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Ore Geology Reviews

journal homepage: www.elsevier.com/locate/oregeorev



Genetic and grade and tonnage models for sandstone-hosted roll-type uranium deposits, Texas Coastal Plain, USA

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ARTICLE INFO

Article history:

Received 1 September 2015

Accepted 16 June 2016

Available online 12 July 2016

Keywords:

Uranium

Texas

Resources

Deposits

Genetic

Model

ABSTRACT

The coincidence of a number of geologic and climatic factors combined to create conditions favorable for the development of mineable concentrations of uranium hosted by Eocene through Pliocene sandstones in the Texas Coastal Plain. Here 254 uranium occurrences, including 169 deposits, 73 prospects, 6 showings and 4 anomalies, have been identified. About 80 million pounds of U_3O_8 have been produced and about 60 million pounds of identified producible U_3O_8 remain in place. The development of economic roll-type uranium deposits requires a source, large-scale transport of uranium in groundwater, and deposition in reducing zones within a sedimentary sequence. The weight of the evidence supports a source from thick sequences of volcanic ash and volcanoclastic sediment derived mostly from the Trans-Pecos volcanic field and Sierra Madre Occidental that lie west of the region. The thickest accumulations of source material were deposited and preserved south and west of the San Marcos arch in the Catahoula Formation. By the early Oligocene, a formerly uniformly subtropical climate along the Gulf Coast transitioned to a zoned climate in which the southwestern portion of Texas Coastal Plain was dry, and the eastern portion humid. The more arid climate in the southwestern area supported weathering of volcanic ash source rocks during pedogenesis and early diagenesis, concentration of uranium in groundwater and movement through host sediments. During the middle Tertiary Era, abundant clastic sediments were deposited in thick sequences by bed-load dominated fluvial systems in long-lived channel complexes that provided transmissive conduits favoring transport of uranium-rich groundwater. Groundwater transported uranium through permeable sandstones that were hydrologically connected with source rocks, commonly across formation boundaries driven by isostatic loading and eustatic sea level changes. Uranium roll fronts formed as a result of the interaction of uranium-rich groundwater with either (1) organic-rich debris adjacent to large long-lived fluvial channels and barrier-bar sequences or (2) extrinsic reductants entrained in formation water or discrete gas that migrated into host units via faults and along the flanks of salt domes and shale diapirs. The southwestern portion of the region, the Rio Grande embayment, contains all the necessary factors required for roll-type uranium deposits. However, the eastern portion of the region, the Houston embayment, is challenged by a humid environment and a lack of source rock and transmissive units, which may combine to preclude the deposition of economic deposits. A grade and tonnage model for the Texas Coastal Plain shows that the Texas deposits represent a lower tonnage subset of roll-type deposits that occur around the world, and required aggregation of production centers into deposits based on geologic interpretation for the purpose of conducting a quantitative mineral resource assessment.

Published by Elsevier B.V.

1. Introduction

Sandstone-hosted uranium deposits are the most significant type in the United States (U.S.). They are responsible for all current uranium production and estimated to contain 85 percent of reasonably assured

resources (RAR) (NEA/OECD-IAEA, 2010). In 1980, just over half of the estimated uranium in potential (undiscovered) resources in the U.S. were assessed from sandstone-type deposits (DOE, 1980). There are three major sandstone-hosted uranium regions in the U.S.; the Colorado Plateau, the Wyoming basins and the Texas Coastal Plain (Fig. 1). Approximately 200 million pounds of U_3O_8 have been mined from the Wyoming basins, 340 million pounds of U_3O_8 from that portion of the Colorado Plateau region in New Mexico, and about 80 million pounds of U_3O_8 from deposits mined from the Coastal Plain of south Texas (Boberg, 2010; Hall, 2013; McLemore, 2011) (Appendix 1). The

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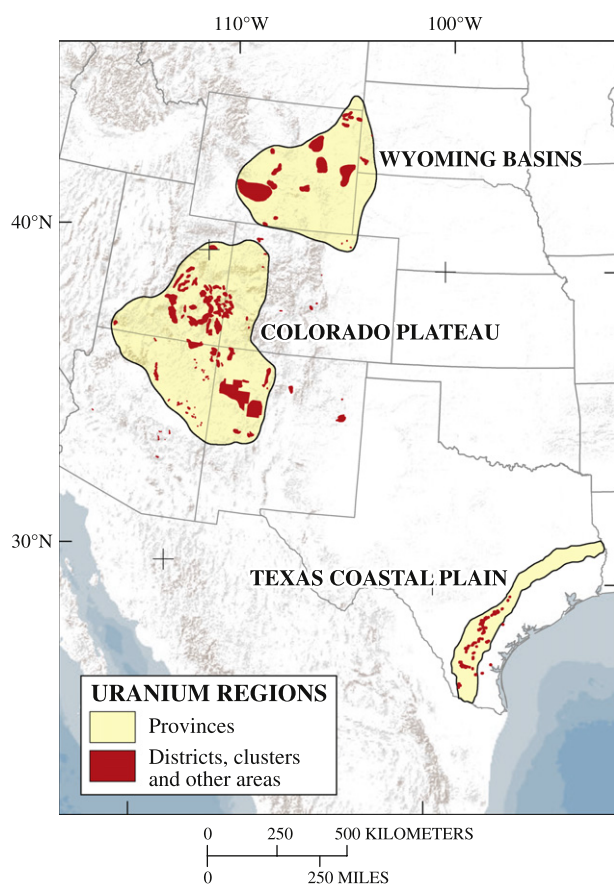


Fig. 1. Principal sandstone-hosted uranium regions of the United States.

Colorado Plateau has the highest estimated amount of in situ uranium resources, the Wyoming basins and the Coastal Plain region, of which the south Texas portion contains the bulk of resources, are second and third, respectively (Table 1) (DOE, 1980; DOE/EIA, 2010). In each of these areas, a unique combination of uranium source, transport and trap formed geologically distinct world-class uranium regions. In the Wyoming basins and Coastal Plain regions, uranium is principally identified as roll-type uranium deposits, whereas Colorado Plateau deposits are dominated by tabular-sandstone deposits. The Wyoming basins and Colorado Plateau regions have been the focus of recent comprehensive analysis and genetic deposit studies, but a comprehensive analysis of uranium deposits in the Texas Coastal Plain has not been published since 1981 (Adams and Smith, 1981; Boberg, 2010; Goldhaber et al., 1990; McLemore, 2011; Northrop et al., 1990; Peterson and Turner-Peterson, 1980; Sanford, 1992; Turner-Peterson and Hodges, 1992).

Uranium has been produced continuously from deposits in south Texas since its discovery in the mid-1950s. Since comprehensive studies

describing uranium deposits in this region were published in the early 1980s, exploration and development of deposits have continued to provide information about the location and geology of deposits; focused theses and research papers have been completed; and a more complete understanding of paleogeography, paleoenvironment and basin evolution has been achieved. A new compilation of occurrences, and a refined genetic model for sandstone-hosted deposits in the Coastal Plain of south Texas have been completed and are presented here. The enhancement of georeferenced databases since the last comprehensive work also provides new analytic methods and a deeper level of analysis of spatial relationships critical for a complete understanding of uranium deposits. All have added a depth of knowledge not available when earlier regional genetic interpretations of these deposits were developed, and form the basis for a refined genetic deposit model for sandstone-hosted uranium deposits in the Coastal Plain of Texas that is presented here.

2. Exploration and mining history

The first uranium mines in Texas were developed within the outcropping Whitsett Formation of the Jackson Group in the Tordilla Hill area in Karnes County. These deposits were identified by airborne radiometric surveys conducted in 1954 by independent oil companies who incorrectly believed oil was associated with anomalous radioactivity (Eargle and Weeks, 1961). Shallow, surface oxidized deposits were mined using open pit methods beginning in 1960, and deeper deposits mostly found at the boundary between reduced and oxidized sediments began to be developed in the mid-1960s. The first in situ recovery (ISR) mine in Texas was developed in 1975, one of the earliest ISR mines developed worldwide. Currently all uranium in Texas is produced using ISR mining.

Many roll-type uranium deposits were initially identified as down-hole gamma anomalies coincident to oil and gas drilling in the region, and this type of reconnaissance exploration method is still used. Regional groundwater sampling from preexisting wells has also been used as a reconnaissance exploration technique to target roll-type deposits in Texas. Modern exploration methods are focused on identifying mineralizing “trends” such as permeable paleochannels, structural domes and lineament features that would channel groundwater flow and/or reducing solutions into host units. Once prospective terrain is delineated, follow-up drilling is used to identify the location of potentially mineralized reduction-oxidation fronts that are defined by subtle changes in the color of subsurface sediments. Geophysical logging of these drill holes with Prompt Fission Neutron technology to directly measure U^{235} content is further used to delineate deposits within roll front systems (Humphreys, 1983).

3. Production and Resources

Between 1955 and 2013, just over 80 million pounds of U_3O_8 were produced from an estimated 92 mines and 1 tailings facility in Texas (Appendix 1). This is about 8% of total U.S. production (DOE, 2009;

Table 1

Mean tons of U_3O_8 reserves and potential resources in the \$100/lb. U_3O_8 cost category within the major sandstone-hosted uranium regions of the U.S.

Region	Reserves ^a (metric tons U_3O_8) (DOE, 1980)	Reserves ^b (metric tons U_3O_8) (DOE/EIA, 2010)	Probable potential resources (metric tons U_3O_8) (DOE, 1980)
Colorado Plateau	542,300	294,000	753,761
Wyoming Basins	407,800	223,000	480,500
Coastal Plain ^c	61,000	20,000	324,400

For a definition of resource categories and NURE resource regions, see DOE (1980).

^a Reserves are not differentiated by deposit type but are predominantly from sandstone-hosted deposits with minor contributions from other deposit types and are reported in cost categories based in 1980 prices and dollars.

^b Reserves are sandstone-hosted deposits and are reported in cost categories using 2010 dollars.

^c The NURE Coastal Plain region includes the Texas Coastal Plain as well as areas of the Atlantic Coastal Plain.

DOE/EIA, 2014). The precise number of mines is uncertain because this information is derived from the U.S. Department of Energy's U.S. Producing Uranium Mines database that does not always track production to a specific mine. Mines developing deposits hosted in the Oakville Formation were the most prolific, followed by those exploiting deposits in the Jackson Group, then the Goliad Sand and the Catahoula Formation (Table 2).

An estimated 60 million pounds of U_3O_8 resources remain in place, which is about 10% of total U.S. reserves mineable at an economic valuation of less than about \$50 USD/lb. U_3O_8 as reported by the Department of Energy–Energy Information Administration (EIA) (DOE/EIA, 2010) (Appendix 1). Identified resource estimates in portions of Texas may be underreported due to restricted land access or lack of public reporting by some private mining companies. There is also strong likelihood some areas of the Texas Coastal Plain are underexplored and that additional resources may have been identified, but not reported.

In addition to identified resources, undiscovered resources of over almost 1.5 billion lbs U_3O_8 were estimated for this region (DOE, 1980). Adding an economic value filter so that only resources mineable at less than about \$30/lb U_3O_8 (in 1980 dollars) are considered reduces this endowment to 640 million lbs U_3O_8 . Even considering this more reasonable economic category, this is still a significant potential resource that has not been developed. The lack of development may be due to persistently low uranium prices since 1980, difficulties in accessing resources on private land in Texas, or possibly estimation techniques that were overly optimistic (Hall, 2013).

4. Regional geology and general characteristics of deposits

Over 250 uranium occurrences including anomalies, showings, prospects, and deposits are hosted in Tertiary strata in the Texas Coastal Plain. In this analysis, anomalies are defined as geophysical or geochemical anomalies, showings are significant anomalies that were visited and physically examined, prospects are showings from which material was removed for evaluation – such as prospect pits and drill holes, and deposits, mined or unmined, are any occurrence with a reported mineral resource. Published information was used to characterize occurrences and to classify them into these categories to reflect their relative importance.

Production and/or in place resources are reported for 126 of these occurrences. Deposits range in size from about 900 lbs U_3O_8 for smaller open-pit mines to 10 million pounds U_3O_8 for the larger ISR targets. Uranium concentration of ore in ISR mines ranges from 0.032 to 0.150% U_3O_8 , and for open pit mines ranges from 0.039 to 0.300% U_3O_8 (Appendix 1).

