Proceedings of the
48th Annual Forum on the
Geology of Industrial Minerals
Scottsdale, Arizona | April 30 - May 4, 2012

Geology of the Voca Frac Sand District, western Llano Uplift, Texas

J. Richard Kyle[1] and Earle F. McBride

Arizona Geological Survey

Special Paper 9
Chapter #2

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M. Lee Allison, State Geologist and Director

Manuscript approved for publication in 2014.
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Suggested Citation: Kyle, J.R. and McBride, E.F., 2014, Geology of the Voca Frac Sand District, western Llano Uplift, Texas, in, Conway, F.M., ed., Proceedings of the 48th Annual Forum on the Geology of Industrial Minerals, Phoenix, Arizona, April 30 - May 4, 2012. Arizona Geological Survey Special Paper #9, Chapter 2, p. 1-13.

FOREWORD

The 48th Forum on the Geology of Industrial Minerals was held in Scottsdale, Arizona, April 30 - May 4, 2012. From across the U.S., Canada, UK, and Jamaica, more than 80 people attended. This was the Forum's second appearance in Arizona; the first being the April 9 – 12, 1985, meeting in Tucson. The earlier Forum celebrated the University of Arizona's centennial. This 48th Forum coincided with celebration of the State of Arizona's centennial. The Forum on the Geology of Industrial Minerals has been held annually since its inception by the late Professor Robert Bates of Ohio State University nearly 50 years ago.

The 48th FGIM was organized by the Arizona Geological Survey with support from the Arizona Geological Society, Clear Creek Associates, Golder Associates, National Exploration Wells & Pumps, the SME Dryer Fund, Arizona Rock Products Association, Arizona Mining Association, and the Arizona Section of the American Institute of Professional Geologists. Field trips were planned and moderated by the late Doug Shakel and included visits and guest lectures on the Colorado Plateau and Mogollon Rim, the minerals and geology of Eastern Arizona, and Phoenix area industrial mineral sites. Special thanks to: John Bezy for his remarks on Sedona; Paul Lindbergh for cogent discussions of Jerome; Brian Langford for his description of Phoenix Cement; the Jerome State Historic Park rangers for their historical overview; David Pelletier for his remarks at Drake Cement; Ted Eyde's for his comments at Lyle Hectorite Pit; Melissa Hadley's overview of Morton Salt; Dan McQuade and Kyle Henderson for guiding us through the Salt River Materials Group Beeline Plant; to Evvy Otis for remarks on Imerys Perlite; and Bob Foster for discussing the Feldman Quarry.

We were fortunate to have Drew Meyer, President of the Society for Mining, Metallurgy, and Exploration (*SME*), as keynote speaker. His thought-provoking presentation set the tone for dynamic discourse throughout the Forum. The wide variety of papers presented fell into the following categories: Carbonates, Potash, Sandstones & Aggregates, Rare Earth Elements, Education & Outreach, Miscellaneous, and Arizona Geology. Papers from the Forum are posted following light editing for general clarity and standardization of bibliographies.

Thank you to all participants, writers, sponsors, field trip coordinators and guides, the Scottsdale Cottonwoods Resort, and AZGS staff for making the 48th Annual Forum a smashing success.

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Geology of the Voca Frac Sand District, western Llano Uplift, Texas

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Geology of the Voca Frac Sand District, western Llano Uplift, Texas

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ABSTRACT

Hydraulic fracturing to enhance petroleum recovery was introduced in the 1940s, but the technology has become increasingly important in the recent development of petroleum production from unconventional reservoirs. The rapid growth of enhanced petroleum recovery via hydraulic fracturing has resulted in a corresponding increase in the demand for proppants. Texas has multiple unconventional petroleum plays, and the in-state production of industrial sands for hydraulic fracturing has doubled in the past decade. One of Texas' major frac sand production areas is near Voca, Texas, where sands are produced from the Cambrian Hickory Sandstone on the northwestern flank of the Llano Uplift.

The Hickory Sandstone, the basal member of the Riley Formation, is as much as 500 feet (150 m) thick and consists dominantly of marine sandstone with minor mudrock, conglomerate, and limestone, plus a local ironstone unit as much as 80 feet (25 m) thick. The Hickory Sandstone was deposited on the "Great Unconformity" developed on the Precambrian basement of Central Texas and elsewhere. The local basement consists of diverse metamorphic rocks and syn- to post-orogenic granites, ranging in age from 1,300 to 1,100 million years. The Late Cambrian Hickory Sandstone is subarkose to arkose, with local quartz arenite units, in which most or all feldspar has been destroyed during diagenesis. Although Hickory sediments were derived ultimately from the Precambrian basement, some were reworked from fluvial deposits and eolian dunes.

Despite its great age, the Hickory remains friable where it was never buried more than 1,500 feet (~1 km), notably along the flanks of the Llano Uplift. Because of its poorly cemented nature and the occurrence of well-rounded quartz grains in sizes appropriate for various proppant applications, the Hickory has been a source of industrial sand for several decades. In response to regional market demand, frac sand production from the Hickory in the Voca area has steadily increased. Production generally is from a near-surface 50- to 65-feet (15 to 20-m) interval in the lower Hickory.

Introduction

Hydraulic fracturing to enhance petroleum recovery was introduced in the late 1940s (Montgomery and Smith, 2010), but the technology has become increasingly important in the recent development of petroleum production from unconventional reservoirs such as shale oil and gas, tight gas sandstone, and coalbed methane. Montgomery and Smith (2010) indicated that 60% of global petroleum wells are hydraulic fractured, and the National Petroleum Council estimated that up to 95% of domestic petroleum wells are now fracked (NPC, 2011).

Current demands for domestic energy production has resulted in a rapid development of shale gas resources through horizontal drilling and hydraulic fracturing, e.g. the Barnett Shale play in north Texas (Fig. 1). The Energy Information Administration estimates current recoverable domestic shale gas at 862 trillion cubic feet (TCF), doubling from 2010 to 2011. Annual shale gas production in 2010 totaled 4.8 TCF, a 5-fold increase from 2006. Shale gas currently accounts for 23% of U.S. natural gas production, which is expected to increase to 46% by 2035.

The rapid growth of enhanced petroleum recovery via hydraulic fracturing has resulted in a corresponding increase in the demand for proppants, the natural or synthetic grains that are injected with the fracking fluid to keep the induced fractures open. Texas has multiple unconventional plays, and the production of industrial sands for this purpose has doubled in the past decade to a 2008 peak of 3.6 Mt with a value of $139 million (Figs. 2, 3). One of Texas' major frac sand production areas is near Voca, Texas, where sands are produced from the Cambrian Hickory Sandstone

on the northwestern flank of the Llano Uplift. In this paper, we review the deposition and subsequent geologic history of the Hickory Sandstone as it relates to its suitability for use as frac sand.

Geologic Framework of Central Texas

The Llano Uplift currently is a broad topographic depression, with the Proterozoic basement of metamorphic rocks and granitic intrusions onlapped unconformably by Paleozoic sedimentary strata (Figs. 4, 5); all of the older units are covered locally by a veneer of Cretaceous carbonates extending away from the Llano Uplift as the Edwards Plateau. Local topographic highs form modest ridges and "mountains" within the Precambrian core of the Uplift where erosional remnants of Paleozoic strata rest upon or are faulted against the basement rocks. Most ridges of lower Paleozoic strata in the region trend northeast to north, representing the orientation of the late Paleozoic faults that bound them (Fig. 5).

