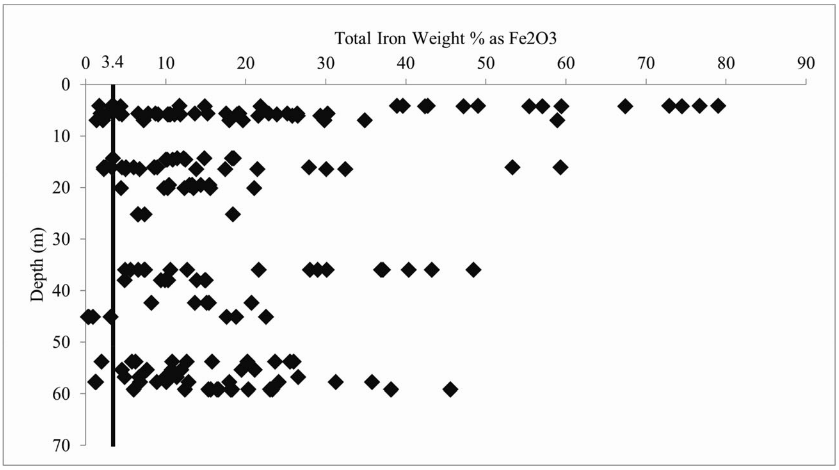


Fig. 6 Images of samples taken from core 10 showing thickness differences. **a** Sample from a depth of 5.8 m shows a relatively thick off-white weathering rind. **b** Sample from a depth of 55.4 m shows a very thin skin that barely covers the fracture face. The pink and white spots are the feldspar and quartz

Fig. 7 Total iron (weight percent) with depth in fracture skins. The data are from cores 8, 10, 19, 32, and 34. The dark vertical line is at 3.4% total iron, which is the average weight percent in the granite of the Llano Uplift (from Johnson et al. 1976)

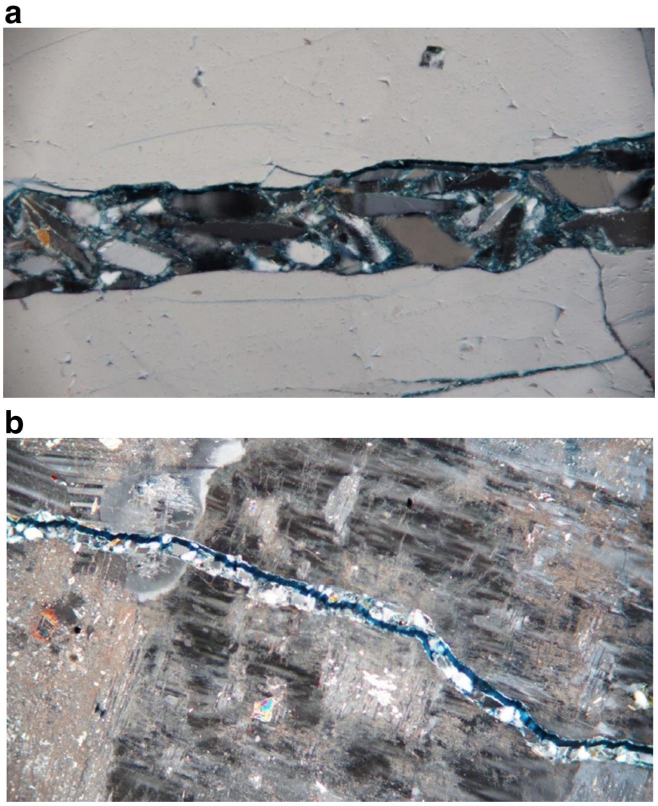


shallow (generally <100 m depth). Although there is considerable data scatter, wells in the Town Mountain Granite tend to be the most productive. Productive wells are also associated with thicker regolith, but as indicated by the low R^2 in Table 5, fractures are the dominant factor and fracture permeability is very heterogeneous, varying orders of magnitude over short distances, which is in agreement with other studies (e.g., Dewandel et al. 2006; Stober and Bucher 2007).

Analyses of driller report data (>2,400 wells), eight drill cores, rock lithology, field observations, and previous studies indicate that in the Llano Uplift:

1. Wells in coarse-grained granite (the Town Mountain Granite) have slightly higher median yields than in fine-grained granites and metamorphic rocks (Tables 1, 2, and 5).
2. Fractures provide the most permeability and fracture transmissivity is the major control on well yields.