Roll-type uranium occurrences are hosted in late Eocene to early Pliocene sediments, located mostly southwest of the San Marcos arch (Fig. 2). In this area uranium has been mined from the Eocene Jackson Group (Whitsett and Manning Formations), Oligocene Catahoula Formation, Miocene Oakville Formation and Miocene–early Pliocene Goliad Sand (Fig. 3). Uranium ore bodies in South Texas are described as deposited

in a C-shaped roll front as viewed in cross-section, although in detail individual ore zones have a complex geometry controlled by sand facies variations and the availability and location of reductants. Individual ore bodies are often small, ore grade material ranges in thickness from a few to tens of meters, width ranges up to 100 m, and ore occurs discontinuously over several kilometers along a reduction/oxidation front. Mineralized fronts are often subparallel in plain view and stacked in overlying permeable units reflecting dominant regional groundwater flow. The practical downdip limit for the occurrence of roll-type deposits is constrained by how far groundwater can transport uranium in transmissive sediments. This in turn is strongly influenced by facies changes and composition—with continental clastic channel and barrier-bar facies typically more transmissive, and offshore fine-grained deltas and shelf deposits less transmissive. In the Texas Coastal Plain, most deposits have been mined within 150 m of the surface; however recent exploration has been reported to about 330 m in the Goliad Sand and 400 m in the Oakville Formation (UEC, 2014).

Host sediment constituents and depositional environment are critical controls of the location of sandstone-hosted uranium deposits in the Gulf Region. Sediment volume and source are in large measure controlled by broad-scale crustal events in the western and southern US. Tertiary sediments along the Texas Coastal Plain formed in response to a significant sea level drop at the end of the Cretaceous coupled with increased sediment influx from uplift of the Rocky Mountains during the Laramide orogeny. Clastic debris was transported to the Gulf Coast along a series of large, well-developed river channels into the Rio Grande, Houston and Mississippi embayments (Fig. 4) (Galloway et al., 2000). Shoreline progradation into the Gulf of Mexico was influenced by migrating river channels, subsidence related to sediment loading, eustatic sea level changes, temporal changes in climate and the volume of sediment supply (Galloway et al., 1991). During the late Paleocene to early Eocene sediment was supplied to the Houston embayment from the Rocky Mountains and Great Plains. During the Oligocene and early Miocene the major sediment source moved to the Midcontinent region and Mexico which included large volcanic complexes such as the Trans-Pecos, Sierra Madre Occidental, Mogollon, San Juan and Great Basin volcanic fields. This source terrain provided sediment to the most prolific host strata in Rio Grande embayment of the Texas Coastal Plain. The dominant sediment influx shifted eastward to the Houston embayment and the source shifted back to the Great Plains during the late Miocene where it remains today (Galloway et al., 2011). Locally, sediment to the region was sourced from the San Marcos arch.

In roll-type deposits in Texas, uranium is adsorbed onto reactive substances including organic debris, titanium oxide, montmorillonite clay, and rock fragments, and forms discrete uranium minerals consisting primarily of coffinite and uraninite (Bomber et al., 1986; Reynolds and Goldhaber, 1978; Galloway and Kaiser, 1980). Uranium minerals coat sand grains composed of carbonate, silicate and sulfide minerals, and volcanic rock fragments, and are described filling pore spaces within the interstices of sandstones associated with opal and micritic calcite cement (Langmuir and Chatham, 1980). Iron disulfide (pyrite and marcasite) is more commonly identified in Catahoula- and Oakville-hosted deposits where it occurs as discrete framboids, euhedral and amorphous crystals replacing plant material, iron-titanium and biotite grains (Langmuir and Chatham, 1980). Carbonate is noted in the vicinity of but not directly related to mineralization. Calcite forms up to 20% of the host rock near roll fronts in the Catahoula Formation and averages 10% in the Oakville Formation (Adams and Smith, 1981; Galloway et al., 1982). Zoned trace metals across uranium roll fronts have also been noted. Uranium and vanadium are commonly found in close proximity to the interface between oxidized and reduced sand. Molybdenum is enriched ahead of the mineralized front in more reduced sediments, and selenium lags behind in more oxidized portions of the system (Adams and Smith, 1981; Galloway et al., 1979; Harshman, 1974).

Table 2

Uranium production and resources for sandstone-hosted uranium deposits in the Texas Coastal Plain.

Host formation	Total production to 2013 (lbs. U_3O_8)	Identified in place resources in 2013 (lbs. U_3O_8)
Jackson Group	22,937,815	3,490,614
Catahoula Formation	9,672,382	10,936,813
Oakville Formation	37,026,575	11,629,994
Goliad Sand	11,442,094	33,464,600
Total	81,438,866	59,162,021

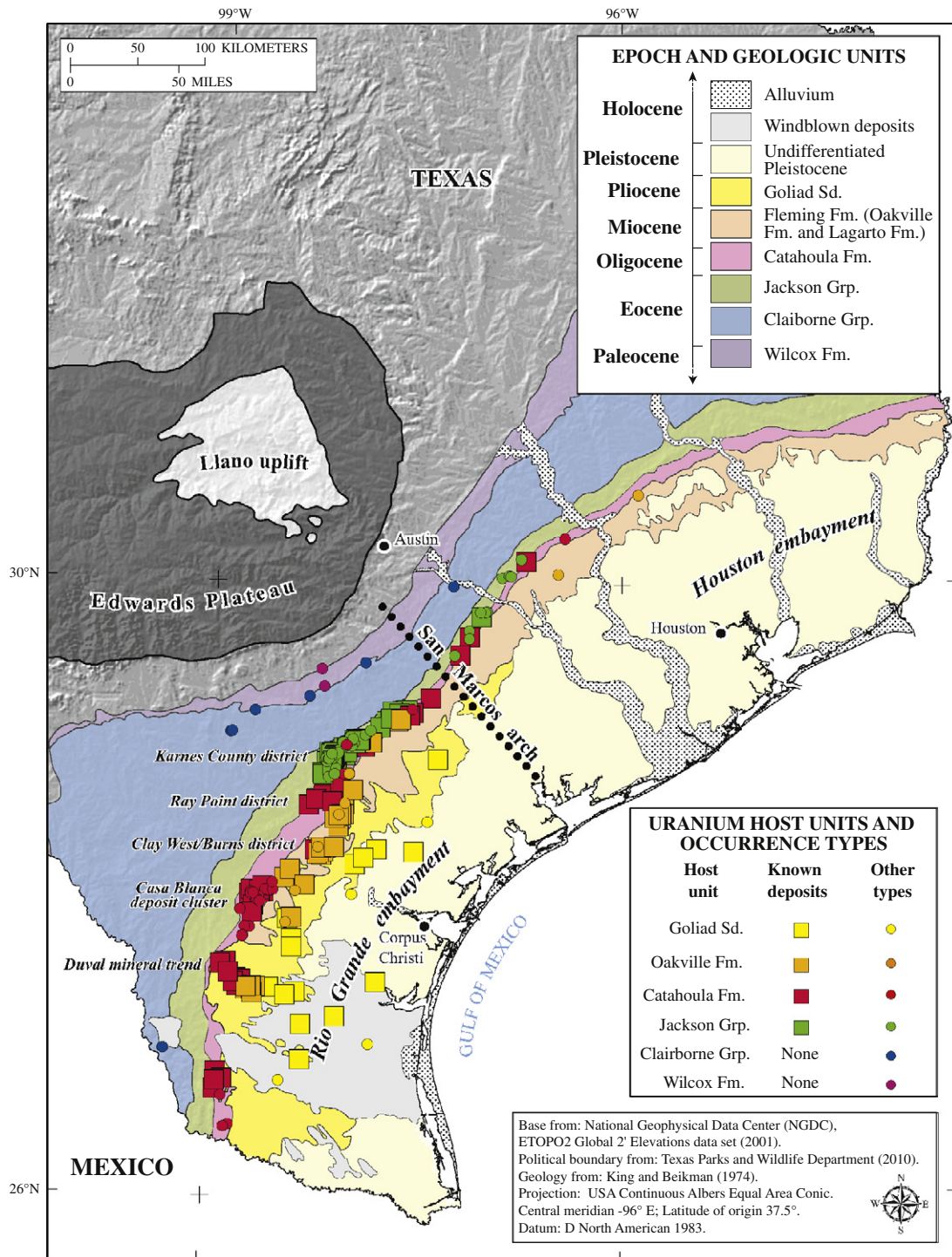


Fig. 2. Location of uranium occurrences in south Texas.

The age of roll-type deposits in Texas is poorly constrained. The most reliable date is 5.07 Ma for the Felder deposit hosted in the Oakville Formation, as determined by using uranium-lead dating methods (Ludwig et al., 1982). Uranium disequilibrium studies indicate that the age of mineralization at the Kingsville Dome mine (Goliad host) ranges from 150,000 to 450,000 years, the Sickenius mine (Catahoula host) is less than 250,000 years old, and the Burke Hollow deposit (Goliad host) is very young with high disequilibrium (Arredondo, 1991; Dickinson and

Duval, 1977; Kunkel, 2013). Uranium disequilibrium studies indicates that uranium may still be migrating in some deposits.

5. Components of the Texas Coastal Plain roll-type deposit system

A source for uranium, a mechanism to transport uranium, and a process to precipitate uranium within host sediments are all required to form economic roll-type deposits. These factors for the Texas Coastal

PERIOD	EPOCH	Ma	Geologic Unit	Uranium Occurrences	Uranium Resources* (lbs. U ₃ O ₈)
Tertiary	Pliocene	5.3	Goliad Sand	21 occurrences: 11 deposits with identified resources 5 deposits with unknown resources 5 prospects	11,442,094 production 33,464,600 in place
	Miocene	23.7	Lagarto Formation		
			Oakville Formation	47 occurrences: 30 deposits with identified resources 6 deposits with unknown resources 9 prospects 1 showing 1 tailings facility reporting production	37,026,575 production 11,629,994 in place
			Anahuac Shale	62 occurrences: 26 deposits with identified resources 15 deposits with unknown resources 17 prospects 4 showings	9,672,382 production 10,936,813 in place
	Oligocene	23.7	Catahoula Formation		
			Frio Formation		
	Eocene	33.9	Vicksburg Formation		
			Whitsett Formation	117 occurrences: 60 deposits with identified resources 16 deposits with unknown resources 39 prospects 1 showing 1 tailings facility reporting production	22,937,815 production 3,490,614 in place
			Manning Formation		
			Wellborn Sandstone		
			Caddell Formation		
			Yegua Formation	7 occurrences: 3 prospects 4 anomalies	
			Laredo Formation		
			Cook Mountain Formation		
			Sparta Sand		
			El Pico Clay		
			Weches Formation		
Tertiary	Paleocene	55.8	Queen City Sand		
			Bigford Formation		
			Reklaw Formation		
Tertiary	Paleocene	55.8	Carizzo Sand	2 occurrences: 1 prospect 1 anomaly	
			Wilcox Formation		

* As of 12/31/2013. Yellow highlights indicate a geologic unit that contains uranium occurrences. Stratigraphy of the Rio Grande Embayment and San Marcos Arch, Central Texas published by Salvador et al. (1989), geologic names conform to the USGS National Geologic Map Database (2015). Epoch boundary ages from Galloway and others (2000; fig.1).

Fig. 3. Tertiary units known to host uranium occurrences in the Texas Coastal Plain (shaded in yellow) showing uranium occurrences and production from each unit.

Plain will be considered below, followed by a discussion of variations specific to individual host units.

5.1. Uranium source

Uranium source is deduced using indirect evidence. To date, studies designed to pinpoint one potential uranium source using a geochemical

fingerprint have not been successful. The origin of uranium in Texas roll-type deposits has been postulated as either rock fragments derived from distal highland areas and now found within arkosic host rocks and/or tuffs interbedded with host sandstones (Adams and Smith, 1981; Eargle et al., 1975). The evidence for both potential sources of uranium in Texas Coastal Plain roll-type deposits is summarized below.