The Proterozoic core of the Llano Uplift consists of a complex series of metamorphic rocks largely of volcanic and sedimentary origin dating from about 1.36 to 1.26 billion years (Helper, 2000; Mosher et al., 2008). These units are intruded by late to post-orogenic granites at about 1.1 billion years (Barker and Reed, 2010). Following the development of Proterozoic metamorphic and igneous rocks, uplift and exhumation during an extensive period of erosion created the "Great Unconformity" surface on which the Late Cambrian sediments were deposited. Estimated depths of granite emplacement require that 8 to 10 km of Precambrian cover were removed to bring the metamorphic and igneous rocks to sea level prior to the deposition of the late Middle Cambrian sediments (ca. 515 Ma).

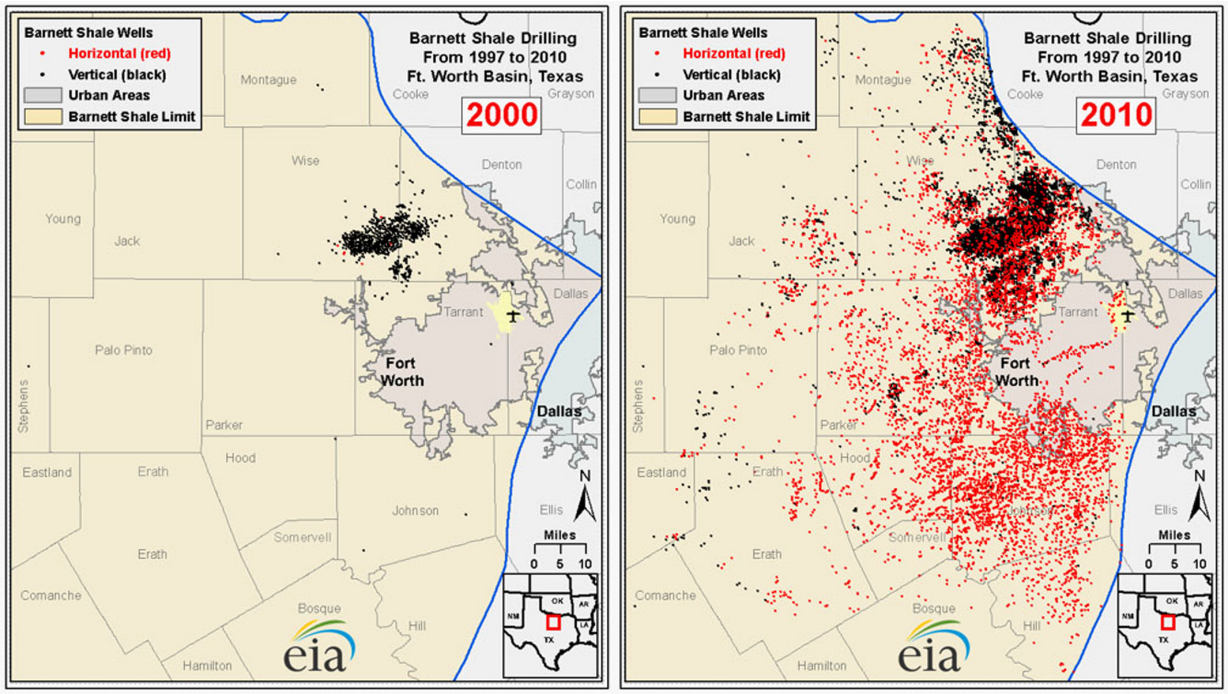

Figure 1. Increase in development of Barnett Shale horizontal drilling and hydraulic fracturing in north Texas from 2000 to 2010.

By the late Middle Cambrian, the Proterozoic crystalline rocks formed an arid, low-relief landscape, not unlike the topography of the Llano Uplift today. Paleotopography appears to have been dictated by weathering of underlying bedrock in an arid environment, with finer grained granite, quartzofeldspathic gneiss, and marble supporting areas of higher relief, and schists, amphibolite and other less resistant rocks underlying lower regions (Barnes and Bell, 1977). The thickness and facies of the lowermost Cambrian strata were strongly controlled by the paleotopography, which had as much as 600 feet (200 m) of relief (Fig. 4). A few topographic highs persisted as islands until they were buried by Late Cambrian sedimentation.

The lowermost Paleozoic sediments of the Llano Uplift comprise the three members of the late Middle to Late Cambrian Riley Formation, the lower member of the Moore Hollow Group (Fig. 4) (Barnes and Bell,

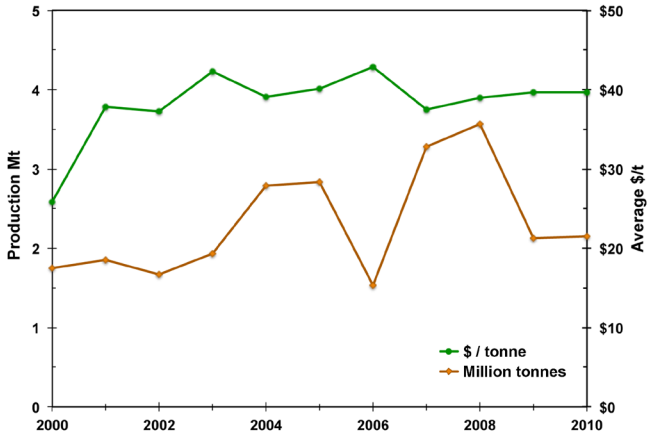

Figure 2. Texas industrial sand production from 2000 to 2010. These data include all types of industrial sands. Current prices of hydraulic fracturing sands are considerably higher than the average value shown. Data from U. S. Geological Survey http://minerals.usgs.gov/minerals/pubs/state/tx.html - myb

1977). From bottom to top, these are the: 1) Hickory Sandstone, a complex succession of terrestrial (basal) and transgressive marine arkosic to quartz arenitic sandstone/siltstone, mudstone and ironstone that is as much as 500 feet (150 m) thick, grading into; 2) Cap Mountain Limestone, consisting of progradational intertidal, subtidal, and shallow-shelf sandstones/siltstones and transgressive shallow-shelf and shoal carbonate packstones and fossiliferous grainstones, with a total local thickness of 500 feet (150 m) grading into; 3) Lion Mountain Sandstone, a regressive unit composed of tidally dominated, progradational, argillaceous glauconite greensand with trilobite coquina lenses and beds, ranging from 20 to 75 feet (6 to 23 m) in thickness (Barnes and Bell, 1977; Krause, 1996). Both the Hickory and the Cap Mountain strata are absent locally on the flanks of basement highs; the Lion Mountain rests directly on basement in those areas.