Fig. 8 **a** 20× magnification of a microfracture on sample from core No. 10 (at a depth of about 4.8 m). This shows the microporosity in blue and the mineral shards filling the fracture. **b** 10× magnification of a microfracture showing that it is open, and the microporosity in blue. There are more mineral shards lining the fracture



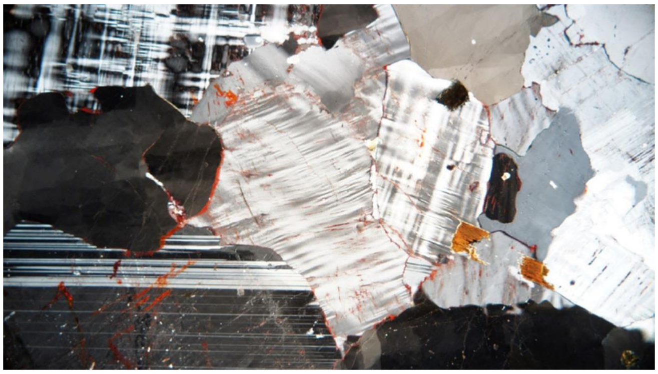


Fig. 9 5× magnification image from core No. 10 (at a depth of 57.2 m). This shows the iron oxide (brown color) filling the fractures along grain boundaries

Fracture permeability varies widely, but generally decreases with depth. Low R^2 shows the spatial heterogeneity of fracture permeability.

3. Productive wells are weakly associated with regolith thickness, which is generally somewhat greater over granitic rocks than over metamorphic rocks. The regolith and the fissured or partially weathered zones are generally permeable.
4. Deeper wells, especially in the granites, have been drilled recently.
5. Rock Quality Designation (RQD < 50%) on diamond drill cores can predict shallow transmissive zones created by weathering, which can be deeper along vertical fractures and fault zones. The RQDs also indicate the fracture heterogeneity in this system.
6. Many near-surface fractures with significant apertures (>1 mm) are filled with rock fragments and fracture skins are be thicker and more ferruginous than those at depth. White weathering rinds had porosities ranging from 6 to <14%.
7. Fracture skins generally become thinner and contain iron oxides in a reduced state with depth.

Llano Uplift trends are not universal—for instance, Chambel et al. (2007) in Portugal found that gneisses and more basic metamorphic rocks were more permeable and had deeper weathering horizons than granites. Davis and DeWeist (1966, their Table 9.2) listed sites both where granites have higher yields than metamorphics and where the reverse is true. Briz-Kishere (1993) found no correlation between well yields and weathered zone thickness or the number of fractures in granitic rocks in South India. Numerous studies have found that wider aperture (subhorizontal) fractures are more common at at shallow depths (e.g., Jahns 1943; Watkins 2007; Hart 2016; Cao et al. 2016), but sampling bias must be considered. Loiselle and Evans (1995) found statistically equivalent fracture yields at different depths in coastal Maine, and no empirical justification for limiting well depths; however, permeability in hard rock aquifer systems generally decreases with depth (e.g., Achtziger-Zupancic et al. 2017; Krasny and Sharp Jr 2007b; Stober and Bucher 2007; Sanford 2017). Winkler and Reichl (2014) used 180 100-m packer tests in faulted crystalline rock boreholes down to 700 m depth to show a decline in hydraulic conductivity K (in m/s) with depth (z) following the equation log K = −2.59 – 2.49 log(z), which is similar to that reported by Stober and Bucher (2007). However, there are occasional sites where deeper (>100 m) wells are very productive. Finding methodologies to predict these productive zones is a great challenge, but would be very valuable.

Table 5 Well yields (Q) in L/min as function of well depth (z) (Fig. 2) and of regolith thickness (h) (Fig. 4) in meters for wells with reported yields

Stratum	Well yield	R^2
Granites, depth (z)	$Q = 260–50.3 \ln(z)$	0.086
Metamorphics, depth (z)	$Q = 221–42.7 \ln(z)$	0.060
All wells, regolith thickness (h)	$Q = 34.5 + 2.32\ h$	0.067

The characteristics of the tectonics and fracturing, the degree and type of weathering, soil development, lithology, rates of recharge and hydrogeologic settings, and anthropic effects vary between crystalline systems. It is suggested that such comparisons might prove insightful as crystalline (hard rock) aquifers cover over 20% of the Earth's land surface. More research is needed including better mapping and definition of the regolith and weathered zones; investigation of controls on fracture skin formation and fracture filling; and quantifying the effects of lithology, geologic structure, soil, climate, and geological history on crystalline rock aquifer properties. This would include trends such as listed in Table 5, fracture system characterization, the development of regolith and fracture skins, and variations in water quality.