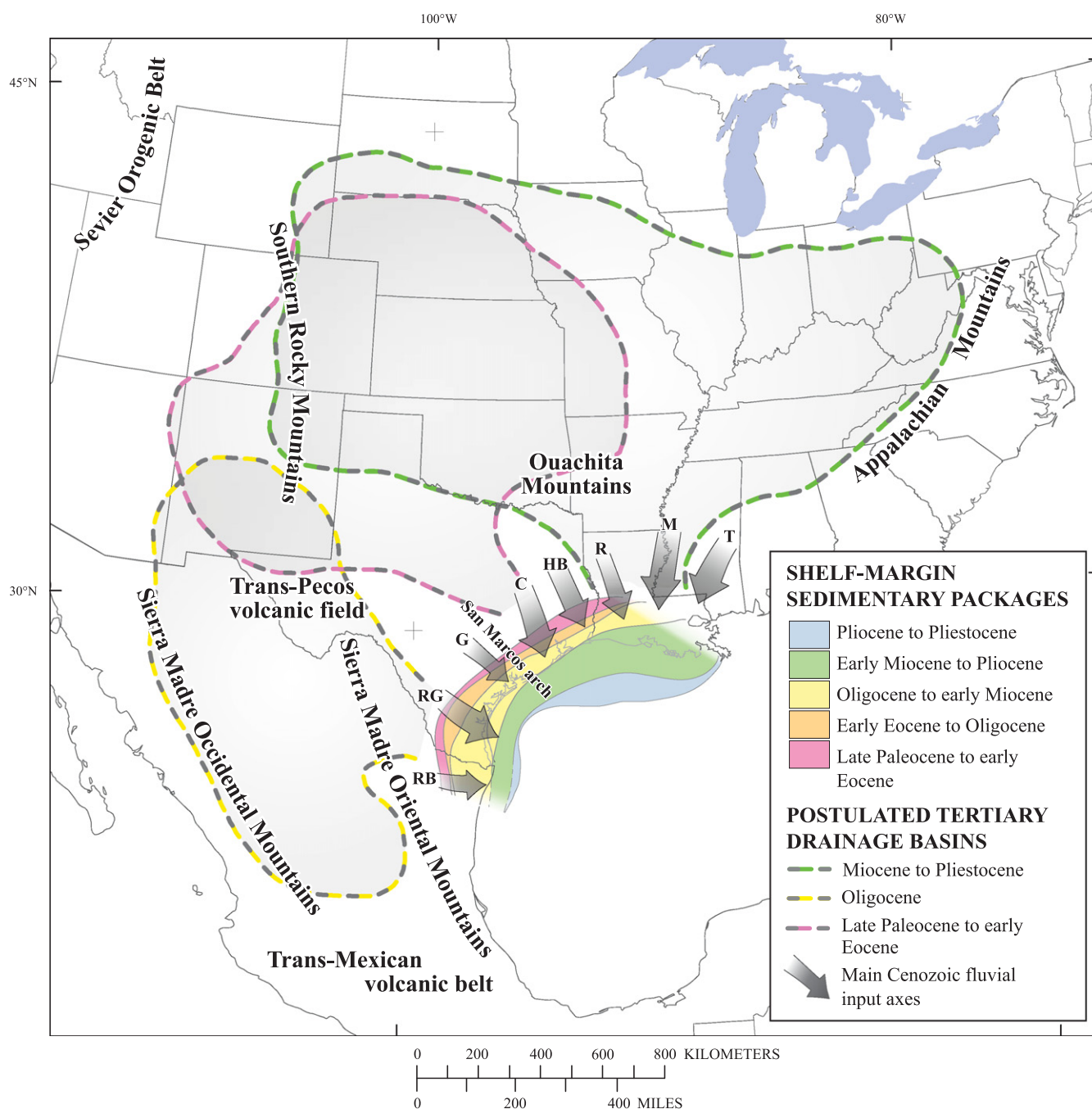


Fig. 4. Regional sources for Tertiary sediments deposited in the Texas Coastal Plain and the location of the main Cenozoic fluvial input axes constructed from information in [Winker et al. \(1981\)](#) and [Galloway et al. \(2011\)](#). RB – Rio Bravo; RG – Rio Grande; G – Guadalupe; C – Colorado; HB – Houston-Bravos; R – Red; M – Mississippi; T – Tennessee.

5.1.1. Volcanic Ash

Volcanic ash is a viable uranium source for roll-type deposits in the western U.S. ([Zielinski, 1983](#)). Several lines of evidence support the principal uranium source in the Texas Coastal Plain as a series of volcanic tuffs and volcanoclastic sediments found in Tertiary rocks in the region. There is a positive correlation between the regional and temporal location of known deposits with volcanic ash and volcanoclastic-rich sediments. Regional rhyolitic volcanism first in Chihuahua, Mexico region then the Trans-Pecos region of West Texas and Mexico and finally New Mexico provided ash and sediment to the most prolific uranium-producing host units in the Rio Grande embayment from mid-Eocene to late Oligocene time ([Galloway et al., 1991](#)). The thickest accumulation of ash (up to 800 m) is in the Catahoula Formation; however, tuffs are also reported in the Jackson Group, Yegua

Formation and Oakville Formation ([Quick et al., 1977](#)). After deposition, the Catahoula was exposed and eroded for some time, which would provide a fresh supply of uranium source rock to the region ([McBride et al., 1968](#)). The volcanic ash reported in the Oakville Formation may be largely reworked from older, underlying units ([Quick et al., 1977](#)).

There is a good age correlation between most uranium deposits in the Texas Coastal Plain and regional volcanism. Portions of the Trans-Pecos magmatic province that have been accurately dated show the field was active from 49 to 16 million years ago, with peak activity and the accumulation of voluminous tuffaceous sediments from 40 to 31.5 million years ([McDowell, 1979](#)). Potassium-argon age-dating of biotite in volcanic rock fragments collected from the middle portion of the Catahoula Formation return dates ranging from 34 to 50 million years ago ([Duex, 1970](#)). This age range supports the Trans-Pecos region as a

source for the tuffs identified in the Whitsett and Catahoula Formations, Oakville Formation and Yegua Formation. The only unit that is mineralized but does not contain tuff is the Goliad Sand (McDowell, 1979). A volcanic vent system in the Catahoula Formation is identified as a possible local source for volcanics in Live Oak County, Texas (Morony, 2010).

There is a regional spatial correlation between known uranium deposits and ash content in host rocks. Whether the source of tuffs was from Chihuahua, the Trans-Pecos region or more locally in southeastern Texas, tuffaceous sediments thin eastward along the coastal plain of Texas. A westward source is presumed based on modern airflow patterns that move west to east across the region. Tuffs are a less important constituent of sediments in the Whitsett and Catahoula Formations in the Houston embayment (Quick et al., 1977). There is considerable variability in thickness of ash in the Catahoula Formation from 75 m in the northern portion of the Rio Grande embayment, thickening southward to over 600 m near the Mexican border. This variation in thickness is unusual for Tertiary clastic sediments deposited on the Gulf Coast, and was likely caused by portions of the Rio Grande embayment that were rapidly subsiding during deposition of this tuffaceous sequence. The distribution of source rocks as predominantly originating and accumulating in the western portion of the coastal plain of Texas may be an important factor explaining the increased abundance of deposits in the southwestern portion of the Texas Coastal Plain.

5.1.2. Uranium-rich highland areas

Worldwide a number of important roll-type deposit systems are hosted in basins that form adjacent to uranium-rich highland areas. Examples include roll-type systems in the Wyoming basins in the U.S., the Lake Frome region of Australia, the Chu-Sarysu and Syrdariya Basins in Kazakhstan and the Erlian Basin in China (Boberg, 2010; Bonnetti et al., 2015; Dahlkamp, 2010; Jaireth et al., 2015). Evaluation of felsic magmatism in uranium-rich regions around the world shows a correlation between rocks of high uranium composition that are chemically leachable and known uranium occurrences (Cuney, 2014). The contribution of uranium from weathering of uranium-rich highland areas, most notably from the Llano uplift or Trans-Pecos volcanic regions, may be an important source of uranium for deposits in the Texas Coastal Plain. Both physical and chemical weathering of uranium-rich highland areas potentially contributed uranium to the region. However based on distance from potential source rock to host sediments uranium chemically released to the environment is likely subordinate to that available from sources that were supplied to the region by mechanical weathering and deposition of uranium-rich clastic sediments in and adjacent to host rocks.

Uplift that accompanied regional volcanism exposed potentially uranium-rich crystalline basement rocks throughout the Western Interior and contributed sediments derived from weathering of these rocks to the Texas Coastal Plain. Feldspar and volcanic rock fragments are more common in the western portion of the Texas Coastal Plain, reflecting a proximal volcanic source for clastic sediments in this region (Galloway et al., 2011). Transport of volcanoclastic sediments into the region during the Paleogene and Neogene was by major long-lived paleochannel systems. Sediment source and volume varied over time in response to climate and tectonic events that affected the continental U.S. Sediment was supplied to the Rio Grande embayment by the Rio Bravo and Rio Grande paleochannels with sediment derived from the Western Interior of the U.S. and northern Mexico. Within the Rio Grande river system uranium-rich components including volcanic clasts, reworked and ash-fall tuff from the Trans-Pecos volcanic field, and sediments from the Sierra Madre Occidental, New Mexico and northern Mexico were transported to the Rio Grande embayment (Galloway et al., 2011). The Rio Bravo paleochannel system also supplied sediments from the Trans-Pecos and Sierra Madre Occidental regions into the Rio Grande embayment, but became less important after its sediment supply diminished in the late Eocene. The Houston embayment was supplied with sediment via the Red and Houston-Brazos paleochannels. The

Houston-Brazos paleochannel system transported sediments from the central Rocky Mountains with some sediments derived from the San Juan volcanic field. The Houston-Brazos channel became inactive in the Miocene and sediment supplied from the Rocky Mountains and northern New Mexico was transported into the embayment via the Red River.

The Sierra Madre Occidental region and Trans-Pecos volcanic belt provided sediment to the Texas Coastal Plain during the Oligocene and Miocene (Galloway et al., 2011). Pebbles and boulders of rhyolite, trachyte and trachyandesite in the Soledad Conglomerate Member of the lower Catahoula Formation can be traced to the Trans-Pecos volcanic field in West Texas and Mexico (Eargle et al., 1975; Parker et al., 1988). Smoky quartz, speculatively formed by radiation damage, is reported proximal to mineralization in both Oakville- and Goliad-hosted deposits, and may be derived from a uranium-rich highland source (Klohn and Pickens, 1970). Felsic magmatic rocks in the Trans-Pecos region may be a potential source for uranium (Cuney, 2014). These are found in the western metaluminous or alkali-calcic belt, containing metaluminous to peraluminous rocks, and in the eastern alkali belt, containing metaluminous to peralkaline rocks (Cameron, 1986; Cameron and Cameron, 1986; Nelson and Nelson, 1986). Within the Sierra Madre Occidental, high-potassium calc-alkaline, peralkaline and peraluminous rocks are identified; variants of each are identified as fertile uranium source rocks (Ferrari et al., 2007). Hydrothermal alteration of these potential source rocks has liberated uranium from accessory minerals in some areas (Rubin, 1993). It is therefore plausible that uranium may have been supplied through the process of erosion from the Sierra Madre Occidental region and Trans-Pecos volcanic belt, and transported in major paleochannel systems to the Texas Coastal Plain. These highland areas provided a uranium source that correlates with formation of the most prolific host rocks.

Sediment weathered from the San Marcos arch was deposited into the Gulf of Mexico periodically and may have supplied uranium-rich source rocks to the region, specifically to local strata surrounding the arch (Galloway et al., 2011). There is a positive spatial correlation between uranium occurrences in the Wilcox Formation, Claiborne and Jackson Groups, and Oakville Formation proximal to the arch. Located at the core of the San Marcos arch, a potential uranium source is the Llano uplift region of central Texas. The Llano uplift is a structural dome that exposes Mesoproterozoic rocks: metamorphosed volcanic, plutonic and sedimentary rocks intruded by granite (Mosher et al., 2008). Metaluminous to marginally peraluminous, high-potassium calc-alkaline plutons are described within the granitic intrusives (Smith et al., 2010) and are a potentially good uranium source rock (Cuney, 2014; Smith et al., 2010). Two uranium occurrences are identified in the Llano uplift and one, the Baringer Hill deposit, produced uranium (Eargle, 1970; Ehlmann et al., 1964). Field studies show uranium is leached from granite and more non-reactive minerals such as zircon are mechanically segregated during weathering and erosion (Tieh et al., 1980). There is some indication that Mesoproterozoic rocks of the Llano uplift may not have been exposed during most of the Tertiary until overlying Cretaceous carbonates were unroofed during the Pliocene or Pleistocene; however, the paleogeographic history of this region is very poorly documented (Tieh et al., 1980).

5.2. Uranium transport

An important factor in the genesis of deposits in the southern Texas Coastal Plain is the ability of groundwater to leach then transport uranium through permeable sediments in sufficient quantities to form economic deposits. These processes require (1) groundwater that is chemically capable of leaching uranium from source material, (2) groundwater capable of transporting uranium in solution, (3) enough energy to transport this groundwater through the system (4) permeable host sediments, and (5) limited sequestration of uranium during transport through sediments.