The thickness and facies of the Hickory Sandstone varies laterally and vertically in response to the paleotopography of the underlying Precambrian surface. The Hickory reaches a thickness of 550 feet (180 m) along the western margin of the Llano Uplift, but generally is less than 350 feet (110 m) thick. The basal Hickory facies predictably is the most variable, ranging from alluvial conglomerates and trough and planar cross-bedded fluvial sandstones in paleo-lows to marine-influenced fine-grained siliciclastic sediments resting directly on granite highs (Fig. 6; Krause, 1996). The basal Hickory sandstones are commonly iron-rich, with hematite and goethite cements that form bands of hematite in areas where it was deposited directly on Proterozoic marble. The basal Hickory units fill solution-collapse features, forming the matrix of karstic breccias where they overlie Proterozoic marble units (Helper, 2000). The upper Hickory also contains local "ironstones" consisting of goethite ooid-bearing marine sandstones (Barnes and Bell, 1977; McBride et al., 2002).

The top of the Lion Mountain member is a disconformity throughout the Llano Uplift, separating glauconite-rich strata of the Riley Formation from the glauconite-poor units of the Wilberns Formation (Fig. 4). Sequence stratigraphic and lithofacies analysis (Krause, 1996) suggests that the Riley Formation is a 2nd order, unconformity-bounded, depositional

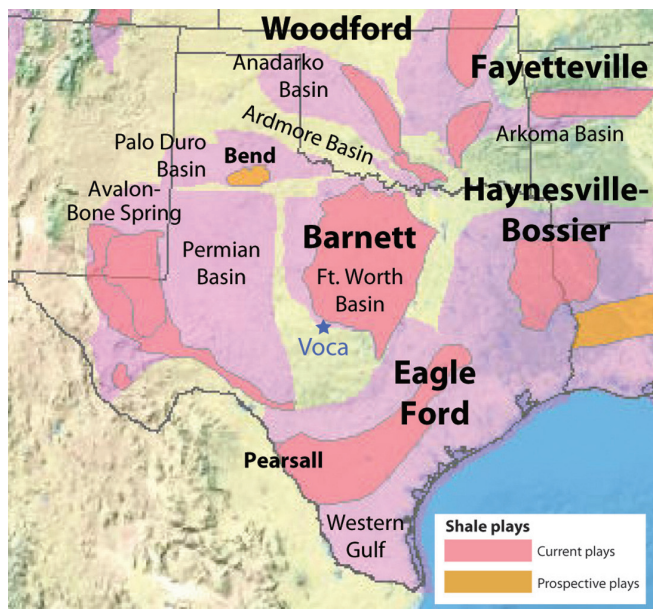

Figure 3. Location of the Voca frac sand-producing area relative to shale gas plays in Texas and the surrounding states. Modified from http://205.254.135.7/oil_gas/rpd/shale_gas.pdf (Energy Information Administration)

sequence representing perhaps as little as 4 million years (ca. 514 – 510 Ma) of deposition.

The Riley Formation is overlain by transgressive and progradational shallow-water marine sandstone, siltstone, limestone, and dolomite of the Wilberns Formation. The Wilberns Formation consists of four members (Barnes and Bell, 1977; Fig. 4), from lower

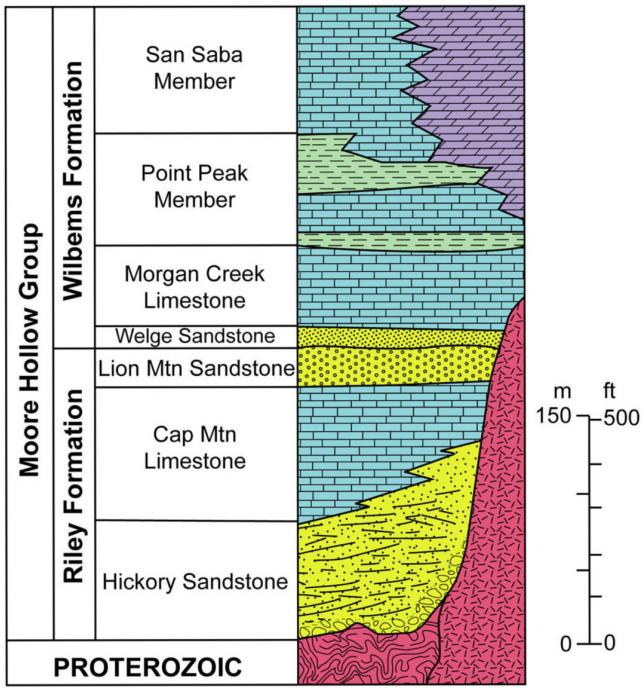

Figure 4. Stratigraphic column for the Cambrian units of the Llano Uplift of central Texas. Modified after Barnes and Bell (1977)

to upper: 1) Welge Sandstone (10 to 30 feet [3 to 9 m] thick) – medium-grained marine sandstones that grade upward into; 2) Morgan Creek Limestone (125 to 145 feet [38 to 44 m] thick) – intertidal and shallow shelf oolitic, glauconitic and stromatolitic limestones; 3) Point Peak Member (average 170 feet [52 m] thick) – terrigenous siltstone, silty and stromatolitic limestones, and intraformational conglomerates, that grade upward into; 4) San Saba Member (280 to 450 feet [85 to 137 m] thick), a laterally variable unit consisting largely of limestone and dolostone that is locally stromatolitic and glauconitic. The San Saba Member is calcareous sandstone and sandy dolomite in the western Llano Uplift and is time transgressive, containing an early Ordovician trilobite fauna (Barnes and Bell, 1977). The boundary with overlying Ordovician Ellenburger Group carbonates is commonly gradational.

Post-Lower Ordovician, pre-Pennsylvanian strata are poorly represented in the Llano Uplift, as the region appears to have been largely emergent during this time, perhaps with short-lived, periodic marine incursions separated by longer erosional events. Pennsylvanian strata (Marble Falls Limestone and Smithwick Formation) record a return to marine conditions, with the establishment of deeper water depositional systems for terrigeneous sediment derived from an easterly source. Sedimentation was in part synchronous with the development of the northeast-trending fault system of the Llano Uplift and overlaps in time with the development of the Ouachita fold-thrust belt, the subsurface extension of which lies to the south and east. Barnes et al. (1972) estimated that some of these faults have displacements of as much as 2,800 feet (900 m).

Rifting to initiate the formation of the Gulf of Mexico during the early Mesozoic (Salvador, 1991) resulted in regional subsidence that created a broad shelf during the early Cretaceous on which the extensive limestones of the Edwards Plateau were deposited. The absence of Permian, Triassic, and Jurassic