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Appendix: Figs. 10 and 11

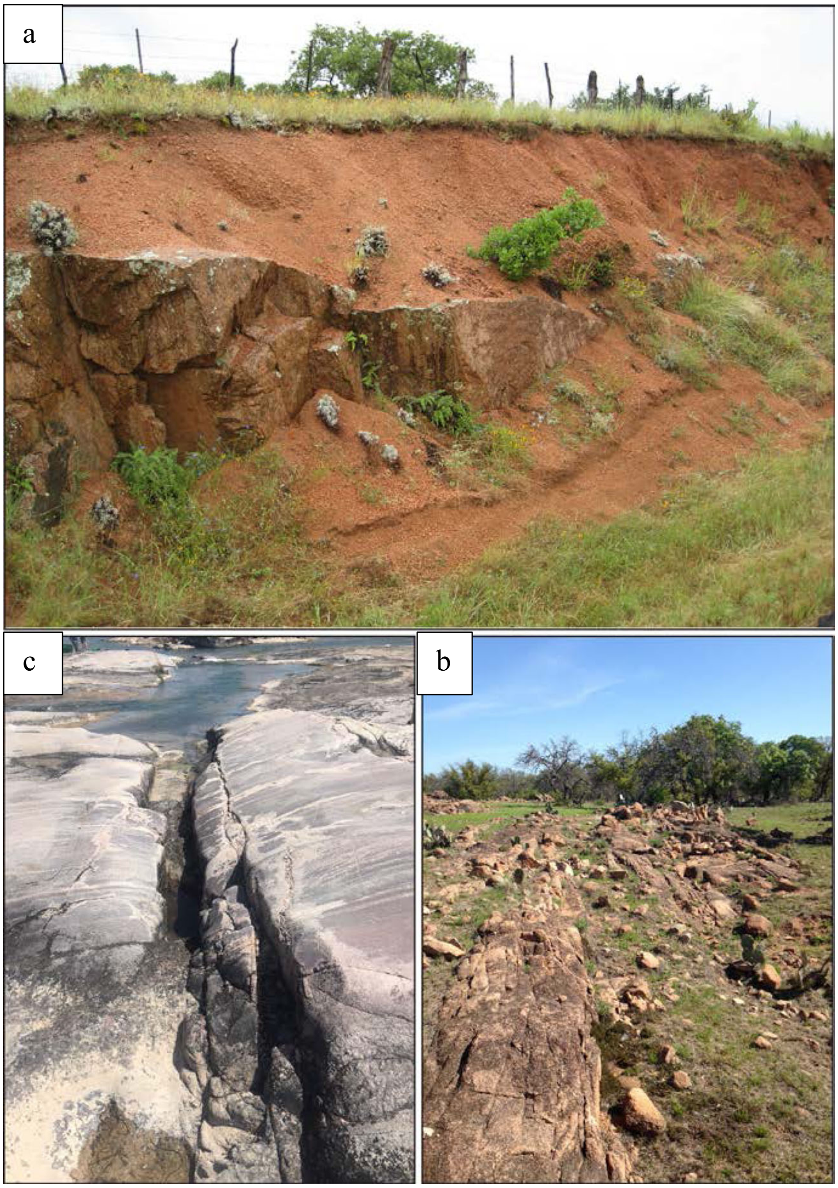

Fig. 10 **a** Road cut in Llano County with granite bedrock overlain by weathered granitic regolith (grus); **b** Faulted and fractured (NNE, ~20°) granitic outcrop in Mason County; **c** Fault within a felsic gneiss (Packsaddle Schist) in the Llano River, Mason County. This is within a 240-m-wide zone trending to the NW (~200°). Two relatively high-yielding domestic supply wells are located about 60 and 210 m from the river's edge. Regolith and alluvium were not present during well drilling of well that indicates yield is from fractures

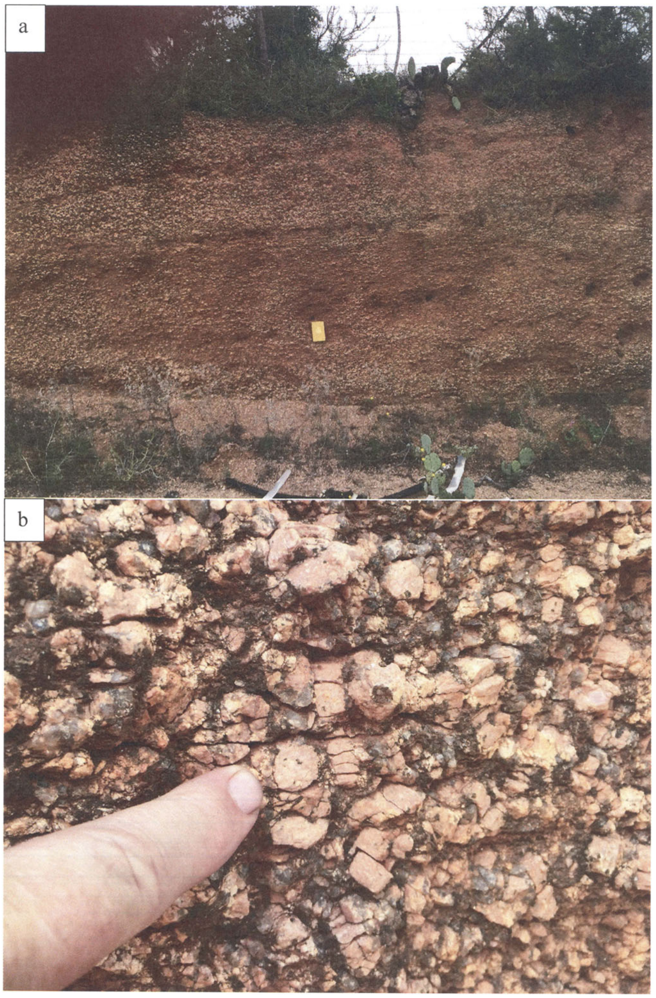

Fig. 11 **a** Regolith showing the development of the saprolite/fissured layer developed on granite in Mason County. Where saturated, this is the zone of high permeability; **b** Close up showing incipient fissuring/layering

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