Study of the Catahoula Formation shows that volcanic ash and rock fragments are weathered and altered by oxidizing, neutral to weakly basic, bicarbonate-rich groundwater, releasing uranium during pedogenesis and early diagenesis (Galloway and Kaiser, 1980; Ledger et al., 1984; Walton et al., 1981). The timing of the release of uranium from volcanic glass and subsequent transport in groundwater determines how it moves through permeable units in the region, a critical factor in the location of economic deposits. Pedogenesis is thought to be more effective in releasing uranium into the groundwater and is consistent with the observation that uranium mineralization occurred early, predating early diagenesis in Catahoula-hosted deposits (Galloway and Kaiser, 1980; Walton et al., 1981). However, the importance of early release of uranium during pedogenesis is disputed (Ledger et al., 1984). In the Houston embayment, glassy volcanic material is less abundant and less pervasively altered than equivalent units to the southwest, limiting the potential uranium that could be released to groundwater in this region (Ledger et al., 1984), although this point is challenged (Galloway and Kaiser, 1980). During devitrification, ash is converted to clay, which decreases the permeability of sediments and therefore movement of uranium in groundwater (Ledger et al., 1984; Walton et al., 1981). Thus, the optimal source would contain sufficient uranium-rich ash diluted by adequate non-reactive content, such that resulting clays will not effectively seal released uranium within source sediments.

By analogy, analysis of uranium transport in modern groundwater may help to understand transport of uranium throughout the Tertiary. The geochemistry of groundwater sampled adjacent to roll-type deposits in Texas is characterized by naturally elevated concentrations of arsenic, cadmium, lead, radium and uranium (Hall, 2009). There is a positive correlation between modern groundwater that is supersaturated with respect to montmorillonite and uranium mineralization (Galloway and Kaiser, 1980). Groundwater in the Rio Grande embayment is characterized by higher total dissolved solids than the Houston embayment; however no predictable pattern of Eh or pH was noted (Henry et al., 1982). Groundwater geochemistry of samples was analyzed as part of the Department of Energy's National Uranium Resource Evaluation (NURE) program. Some systematic variations in sample values between map sheets are evident in the Houston embayment likely related to analytic techniques of different contractors who performed the analyses. However, variations related to analytic and sampling differences do not obscure an overall pattern of higher uranium concentration in groundwater measured from the Rio Grande embayment south of the San Marcos arch (Fig. 5). Detailed examination does not show a clear correlation of elevated uranium or other trace elements in groundwater with specific deposits or districts. Local dispersion of uranium from known mineral deposits is noted, but this is not a universal pattern. There are poorly defined plumes of elevated uranium concentration adjacent to historical mines in Karnes County and in groundwater up to about 15 km down-gradient of known deposits in the Duval mineral trend. Elevated uranium is noted up dip of the Ray Point district in the Oakville Formation (Henry et al., 1982). Uranium mineral equilibrium modelling was not successful in this region because of the lack of available chemical and physical parameters to constrain models.

Thick interconnected clastic sedimentary sequences with well-developed channel systems are the first-order controls on groundwater flow and by corollary, uranium transport in the region (Galloway et al., 1982; Winker et al., 1981). These channel systems range from bedload-dominated channels of low sinuosity to more sinuous, meandering mixed-load dominated channels. Within the Houston embayment, sinuous, meandering streams with carbonaceous overbank deposits and tuffaceous muds dominated the Jackson Group and fed a strand plain-barrier-bar system dominated the coastline (Fisher et al., 1970). To the southwest, fluvial sands diminish in importance, but strand plain systems continue to dominate the coastline (Fisher et al., 1970). Channels in the Catahoula Formation in the Rio Grande

embayment are bedload-dominated with low sinuosity and well-developed levee systems characterized by incised crevasse channels; whereas in the Houston embayment channels were sinuous to meandering mixed-load types (Galloway, 1977). Laterally continuous channel fill in this sandy braided system resulted in good to excellent sandstone continuity (Ambrose, 2007). The overlying Oakville Formation was a bedload-dominated fluvial system deposited by several major coastal river systems and streams that graded basinward into a mixed-load fluvial then barrier-bar and delta system (Galloway et al., 1982). In the lower Goliad Sand, the fluvial system was bedload dominated and deposited medium- to coarse-grained sandstones; whereas in the upper Goliad, channel fill resulted in fine-grained sandstone (Ambrose, 2007).

Regionally, groundwater flow is toward the coast. However, water also moves up dip, particularly adjacent to faulting, where connate waters flow upward in response to compactional loading (Fig. 6). Stacked, vertically and laterally connected paleochannels are critical in order to transport uranium at high enough concentrations and gradients to form economic deposits in this region. The largest deposits and longest reaction fronts are found in regions where thick permeable sands are interconnected (Adams and Smith, 1981).

Both basinward and upward flow of groundwater connects aquifers in the Catahoula Formation, Oakville Formation and Goliad Sand, providing the interconnection needed to distribute uranium through all three stratigraphic units. The best example of this is in the Duval mineral trend where successively younger deposits formed down-dip along interconnected sandstones deposited as part of the ancestral Rio Grande channel complex. In the trend, the mineralized interval ascends through stratigraphy, in places proximal to faulting. This pattern begins in the Bruni Mine cluster hosted in sandstone beds within the Fant Tuff Member of the lower Catahoula Formation, to the Holiday–El Mesquite mine hosted within sandstones of the Soledad Conglomerate Member of the Catahoula Formation. It continues to the Hebronville Mine cluster hosted in the lower Oakville Formation, and finally to Alta Mesa mine hosted in the Goliad Sand (Adams and Smith, 1981; Kurrus, 2016). The source of mineralization in this rich trend is presumed to be ash in the Catahoula Formation that was transported into adjacent host rocks through interconnected aquifers. This pattern may hold for other regions, for instance in the Casa Blanca deposit cluster or Clay West/Burns district, but detailed stratigraphic analysis needed to confirm this pattern of uranium transport has not been completed.

In detail, uranium occurrences in the south Texas Coastal Plain are found in the more permeable portions of their host units. In the Catahoula Formation, occurrences are found along NW-SE trends that correspond to ancestral drainage systems. In the Jackson Group, occurrences are more common where permeable ancient barrier island sands interfinger with overbank and lagoonal muds (Reynolds et al., 1982). Within fining-upward sequences uranium is generally higher grade in the basal coarser grained units. One example of this enrichment is illustrated by the uranium distribution at the Salvo deposit in the Goliad Sand where the highest grades, 2.5 m of 0.3% U_3O_8 , are recorded within the lowermost coarser portion of the fining-upward beds (Carothers, 2010). At Salvo, analysis of drill cuttings reveals abundant carbonized wood fragments deposited in the poorly sorted basal lower Goliad Sand (Kurrus, 2016).

Another component of an effective uranium roll front system is adequate energy to drive groundwater flow through aquifers. Along the Gulf Coast this energy is provided by regional sediment loading, subsidence and sea level fall. Regional dip and groundwater flow are influenced by sediment loading towards the Gulf of Mexico and isostatic uplift which tilts sediments upward towards land (Galloway et al., 1991). Fluctuating sea level stands during the Tertiary may also have been an energy driver for groundwater flow by rejuvenating fresh groundwater flow as the hydraulic head inland increased during intervals of sea level lowering. Lowering sea level would also deepen the

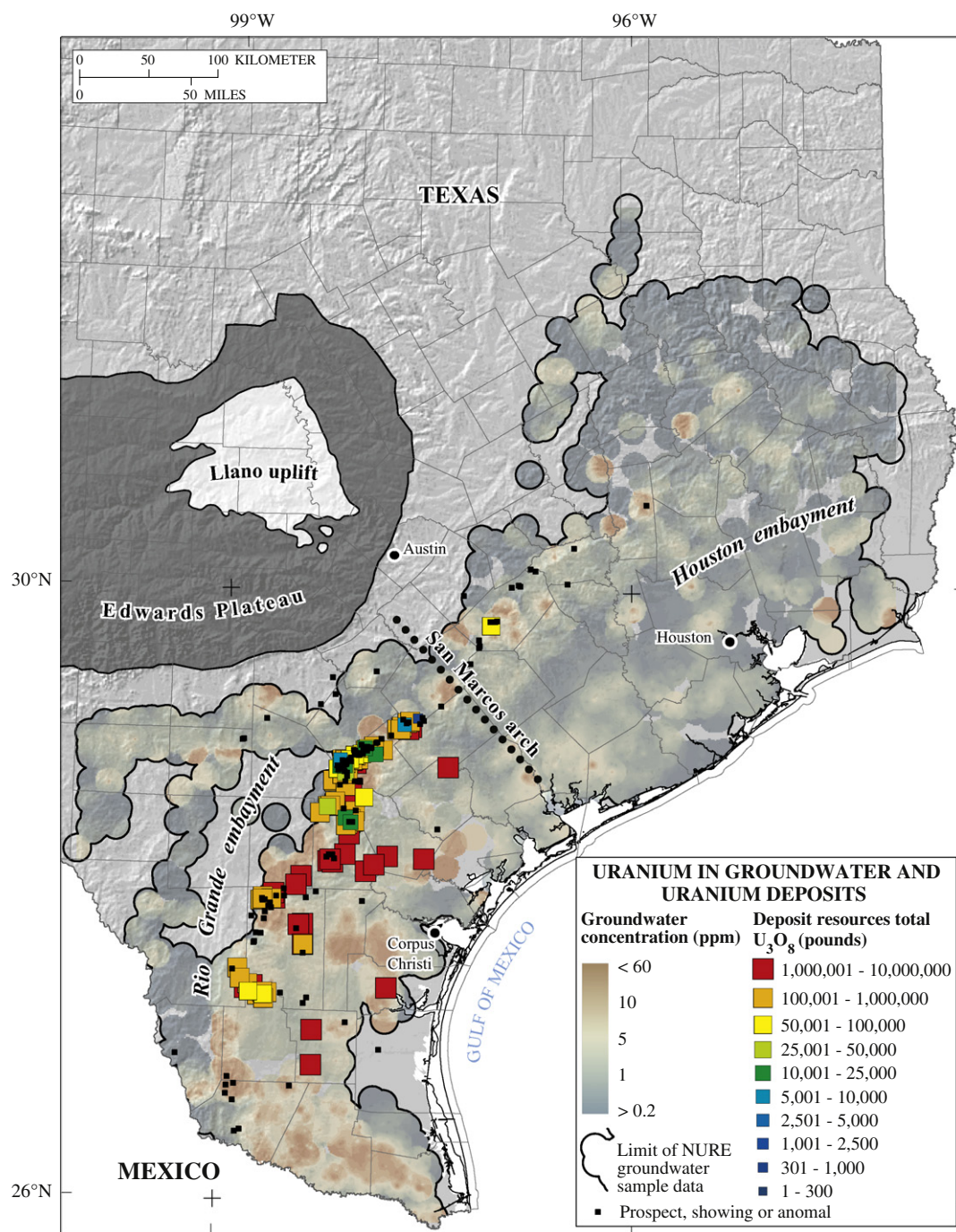


Fig. 5. Uranium in groundwater as measured during the NURE program and uranium deposits in the coastal plain of Texas.

effective oxidation zone by lowering the level or depth of groundwater. Sea level lowering (Vail, 1979) corresponds with deposits found in the Jackson Group, Catahoula Formation, and Goliad Sand. No sea level lowering is associated with mineralized intervals in the Oakville Formation; however, this unit is hydrologically connected with the Catahoula Formation so increased groundwater flow would influence both units. Some offlap sequences, such as those identified in the Pleistocene, do not correlate with known roll-type deposits, and may be used as exploration tools to identify potential mineralized sequences at a regional scale. The one firm age date for roll-type deposits in the Texas Coastal Plain (5.07 Ma as measured from the Oakville-hosted Felder deposit) supports a connection between sea level fall and mineralization as it corresponds to a coastal offlap episode caused by falling sea level in the Neogene. However, a lack of age dates for other roll-type deposits

in Texas precludes further analysis of a causal link between sea level fall and uranium mineralization.