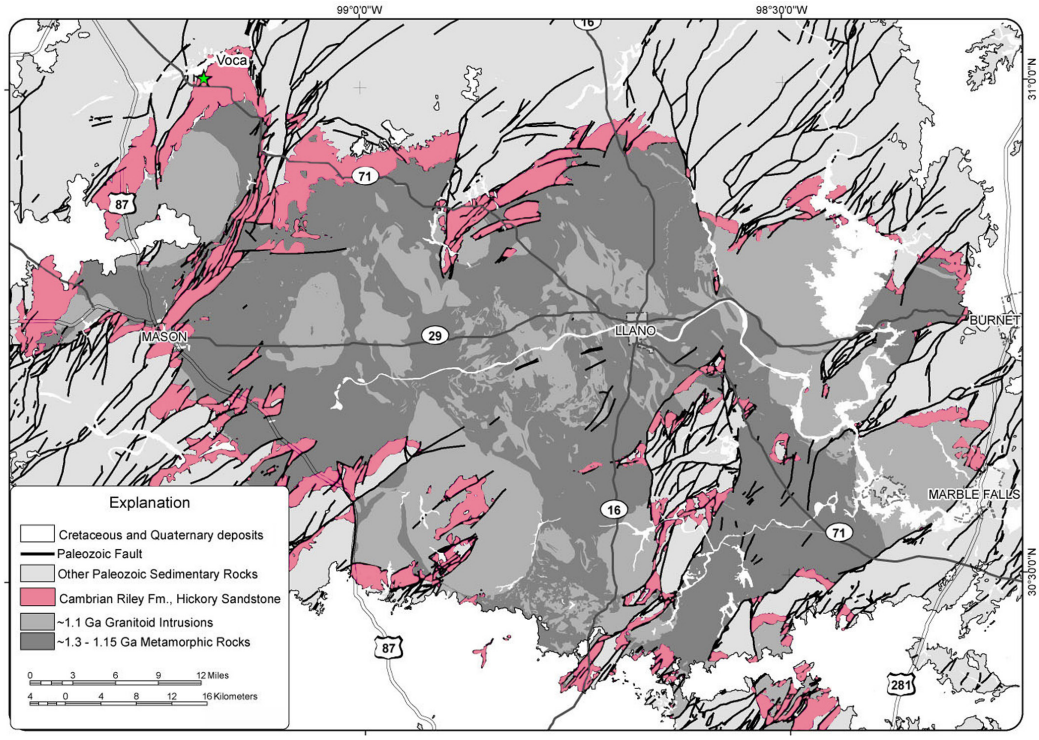

Figure 5. Geologic map of the Llano Uplift highlighting the surface distribution of the Hickory Sandstone. Modified from Llano and Brownwood Geologic Atlas of Texas (1:250,000) sheets.

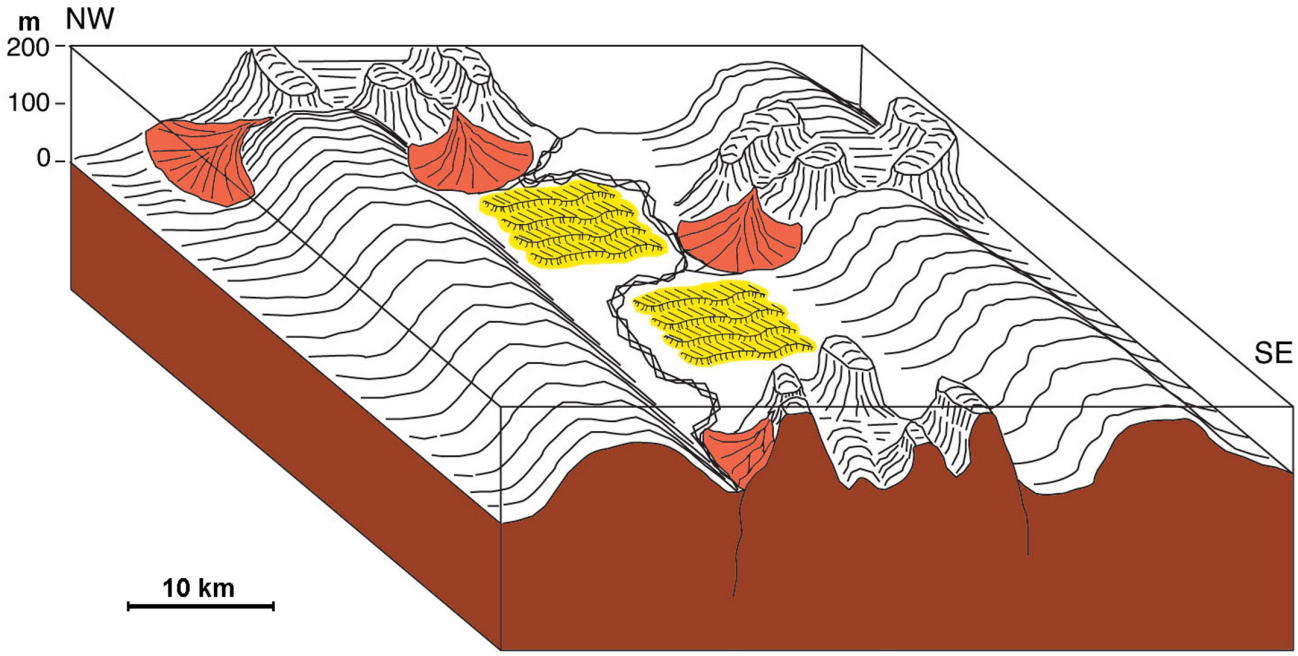

Figure 6. Cambrian depositional environments of the Hickory Sandstone showing the presence of sand dunes (in yellow) that are reworked by fluvial and marine shoreline currents. Modified after Krause (1996).

strata beneath the Cretaceous strata records another extensive period of subaerial exposure and erosion. Erosion on the uplifted northwest side of the Llano Uplift resulted in the removal of the thin veneer of Cretaceous to Eocene strata (Corrigan et al., 1998), producing the present Llano Uplift character (Fig. 5). A reconstructed burial history indicates that the Hickory strata were never buried more than 1500 feet (~1 km) around the flanks of the Llano Uplift (Fig. 7; McBride et al., 2002).

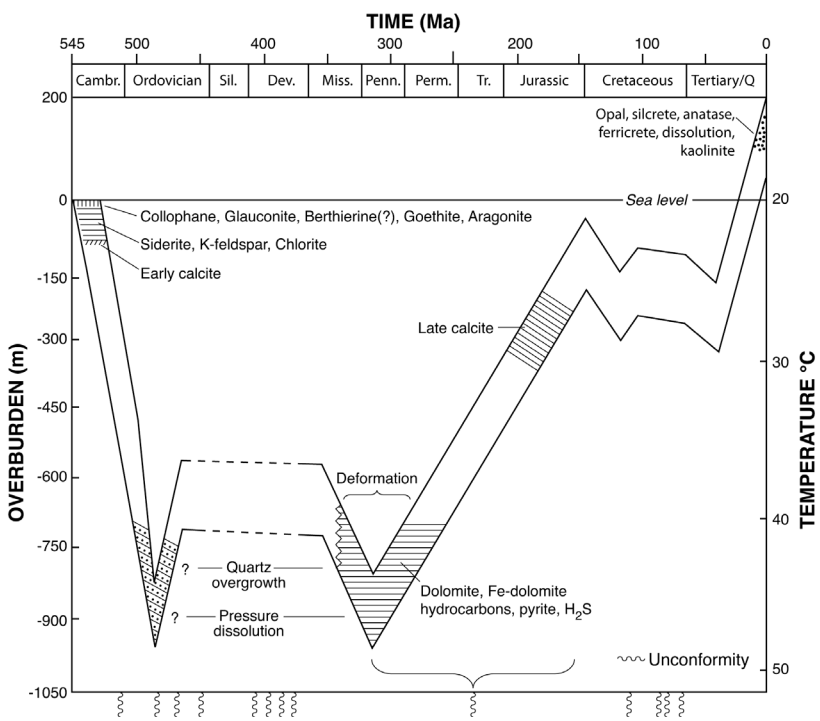

Figure 7. Burial history of the Hickory Sandstone in the Llano Uplift. Modified after McBride et al. (2002)

Petrography of the Hickory Sandstone

The Hickory is 85% sandstone (Fig. 8A) with the remainder composed of ironstone, siltstone, mudstone, conglomerate and limestone; the latter is present only at the contact with the overlying Cap Mountain Limestone. Conglomerates with pebbles of vein quartz and other basement rocks occur in the basal fluvial deposits; centimeter-thick intraformational conglomerate layers with rare phosphate-cemented sandstone clasts are scattered throughout the member. Studies of the Hickory have divided the unit into from two to eight rock facies based on rock type and stratification type that represent different environments of deposition (e.g., Bridge et al., 1947; Goolsby, 1957; Cornish, 1975; Krause, 1996). The consensus is that the Hickory was deposited in a

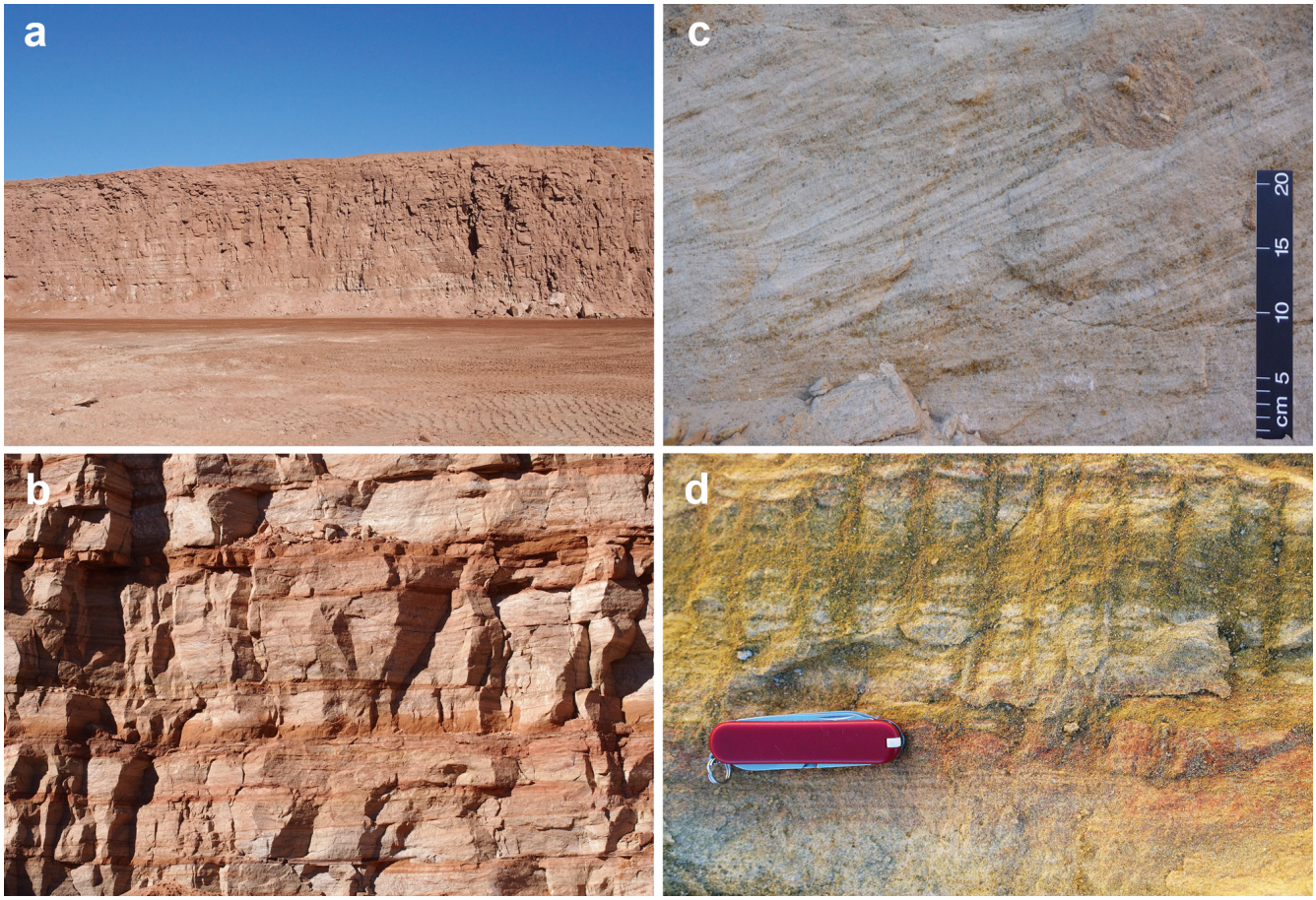

Figure 8. Photographs of the Hickory Sandstone in the Voca area frac sand-producing pits.
A. Subhorizontal bedded Hickory Sandstone, Proppant Specialists operation.
B. Tidal flat facies of the Hickory Sandstone, Cadre Proppants operation. Vertical face is about 10 feet (3.5 m) high.
C. Cross-bedded and poorly sorted Hickory Sandstone.
D. Burrows of Scolithos, a shallow-marine trace fossil. Knife is 2.5 inches (6 cm) long.

marginal marine setting with a strong tidal influence (Fig. 8B) with mostly marine coastal deposits in the upper part. Alluvial fan and fluvial deposits of bed-load rivers at the base (Krause, 1996; Perez, 2007) pass upward into tidal-flat deposits (Krause, 1996; Perez, 2007; Figs. 8B, C). Body fossils, including lingulid brachiopods, pelmatozoa, bryozoa, and trilobites, are sparse in the uppermost beds, although lingulid brachiopods are scattered throughout the member, and trace fossils are common in mudstone beds and locally in sandstone beds (Fig. 8D).

Owing to the presence of iron oxide grain coats and local pore-filling cement, most Hickory beds are some shade of reddish brown. Ironstone and rare mudstone beds are deeper red. During a bleaching event, probably resulting from the local invasion of H2S and hydrocarbons (cf. Levandowski et al., 1973; Parry et al., 2004), many iron-oxide grain coats were removed from Hickory beds to lighten their color to shades of gray or white.

Sandstones are relatively uniform in texture, composition, and degree of cementation. Those that have never been deeply buried are friable, porous, and weakly cemented (9A). Exceptions are sandstones at the base of the member that locally are tightly cemented by quartz or iron oxide and calcite-cemented beds at the top of the member. Compaction was strong enough to produce moderately tight packing of sand grains and slight pressure solution at grain contacts. These pressolved grain contacts are the main reason for the degree of induration the Hickory displays. In contrast with shallowly buried beds, Hickory sandstones intersected at depths of 3,000 to 6,900 feet (965 to 2,225 m) around the flanks of the Llano Uplift are strongly cemented by quartz and have porosities less than 5% (McBride et al., 2002).