Climatic variability through time may also provide a critical control on the genesis of roll-type deposits. Sedimentary sequences deposited during dry periods and in arid regions are more favorable to the development of roll-type deposits in the Texas Coastal Plain. Wet climates, such as those recorded in the upper Oakville Formation, Fleming Formation and upper Goliad, do not favor the formation of roll-type deposits. In the more humid, eastern portion of the Coastal Plain, uranium is sequestered in organic-rich facies that are common in rocks formed here. This may explain in part the lack of economic roll-type uranium deposits found in the Houston embayment. The only uranium deposit identified in the Houston embayment, the Washington-Fayette deposit, is described as the tabular sandstone type with a minor superimposed

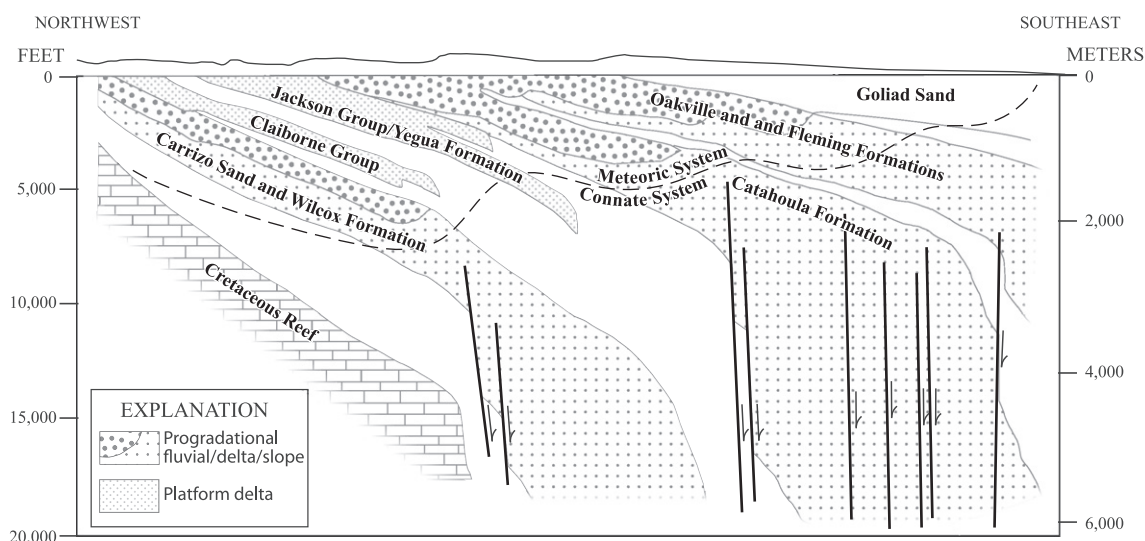


Fig. 6. Schematic cross section of Tertiary strata that host uranium mineralization in the Texas Coastal Plain illustrating the relationship between the connate and meteoric water systems as connate waters flow upwards along faults (vertical exaggeration approximately 250×) (modified from Galloway et al., 1982).

redox front (Galloway and Kaiser, 1980). In this deposit, uranium is entrained in organic-rich host rocks with only a minor portion available for mobilization into roll fronts. Roll-type deposits in Texas are preferentially formed in regressive sequences and arid environments in the late Oligocene (Catahoula Formation) and middle Pliocene (Goliad Sand) that are preceded by wet, transgressive sequences (Adams and Smith, 1981). The relationship between climate and uranium roll-type deposits is speculated to be related to a lack of organic debris within clastic sedimentary sequences due to low biologic productivity in the arid climate that characterized the Rio Grande embayment during and after the Oligocene. More organic debris within sediments entrains uranium, reducing the overall availability of uranium to groundwater in quantities needed to form economic roll-type deposits.

5.3. Uranium Traps

Solubilized uranium is transported in oxygenated groundwater until buffering in sediments exhausts oxygen and reducing conditions and/or reactive substrates are encountered. In the southern Texas Coastal Plain, both extrinsic gasses or connate fluids and intrinsic reducing sedimentary facies control the location of roll-type deposits (Carothers, 2010; Classen, 1981; Reynolds et al., 1980a, 1982).

5.3.1. Intrinsic Reductants

Intrinsic reductants are sedimentary facies that are capable of changing the Eh of groundwater sufficient to reduce uranium to its insoluble form. In addition, in some areas uranium adsorbs onto organics within sedimentary facies. Within host sandstones, intrinsic reducing facies include overbank deposits formed by crevasse splays that are found adjacent to paleochannel systems (Catahoula Formation) and interfingering lagoonal muds and strand-line sands found in barrier island sequences (Jackson Group). Deposits formed from intrinsic reductants typically contain measurable organic carbon. In some channel sandstones, deposits are richest where a facies change from very permeable channel sands interfinger with muddy organic-rich overbank deposits along the flanks of the channels. This control may be related to fluid flow, the presence of organics in overbank deposits or both. Intrinsic reductants are most commonly associated with mineralization in the Jackson Group, and the channel margin facies of the Catahoula Formation.

5.3.2. Extrinsic Reductants

Extrinsic reductants are an important control of roll-type deposits in some portions of the basin, and dominate in Catahoula- and Goliad-

hosted deposits. Considering the well-developed petroleum systems in this portion of the Texas Coastal Plain, fluids related to these petroleum systems would be a logical choice to supply reductants to potential host rocks, and it is useful to place them in this context. The exact nature of extrinsic reductant is poorly understood, and has been described variously as oil-field brine, saline fluid, and connate water. Most south Texas uranium exploration geologists believe there is a definitive correlation between uranium deposition and shallow gas (Kurrus, 2016). Hydrogen sulfide is commonly reported during exploration and development drilling programs in the Texas Coastal Plain, and in some cases is so abundant blow-out preventers have been used on uranium exploration drill rigs (Adams and Smith, 1981; Klohn and Pickens, 1970). Hydrogen sulfide in the Rio Grande embayment could have formed either by sulfate reduction during diagenesis or thermochemical gas generation at higher temperatures (>80 °C) during catagenesis (Machel et al., 1995; Rice and Claypool, 1981). Natural gas also typically contains carbon dioxide and methane; however, uranium deposits in the Catahoula and Goliad commonly contain very low carbon which indicates methane is either not an important component of reductants in these areas or is transient.

Transport of reductants into host sediments by connate or oil-field-related brines is the favored method based on studies of modern groundwater near known uranium districts (Galloway et al., 1982; Henry and Kapadia, 1980; Orr, 1977). After they have formed, carbon dioxide and hydrogen sulfide are selectively and efficiently mobilized from oil and gas reservoirs by connate brines. The solubility of methane in brines is significantly lower and could also explain a lack of methane (carbon) within host rocks of uranium deposits thought to be related to external reductants. A study of the deuterium and oxygen isotope composition of modern groundwater at the Ray Point district (Oakville host) shows meteoric water is mixing with deep oil-field related saline waters (Goldhaber and Reynolds, 1991; Goldhaber et al., 1983). In this and similar host rocks an interface between reducing brines and oxidizing uranium-rich groundwater may form, with roll-type deposits forming close to this interface. At Ray Point, isotopically heavy sulfides close to underlying petroleum source rocks characterize portions of the deposit and indicate a petroleum system source for reducing fluids (Goldhaber et al., 1983). Other sulfide phases record the influence of sulfate-reducing bacteria by a broad, negative sulfur isotope signature. The divergent signatures could be explained by temporal variations wherein bacterial sulfide reduction occurred during early diagenesis, and heavy sulfides formed later when oil-field-related brines infiltrated the sediments. The sulfur isotope signatures can also be explained by an active mixing

zone characterized by pulses of extrinsic, oilfield-derived reducing fluids that react with groundwater within the uranium host Oakville Formation.

The presence of a dynamic, fluctuating zone where reducing connate brines and uranium-rich groundwater mix explains why some roll fronts are encased in reduced sediments. Periodic influx of oil-field brines or decrease in meteoric water flow may force the reducing reaction front beyond that responsible for deposit formation. In this scenario, a uranium roll-type deposit would become a static feature encased in fully reduced host rock. Throughout the region many roll-type deposits, particularly those hosted by the Oakville Formation and Goliad Sand, are encased in reduced sediment which has halted the movement of roll fronts. Within the Goliad Sand, the main producing unit at the Alta Mesa Mine, upper portions of the Burke Hollow deposit and some of the roll fronts at the Palangana deposit are located within reduced sediments. These re-reduced deposits are generally located proximal to faulting (Kurrus, 2016).

In response to the introduction of external reductants, iron disulfide mineral phases form from iron present within host rock (Adams and Smith, 1981; Eargle and Weeks, 1961; Galloway, 1981). Sulfides form at the expense of detrital iron-titanium oxides and silicates including ilmenite and titanomagnetite (Adams and Smith, 1981; Arredondo and Thomann, 1996; Bomber et al., 1986; Reynolds and Goldhaber, 1978). Sulfides then act as reductants for uranium carried into the environment in groundwater. In detail, there is a strong correlation between titanium, likely from titanium oxide precursor minerals, and uranium reflecting this paragenetic sequence. Calcium carbonate noted in the vicinity of roll fronts at the top of ore-hosting sandstones and along faults zones, may have formed near the brine/water interface (Galloway et al., 1982). The carbon isotope composition of carbonates collected from the Ray Point and George West districts hosted in the Oakville Formation indicates these carbonates formed at a mixing zone from a mixture of isotopically light carbon associated with faults that reflects a hydrocarbon origin and meteoric water or pedogenic carbon source (Galloway et al., 1982). Carbonate may characterize the brine/water interface in a more widespread fashion, but carbonate is only coincident with mineralization in locations where meteoric water contains dissolved uranium or in host sediments with sufficient iron-titanium oxides to form iron disulfide minerals that maintain local reducing conditions.

Extrinsic reductants were likely introduced into host rocks through structural pathways. In the Texas Coastal Plain, most uranium occurrences (over 70%) are found within 2 km of a regional fault (Fig. 7), and many are found proximal to structural highs, such as salt domes and shale diapirs, particularly in the Goliad-hosted deposits (Arredondo, 1991; Carothers, 2008; Kurrus, 2016). At the Bruni Benavides deposit (lower Catahoula host) iron titanium oxides are chemically reduced to sulfide within 1.5 km of a fault that transects the deposit. This provides a finite spatial context that reducing zones typically develop within 2 km of faults, and that many deposits will also be found within this reducing zone (Goldhaber et al., 1978).

To determine if the location of oil or gas fields was predictive of uranium deposit clusters, these locations were compiled and compared to known uranium deposits. While there is a broad regional association of oil and gas trends and uranium deposits within the Texas Coastal Plain, in detail there is a negative correlation between known uranium deposits and individual oil and gas fields (Fig. 8). This inverse relationship is probably related to the local migration of hydrocarbons. In areas without geologic features that trap hydrocarbons and associated formation brines, these reductants move upward through permeable sediments, along faults or the flanks of structural domes into overlying Tertiary sediments. As a result, overlying sediments are chemically reduced. In locations where there are geologic conditions that would trap hydrocarbons and form oil and gas fields, this leakage would not occur and overlying sediments would not be affected. The movement of gas into shallow sediments that host uranium deposits is more complex than can be resolved by a regional analysis.

6. Roll front systems in the Texas Coastal Plain

The characteristics and deposit controls of uranium deposits in the Texas Coastal Plain, described in general above, vary in detail within each successive stratigraphic host sequence. Important genetic parameters including source, transport, trap, preservation and general indicators of potential for more deposits are discussed below by host unit in ascending stratigraphic order. When considering deposits formed in proximal deposit clusters and uranium trends, such as the Duval mineral trend, genetic factors that form one set of deposits may be related to deposits found in adjacent host units. In these cases, the discussion of deposit controls spans the stratigraphic host unit.

6.1. Early to middle Eocene occurrences

There are 9 uranium occurrences in the lower to middle Eocene Wilcox Formation and Claiborne Group (Carizzo Sand, Queen City Sand, and Laredo Formation); 4 prospects and 5 radioactive anomalies (Figs. 3 and 9, Appendix 1). The paleochannel locations in Figs. 9–12 and 14 are defined by Galloway et al. (2000). No economic deposits have been identified in early to middle Eocene sediments within the Texas Coastal Plain.

In the Wilcox Formation, a radioactive anomaly and prospect are identified west of the San Marcos arch. No anomalies are known to be ore-grade in this region. The Wilcox Formation contains abundant lignite, which can contain trace uranium when a local uranium source is available, and is considered an unconventional uranium resource. The occurrences identified in the Wilcox Formation are likely attributable to trace uranium commonly found within lignite beds.