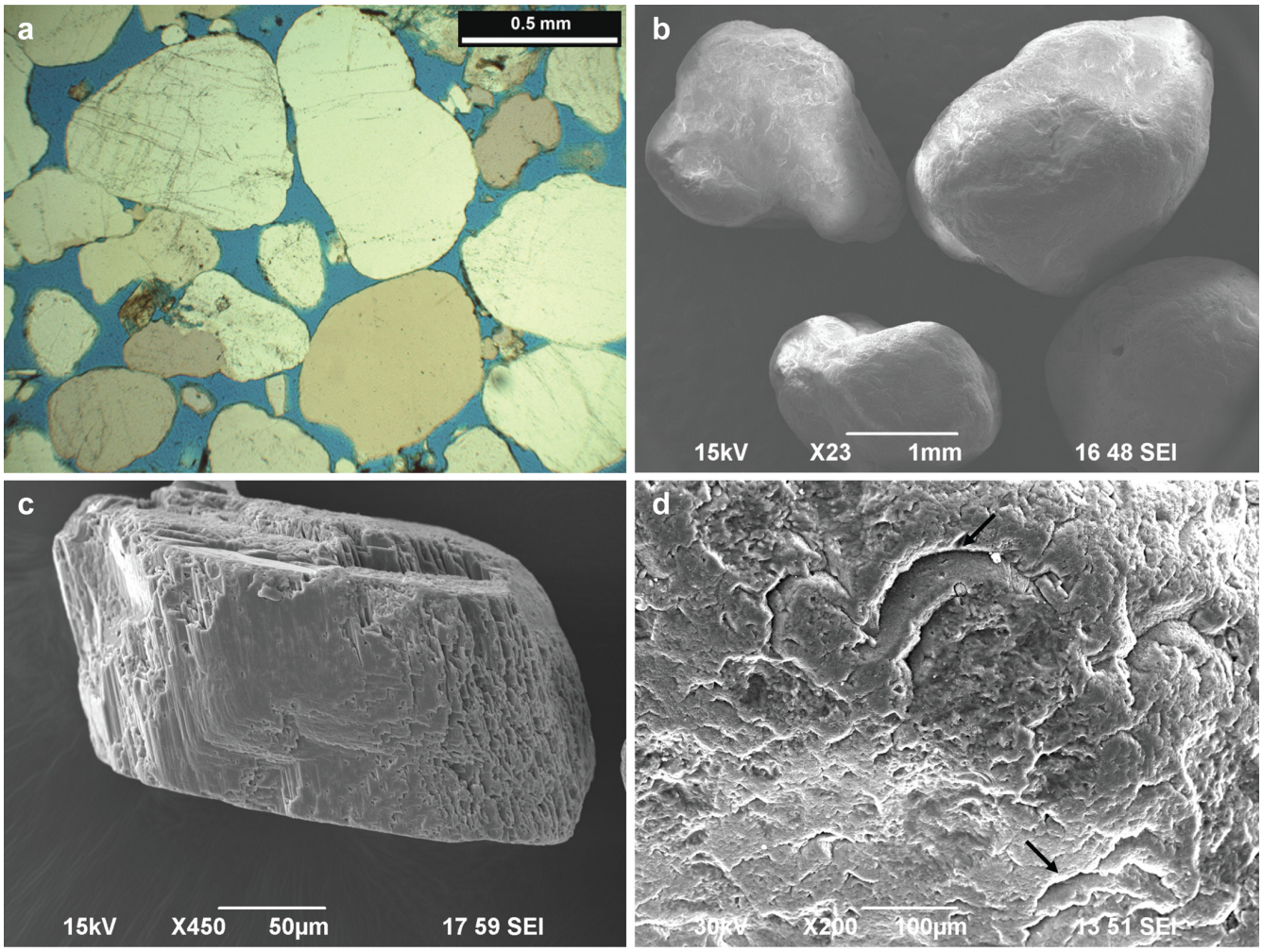

Figure 9. Photomicrographs and scanning electron microscope (SEM) images of the Hickory Sandstone.
A. Thin section of typical weakly cemented Hickory Sandstone from the Voca area (blue is epoxy filling original pores).
B. SEM image of well-rounded quartz grains.
C. SEM image of potassium feldspar grain.
D. SEM image of crescentic impact structures (arrows) on quartz grain surfaces indicative of eolian transport.

Cross-beds and laminations are the dominant bedding types (Fig. 8C), whereas burrow-mottled (Fig. 8D), structureless and contorted bedding are minor types. Laminations in cross-beds and horizontal laminations are manifested by alternations of coarse to very coarse sand (mean size = 1.0 mm) and fine sand (0.2 mm). Individual laminations are well sorted, but overall sorting of beds is poor (Fig. 9A). Tabular and trough cross-beds are both common and nearly unidirectionally oriented toward the southeast, the seaward direction (Wilson, 1962).

Sandstones, except for the ironstone beds, are composed almost entirely of quartz and pink K-feldspar. The average composition is 88% quartz, 10% feldspar, and 2% rock fragments (McBride et al., 2002). Roundness of quartz grains runs a spectrum from angular to well rounded, with most in the rounded to well-rounded category (Fig. 9B). Feldspar abundance decreases upsection and is most abundant in the fine to very-fine sand fraction, where it can exceed 30%. Feldspar is all well rounded, although not all spherical (Fig. 9C). Rock fragments are chiefly intraformational sandstone clasts cemented by iron oxide or collophane and clay rip-up clasts, and, at the base of the member, metamorphic and igneous basement rocks. Muscovite, biotite, and heavy minerals are trace components.

Hickory sandstones are free of clay matrix, except where burrowing animals shuffled clay from the thin mudstone beds into underlying sand beds. Detrital clays are sparse in the Hickory similar to Cambrian

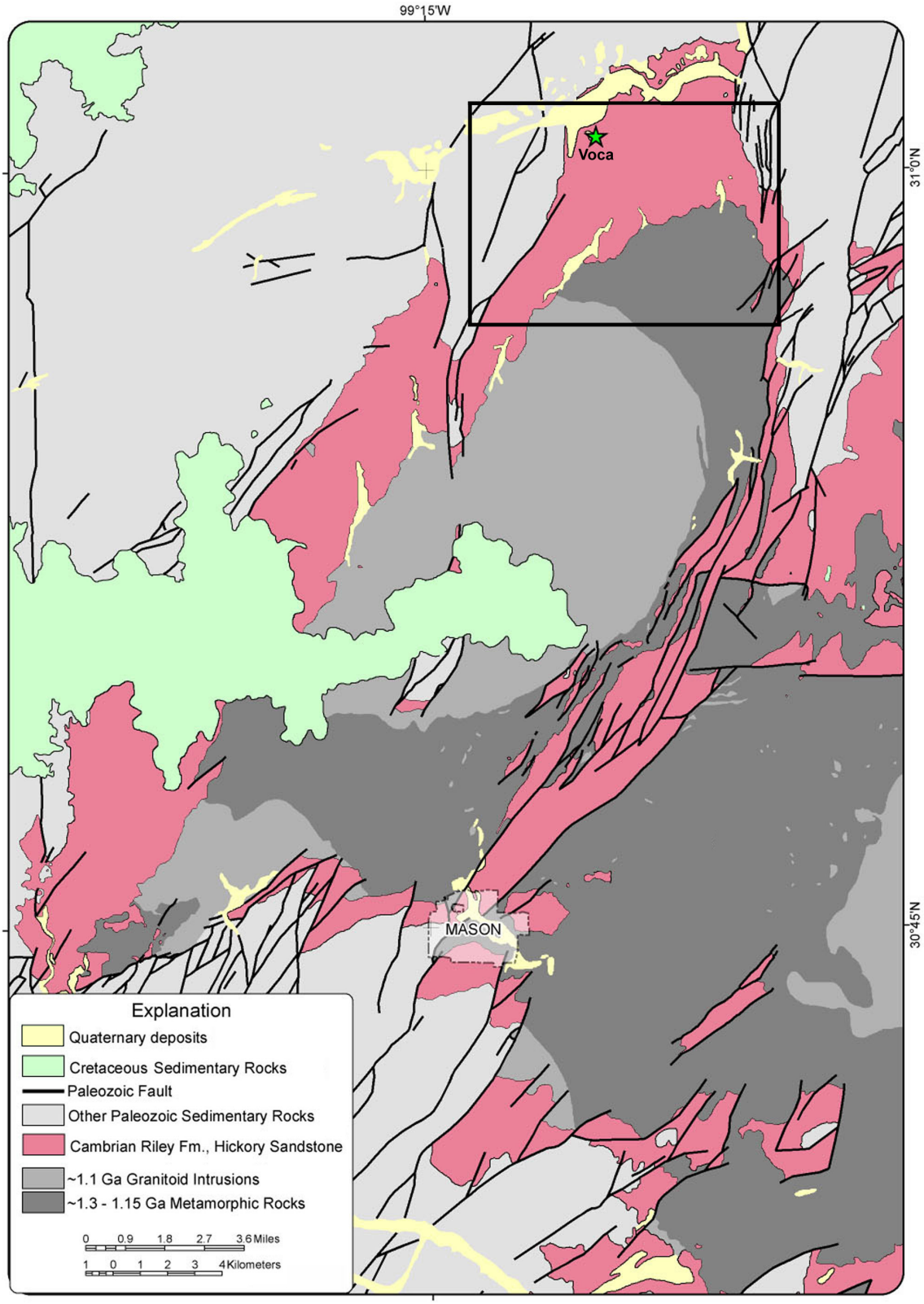

Figure 10. Geologic map of the Voca frac sand-producing area in the northwest Llano Uplift. Modified from Llano and Brownwood Geologic Atlas of Texas (1:250,000) sheets.

sedimentary rocks everywhere.

Post-depositional (diagenetic) changes that affected Hickory sandstones include compaction; cementation by iron oxides (goethite and hematite), calcite, and minor amounts of quartz and 13 other scarcer mineral phases; dissolution loss of at least 3% feldspar; and local bleaching of beds by some reductant such as H2S and/or hydrocarbons. Compaction produced tighter packing and some fractured quartz grains, both of which reduced initial porosity. However, porosities greater than 20% are common (McBride et al., 2002), accounting for the Hickory being a regional groundwater aquifer (Delaney, 1990). There is evidence that some beds once cemented by calcite have been leached of their calcite to produce their current porosity and friability.

Geology of the Voca District

The geology of the Voca area is typical of the exposures around the flanks of the Llano Uplift where the basal Cambrian strata unconformably overlap the irregular paleotopography developed on the Proterozoic metamorphic and igneous basement (Fig. 10). In addition to the onlapping relationships, the Hickory is preserved in a series of northeast-trending fault-bound panels that have preserved the Hickory within grabens in the Proterozoic basement. Post-Hickory Cambrian strata are affected by these structures, as well as the extended normal succession to the northwest. A thin veneer of Cretaceous strata is preserved in the west central area; minor amounts of Quaternary alluvium are present along the San Saba River and lesser drainages (Fig. 10).

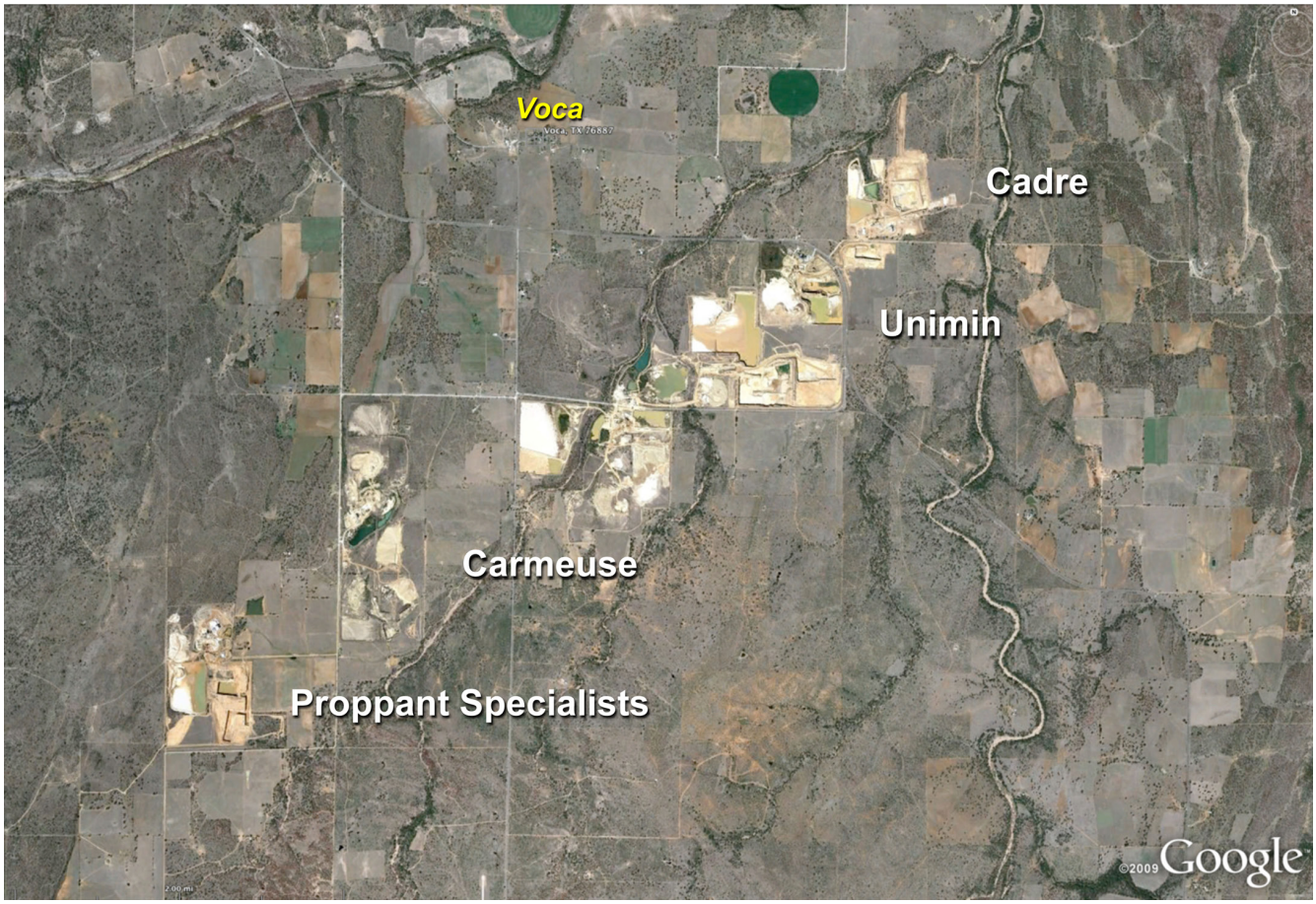

Figure 11. Google Earth view of the Voca frac sand-producing area. Image is approximately 16 miles (25.7 km) wide; location shown on Figure10.