Three prospects and four radioactive anomalies are identified the Claiborne Group (Fig. 9, Appendix 1). The Claiborne Group is a series of fluvial-deltaic and marine sediments, with a barrier-bar system developed adjacent to the San Marcos arch. Most occurrences are located within the Queen City and Carizzo Sands adjacent to the arch within the barrier-bar facies, and one prospect is identified in the Laredo Formation, in the lower shoreline-facies of a barrier-bar system. Uranium occurrences were likely reduced by intrinsic reductants within this barrier-bar sequence. The uranium source for these occurrences could have been (1) sparse ash layers interbedded in Claiborne Group sediments, (2) overlying ash-rich units where they were hydrologically connected to sandstone host units, or (3) uranium-rich rocks provided to the area by the Colorado mega-channel or weathered from rocks exposed on the San Marcos arch. During the early and middle Eocene, the major fluvial input into the region was the Colorado mega-channel—a well-developed channel complex that was centered near the San Marcos arch. This system supplied sand for barrier-bar sequences as well as potential uranium source rock in the form of weathered uranium-rich granites. Known occurrences within the Claiborne Group are spatially clustered adjacent to identified uranium-rich granites in the Llano uplift that are exposed along the San Marcos arch about 120 km from the ancestral shoreline. Supporting a uranium and clastic sediment source from the Llano uplift, studies of the Carizzo Sand and Queen City Sand concluded that both units contain sediment derived from a similar igneous/metamorphic source, although that source is not directly tied to rocks in the Llano uplift (Adams and Smith, 1981; Calender, 1958). The Trans-Pecos region was not as active during the early to middle Eocene as it was during the late Eocene and Oligocene, and uranium input from this important source was minimal at the time when sediments of the Claiborne Group were deposited. A lack of locally productive uranium source rocks may limit the potential for the formation of economic uranium deposits within the Claiborne Group.

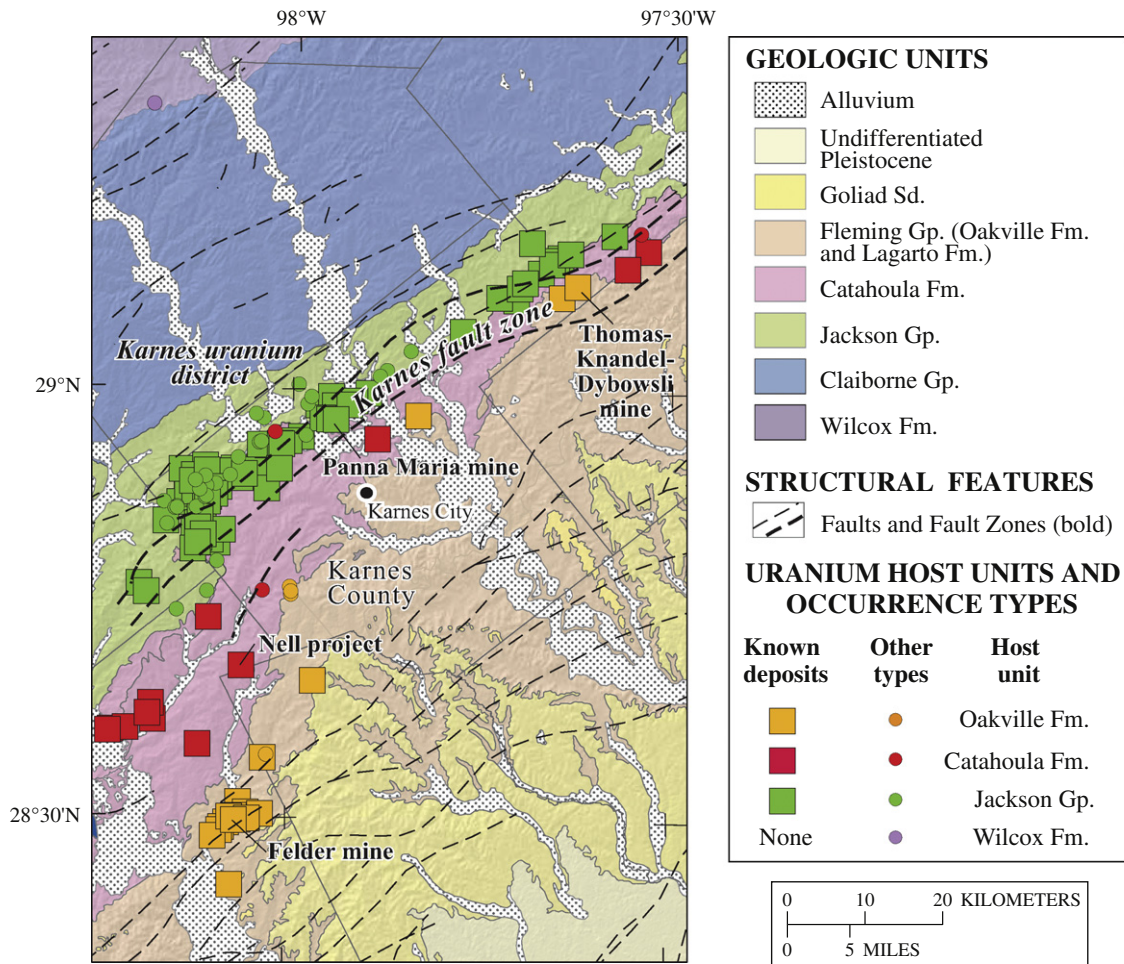


Fig. 7. Example from the Karnes County uranium district illustrating the positive relationship between most uranium occurrences and faulting in the region.

6.2. Eocene Jackson Group occurrences

There are 117 uranium occurrences in the Jackson Group; 76 deposits, 39 prospects, and 1 showing, including one tailings facility that has reported production from Jackson Group ore (Figs. 3 and 10, Appendix 1). Forty-seven deposits produced uranium, and one of these contains additional in-place resources. In addition, 11 unmined deposits remain with identified resources. The total resources of individual deposits range between 900 pounds and 5 million pounds of U_3O_8 (Appendix 1). Predominantly open pit mines were developed immediately east of the San Marcos arch, in southern Karnes and adjacent Atascosa and Gonzales Counties. Discovered by airborne radiation anomalies, the first deposits mined in Texas were tabular, oxidized deposits in the Whitsett Formation of the Jackson Group. Beginning in the mid-1950s until 1964, relatively small open pit mines yielding about 200,000 t of ore averaging 0.20% U_3O_8 , exploited outcropping mineralization in Karnes County (Eargle, 1956). Larger, lower-grade roll-type deposits along fronts up to 10 km long were found southeast of outcropping deposits and many of these were mined later via open pit methods. Three ISR mines were developed in the Jackson Group. In at least two of the mines, the Tex-1 and Hobson deposits, ISR mining was unsuccessful because marine and marginal marine muds and clays, both interstitial and as clay or mud lenses intercalated within host sands in the Jackson Group, reacted with leachate solutions altering the pH of the lixiviant, and reducing permeability (Kurrus, 2016). In addition to the occurrences in Appendix 1, there may be a number of remaining unmined Jackson trend deposits which were beyond the transport limit of the

now decommissioned uranium mills in the area or below the depth limit for economic open pit mining.

The Jackson Group was deposited in a marginal marine setting. East of the San Marcos arch in the Houston embayment the Jackson Group is a series of deltaic sands, muds and some lignites. West of the San Marcos arch in the Rio Grande embayment the Jackson Group is characterized by strand-plain barrier-bar systems cut by channel sands (Fisher et al., 1970). Uranium is found in sand lenses within the Dilworth, Deweesville and Tordilla Sandstone Members of the Whitsett Formation within the Jackson Group. These sands are separated by unmineralized silts, clays and lignites. Ore is distributed in the coarsest grained, most permeable units within the barrier-bar/delta sequence. Jackson-hosted deposits are all found where the thick strand-plain sand sequences interfinger eastward into reducing marsh deposits and lagoonal muds (Dickinson, 1976; Fisher et al., 1970). Uranium is also found in lignite (up to 0.45% U_3O_8) where it directly overlies mineralized sandstone (Reynolds et al., 1982). Cross-cutting, dip-oriented channel sands are not mineralized which suggests they may have acted as conduits for uranium-rich groundwater (Fisher et al., 1970).

Mineralization parallels the paleocoastline, mirroring the geometry of thicker sand units adjacent to and southwest of distributary channels and fan/delta systems (Galloway et al., 1979). The orientation of roll fronts within permeable sand units shows considerable variability, which may reflect the complexities of local groundwater flow (Adams and Smith, 1981). Uranium occurrences are found both east and west of the San Marcos arch, between the axes of the Houston-Brazos and Rio Grande paleochannel complexes (Fig. 10). Economic deposits are

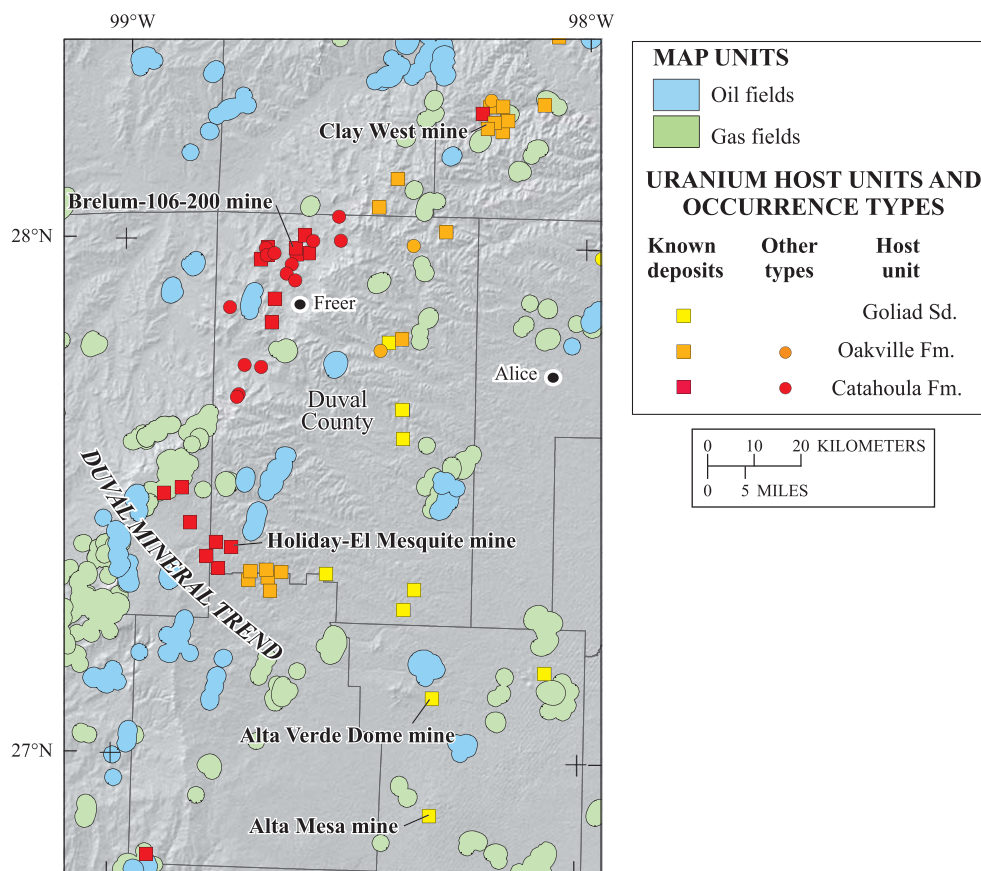


Fig. 8. Identified mineral deposits and oil and gas fields in the Duval mineral trend showing that at the district scale, deposit locations and known oil and gas fields are negatively correlated.

currently restricted to an area just west of the arch within a barrier–bar system that formed north of the Rio Grande channel complex adjacent to the San Marcos arch. No economic deposits have been found in the deltaic portion of the Jackson Group in the Houston embayment where subeconomic uranium is found in lignites, carbonaceous mud and thin sand (Fisher et al., 1970). Southward, where the Rio Grande paleochannel interrupts the barrier–bar depositional environment, uranium deposits are not found within mudstones that crop out south of Atascosa County (Fisher et al., 1970). The barrier–bar system continues south to the Mexican border, however the critical interface between the lagoon and barrier–bar facies does not crop out and it is unknown if this region has been thoroughly tested for mineralization (Galloway et al., 1979). Where the barrier–bar system outcrops occur again southward in Starr and Zapata Counties, economically significant uranium deposits have not been discovered to date.

6.2.1. Source

Volcanic ash interbedded in the Jackson Group is a potential source for uranium in Jackson Group hosted deposits (Weeks and Eargle, 1963). The Trans-Pecos volcanic field was becoming more active during the late Eocene. This increased volcanic activity is recognized at the lowermost contact of the Jackson Group where a distinctive white volcanic ash is used to identify the contact between the Jackson and underlying ash-poor Claiborne Group (Eargle, 1968). Tuffs interbedded in the Jackson Group are found close to mineralization and may have acted as a local source for uranium occurrences (Fisher et al., 1970; Weeks and Eargle, 1963). Alternatively, uranium may have been derived from the overlying Catahoula Formation, and migrated into the Jackson Group through gravel-filled channels that cut into sandstones of the Jackson Group in the Karnes area (Eargle, 1970). Despite an extensive system of coupled transmissive and reducing sediments with a barrier–bar system that favored the formation of roll fronts, deposits have only been

identified north of the Rio Grande mega-channel. In this area, the Frio Formation is eroded and the Catahoula Formation (a potential uranium source) rests unconformably on the Jackson Group and may be an important factor in localization of deposits in this area (Weeks and Eargle, 1963). If the source of uranium is the overlying Catahoula, deposits would only be expected to form in the Karnes County district where permeable sandstones of the Catahoula were in direct contact with the Jackson Group. In other areas where this hydraulic connection is interrupted, such as by the Frio Formation in the Duval mineral trend, the Jackson would not be mineralized (Adams and Smith, 1981).

Another potential source that may explain the regional clustering of known occurrences is the weathering of sediments from the San Marcos arch. Known uranium-rich source rocks of the Llano uplift were located about 150 km inland of the paleoshoreline during the late Eocene. Similar to the underlying Claiborne Group, uranium occurrences cluster adjacent to channels that supply sediment from uranium-rich rocks of the arch. However, unlike the scenario in the underlying Claiborne Group, the major fluvial input axis shifted south to the Rio Grande channel complex, and the dominant sediment supply was no longer transecting the San Marcos arch. If the uranium source was from sediments exposed in the San Marcos arch, deposits could have been limited to an area of influence around local paleodrainage systems that drain the arch and may have been dispersed southwestward by the prevailing longshore current along the paleocoastline (Fisher et al., 1970). Both sources cannot be unequivocally eliminated, and both scenarios can explain the distribution of deposits and remain as working hypotheses.

6.2.2. Transport and Trap

Uranium was transported in groundwater through dip-oriented channels into permeable barrier–bar sands in the Jackson Group. The negative association of deposits with channel sands may explain the lack of deposits where the Rio Grande paleochannel influences Jackson

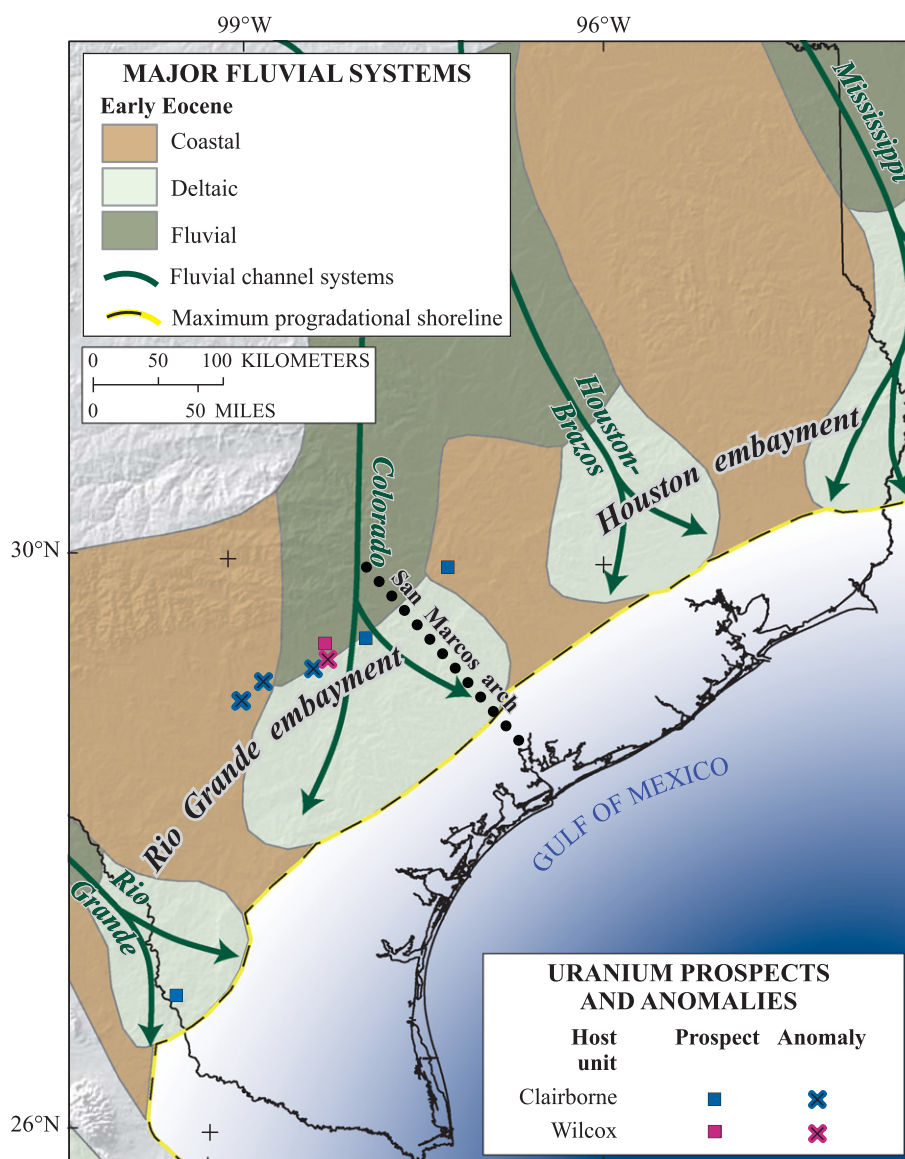


Fig. 9. Uranium occurrences hosted in the Eocene Wilcox Formation and Claiborne Group in relation to the major fluvial channel complexes and the paleodepositional environment during the early Eocene.

Group sediments at the southern end of the Karnes County deposit cluster (Fisher et al., 1970) (Fig. 10). A significant source of sediment for transmissive sediments of the barrier-bar system was from a local channel in central Karnes County, which supplied sediment to form a greater than 120 meter thick sequence of stacked and interfingering strand plain and barrier-bar sands that host deposits (Fisher et al., 1970).

A number of factors combine to support the importance of intrinsic reductants in deposits formed in the Jackson Group. The high organic content of uranium, for example averaging 0.42 weight percent at the Panna Maria deposit, contrasts markedly with analysis of deposits found in the overlying Catahoula Formation and Oakville Formation that contain negligible carbon (Dickinson and Duval, 1977; Reynolds et al., 1982). Regionally, uranium is associated with carbon-rich facies, and a relationship between organic debris and uranium in core samples is observed. Externally derived hydrocarbons are not indicated in host rocks. These factors lead to the conclusion that uranium was reduced by pyrite-rich geochemical cells formed around organic-rich lagoonal and marsh facies (Fisher et al., 1970; Reynolds et al., 1982). These pyrite-rich portions of the host rock may have formed by bacterial sulfate reduction, which is supported by the negative and variable isotopic

range of pyrite, -1 to -34 ‰ $\delta^{34}\text{S}$ and presence of pyrite framboids (Reynolds et al., 1982). Where analyzed, isotopically heavy sulfur, from extrinsic sources, is absent (Reynolds et al., 1982). The relative absence of marcasite in Jackson Group deposits also supports intrinsic reductants, as marcasite is not favored where abundant carbon in sandstones creates a higher pH environment (Reynolds et al., 1982). These lines of evidence support the importance of intrinsic reductants to the location of uranium deposits in the Jackson Group (Reynolds et al., 1982).

6.2.3. Preservation and potential

Outcropping deposits were mined in Karnes, Live Oak, Atascosa and Gonzales Counties. Deposits are oxidized to about 25 m in depth, and are partially weathered. The uranium is in strong disequilibrium indicating it has been recently mobilized (Eargle et al., 1975). In this region, most deposits are found associated with northwest-trending faults, within a graben in the Karnes fault zone defined by the Falls City fault to the north and Fashing fault to the south (Eargle et al., 1975). This fault system may have helped to preserve these deposits by down-dropping them to limit exposure and erosion due to surface weathering. Potential for concealed deposits exists where the mineralized interface

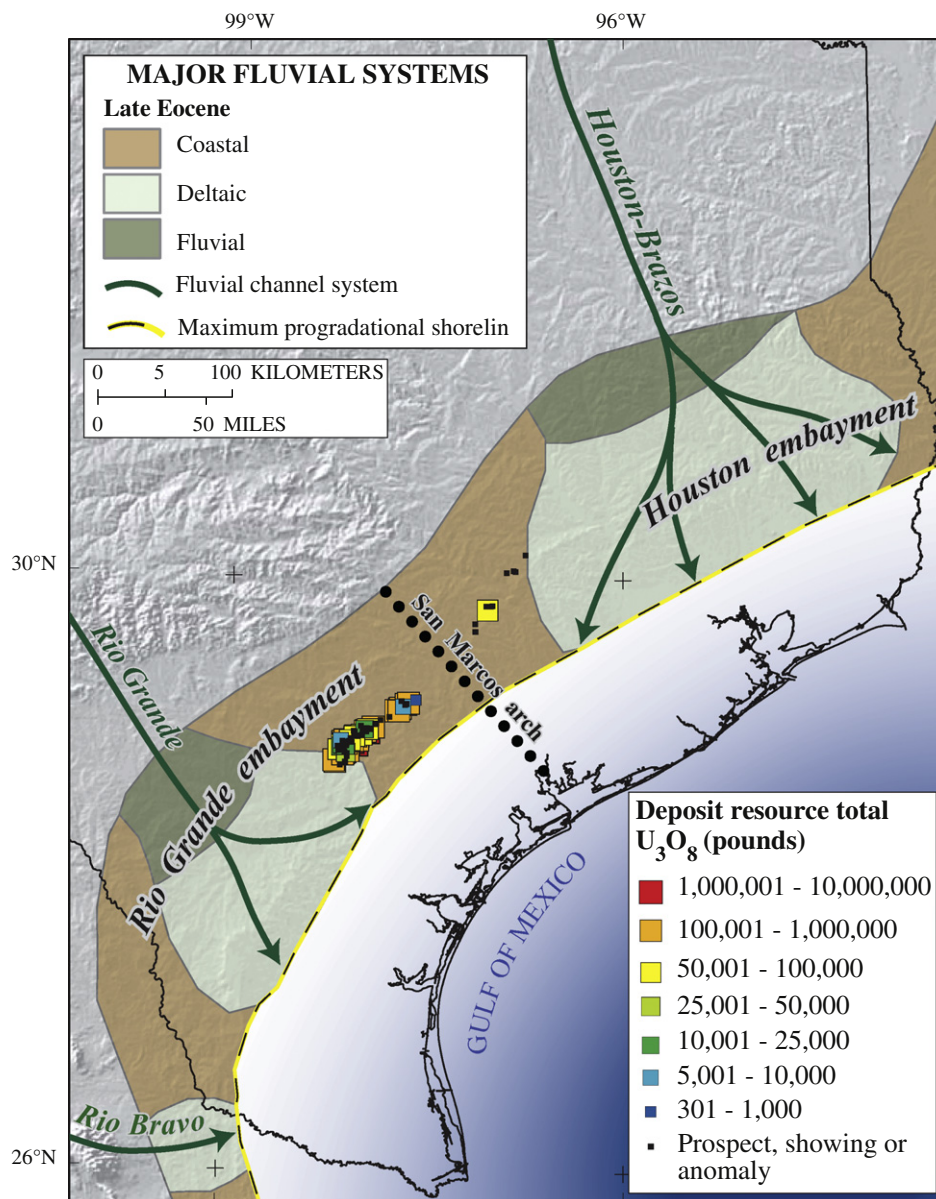


Fig. 10. Uranium occurrences hosted in the Eocene Jackson Group showing the relative size of deposits with known resources in relation to the major fluvial channel complexes and the paleodepositional environment during the late Eocene.

between barrier sands and lagoonal sediments is not exposed southwest of identified deposits, particularly in areas where tuffs in the Catahoula Formation are in contact with transmissive sediments of the Jackson Group. However, this potential may be limited by the influence of the Rio Grande channel system where deposits would not form because the continual flow-through of oxidizing groundwater would remobilize uranium (Fisher et al., 1970).