The Hickory frac sand-producing area extends about 6 miles (10 km) northeast-southwest along the Hickory outcrop belt near the basement exposures south of Voca (Fig. 11). Production of glass-sands started in the Voca area in the central part of the current area in the 1940s, but the fracing sand potential

was recognized early by Barnes and Schofield (1964). Four companies (Proppant Specialists, Carmeuse Industrial Sands, Unimin, and Cadre Proppants) are presently in production, with Proppant Specialists and Cadre Proppants representing the most recent developments on the southwest and northeast ends of the district, respectively (Fig. 11). Production is restricted to the poorly cemented near-surface 50- to 65-ft (15 to 20-m) interval in the lower Hickory above the water table (Fig. 8A).

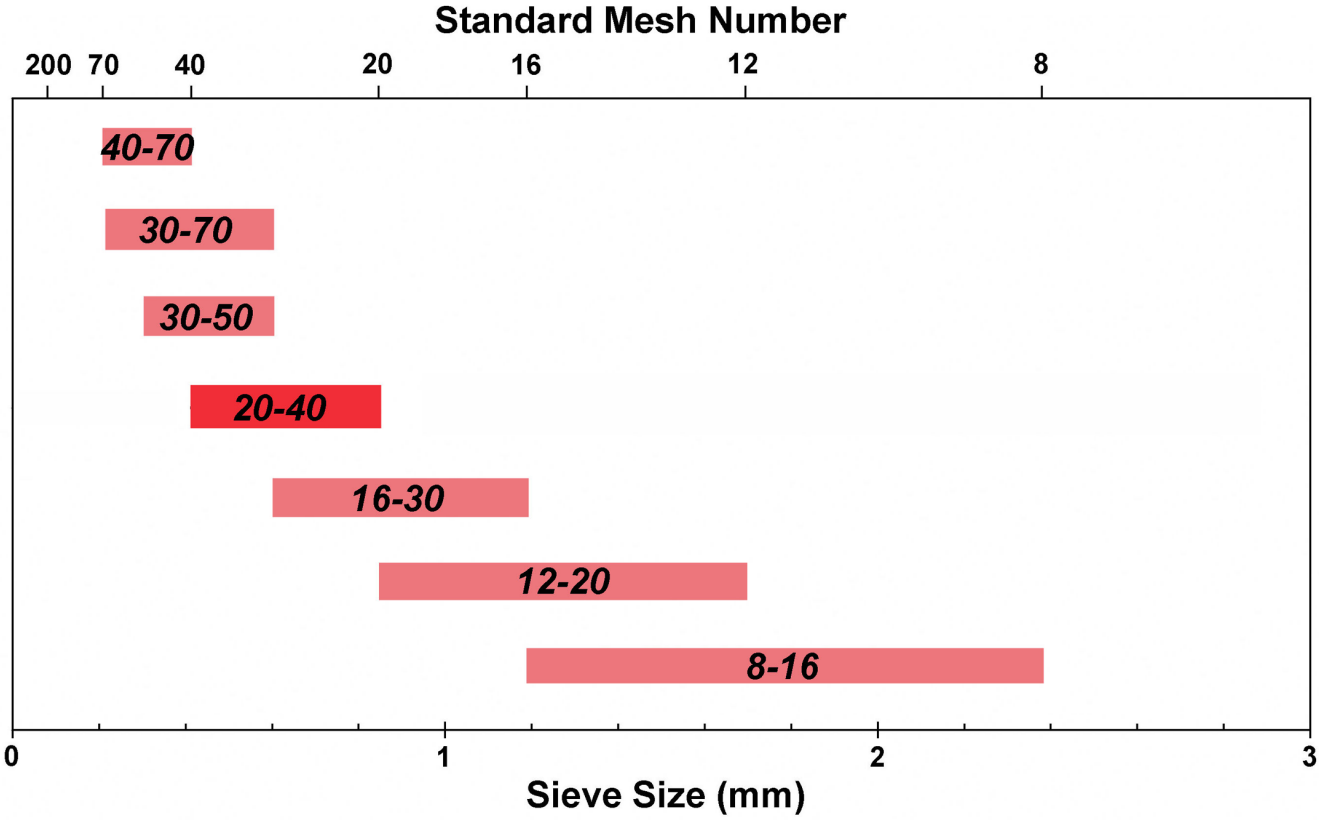

Figure 12. Grain size ranges of typical Voca area frac sand products in US-standard mesh. The frac sand size used depends on formation properties, but the -20 +40 size fraction is the most commonly used, comprising 85% of the current usage (Montgomery and Smith, 2010).

Except locally where quartz, calcite, or iron oxide cements fill all pores and produce hard, strongly indurated beds, the Hickory sandstones exposed around the flanks of the Llano Uplift are friable. Weak induration of these friable beds is produced by the combination of minute quartz and K-feldspar overgrowths plus interpenetrating surfaces at pressure solution pits developed at contacts between quartz grains (Fig. 7). Thus, these units are easily crushed and processed to produce frac sands with desired characteristics and in a variety of size ranges (Fig. 12).

Quartz grain roundness is highly variable (angular to well rounded), which indicates there are populations of grains that have different sources and abrasion histories. Subangular grains dominate the lower Hickory and subrounded grains the upper units. Well-rounded grains are interpreted to have been derived from eolian deposits that covered parts of the Precambrian basement prior to deposition of the Hickory (Fig. 6; Krause, 1996; McBride et al., 2002). Many grains have the rounded, bean shape typical of eolian-abraded sands (Merino and Hoch, 1988; Werner and Merino, 1997). In addition, many well-rounded grains also have crescentic surface fractures that develop from grain impacts during eolian transportation (Fig. 9D).

Conclusions

In the past few years, the United States has experienced a game changer in natural gas supply via a combination of horizontal drilling and advanced hydraulic fracturing of unconventional reservoirs. A corresponding growth in proppant demand is related to

these widespread hydraulic fracturing operations. The quartz-rich composition, well-rounded texture of most quartz grains, and poorly consolidated character of Hickory sandstone beds combine to make the Hickory Sandstone of the Voca area an excellent source of frac sand. The western Llano Uplift is favorably located as a supply source for several major plays. Increased production from existing and new sand mines, linked with increased truck transport, has both benefitted the local economy and brought concerns to the impacted residents. Resources for continued production at current rates have been identified, and additional properties are in various stages of permitting and development.

Acknowledgments

Field work, research, and travel funding was provided by the Yager Professorship of the Geology Foundation of the Jackson School of Geosciences. We are grateful to Proppant Specialists and Cadre Proppants for permission to visit and sample their Voca frac sand quarries. Marty Bentson of Proppant Specialists generously shared his knowledge of the past and current Voca district operations. We thank Mark Helper for the digital geologic maps of the Llano Uplift.

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