6.3. Oligocene Catahoula Formation occurrences

There are 62 uranium occurrences in the Catahoula Formation; 41 deposits, 17 prospects, and 4 showings (Figs. 3 and 11, Appendix 1). Uranium was produced from 14 deposits, 2 of these contain additional resources that have not been produced and an additional 12 deposits contain identified in-place resources. The resources in Catahoula-hosted deposits range in total size from 23,000 to 6 million lbs U_3O_8 (Fig. 11, Appendix 1). Seven ISR mines were developed in the Duval mineral trend, and nine open pit mines in the Karnes County and Ray Point districts. Deposits formed in a variety of geologic environments,

responding to both intrinsic and extrinsic reductants and the ore habit is described as both tabular and of the roll-type. Almost 90% of production from the Catahoula is from the Duval mineral trend where mineralization is associated with the thickest and coarsest sands, within which isolated uranium pods form within even less permeable siltstone beds and lenses (Galloway, 1977). The Catahoula Formation contains the thickest volcanic ash sequences within Tertiary units in Texas; however, the Catahoula has produced surprisingly little uranium considering the large volume of potential source material (Table 2). This disparity may be due to discontinuous and low permeability within the formation. The very ash that provides uranium to the region may also be responsible for limiting the formation of economic deposits by creating impermeable clay-rich lenses and beds after ash alters to clay during early burial diagenesis thus limiting uranium transport.

6.3.1. Source

The uranium source for these deposits is most likely the abundant volcanic tuffs found in the Catahoula Formation. Uranium may also be derived from lithic clasts derived from local weathering of the

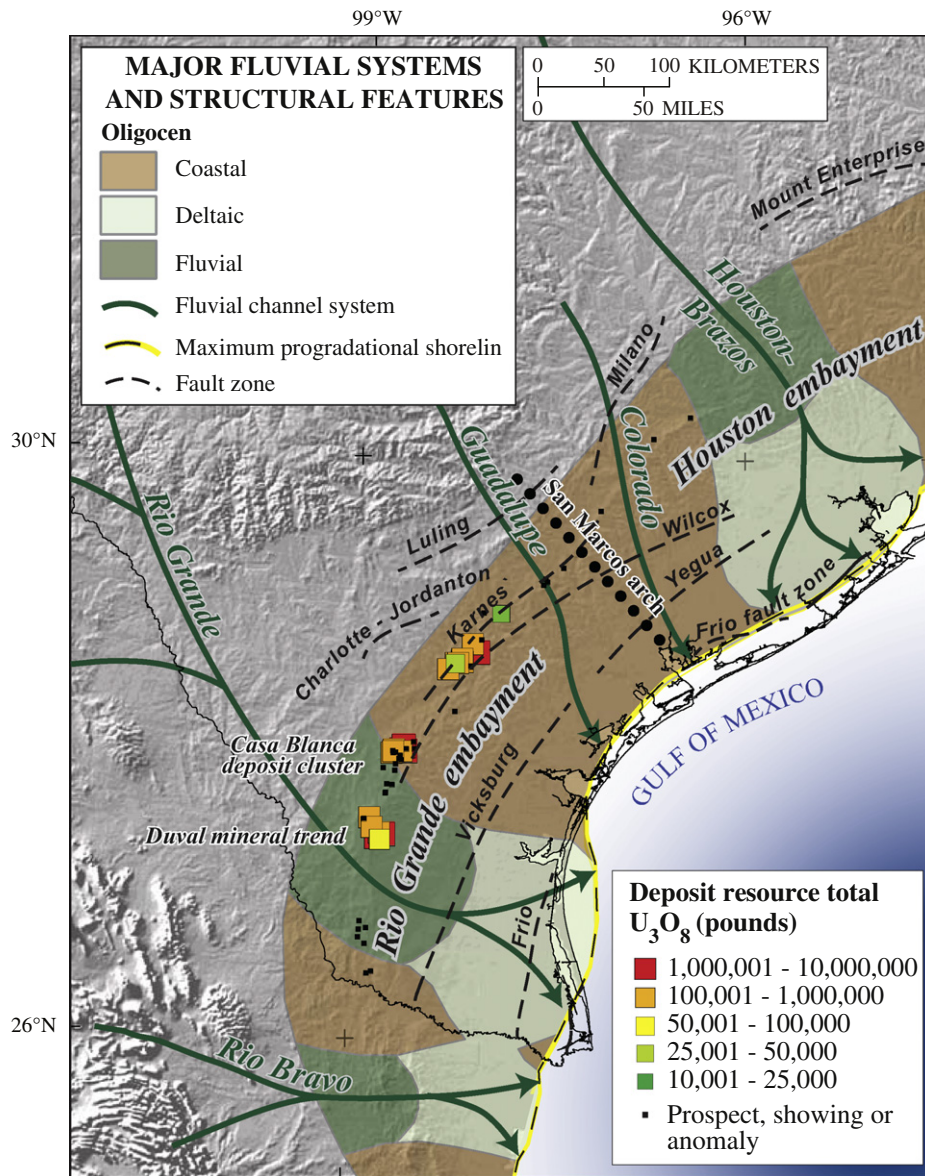


Fig. 11. Uranium occurrences within the Oligocene Catehoul Formation showing the relative size of deposits with known resources, Oligocene paleochannel complexes, the paleodepositional environment and major fault zones.

Catehoul. An additional uranium source could be clastic sediments derived from inland areas including the Colorado Plateau and Rocky Mountain regions with their numerous volcanic fields, and from the Rio Grande rift basin, all typified by periodic volcanic activity, regional crustal uplift and erosion (Galloway et al., 2011; McBride et al., 1968).

6.3.2. Transport and trap

Uranium transport in the Rio Grande embayment would be within Catehoul Formation sediments deposited by low sinuosity, bed-load dominated channel fluvial systems. Sediments deposited by mixed load, sinuous fluvial systems in the Houston embayment would be less favorable for transport via groundwater (Galloway, 1977). Downdip, the Catehoul Formation grades into the Frio Formation and Anahuac Shale that were deposited in an offshore marine setting; a setting that would not support the fluid flow necessary for roll-type deposits. During the Oligocene, the major sediment influx into the Texas Coastal Plain was through the Rio Grande and Rio Bravo fluvial axes in the Rio Grande embayment (Fig. 11) (Galloway et al., 2011). Sandstone thicknesses greater than 300 m are reported from the Rio Grande ancestral channel complex in central Duval County (McBride et al., 1968).

Fluvial channels in this region are about 5 km wide, and are flanked by broad, expansive crevasse splays, typically 15 m thick, that contain narrow anastomosing channels (Galloway et al., 1979; Galloway and Kaiser, 1980). Uranium was transported through permeable channel sandstones, with most deposits located along the flanks of large fluvial channels. Some of the largest deposits are found within the coarser grained members of the Catehoul Formation; the Holiday–El Mesquite and Benavides deposits in the Soledad Conglomerate, and the O'Hern and West Cole deposits in the sandy Fant Tuff Member (Kurrus, 2016). The Catehoul was deposited during a regional regression that corresponds to a worldwide lowering of sea level 25 to 30 million years ago (Vail et al., 1977). This regression may have rejuvenated groundwater flow through sandstones within the Catehoul and hydrologically connected units, providing the energy needed to transport uranium at a rate high enough to form economic deposits (Adams and Smith, 1981).

By the Oligocene, a strong climatic difference was established between east and west Texas that persists today. The Rio Grande embayment was typified by an arid to semiarid environment which transitioned eastward to a subtropical environment in the Houston

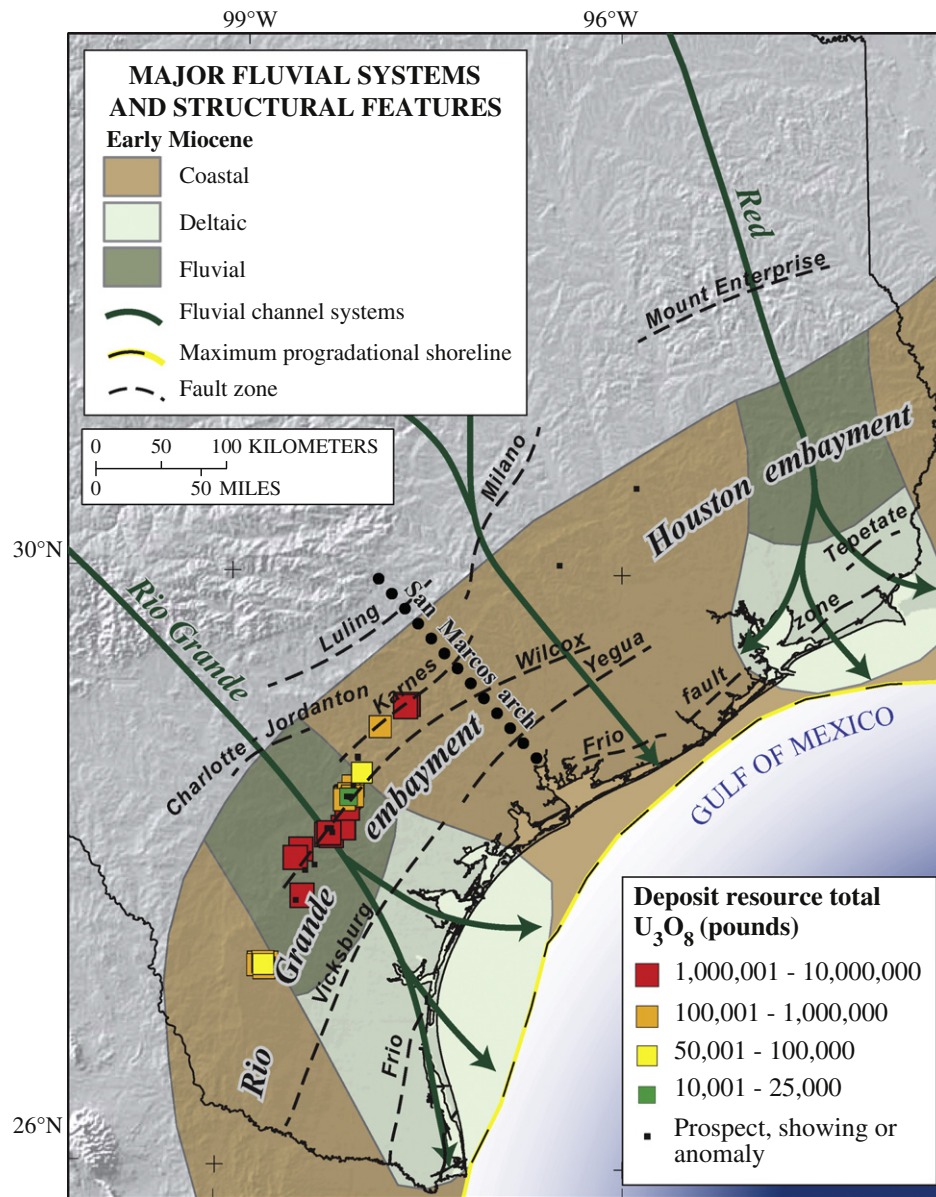


Fig. 12. Uranium occurrences within the early Miocene Oakville Formation showing relative size of deposits with known resources, ancestral paleochannels, paleodepositional environment and major fault traces.

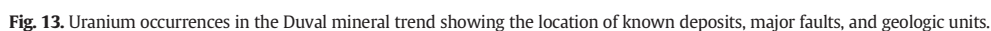
embayment (Galloway et al., 2011). The more arid environment in the Rio Grande embayment favored transport of uranium in oxygenated groundwater. In the humid Houston embayment, more abundant organic matter was available to sequester uranium and the high gradients necessary for economic roll-type deposits did not develop explaining in part the lack of uranium deposits in this region.

Roll-type deposits in the Casa Blanca cluster parallel the NW-SE trending Wilcox fault system (Fig. 11) (Adams and Smith, 1981; Galloway, 1978). In other places roll fronts do not follow fault traces. One example is in the Duval mineral trend where extensive alteration fronts can be traced for more than 8 km paralleling facies changes at the edges of fluvial channel sands (Galloway, 1977; Galloway and Kaiser, 1980). In the Karnes County district, roll front geometry is poorly developed with deposits found in sand lenses within coastal lakes. Throughout the Catahoula, mineralization is believed to be an early process, interrupted when altered ash reduced permeability and groundwater could no longer move freely through sands (Galloway, 1977).

Both intrinsic and extrinsic reductants appear to have been important. Reductants include organic debris, humates and iron sulfides that

formed syngenetically or from extrinsic sulfide emanating from deeper sources (Galloway and Kaiser, 1980). Pyrite is thought to have formed both before and after mineralization from sulfur-rich water that migrated into the area through permeable sands originating from deep-seated growth faults about 2 km away from known deposits (Galloway and Kaiser, 1980; Goldhaber et al., 1978). Sulfide or organic rich mudstone overbank deposits adjacent to sands deposited in crevasse splays provide intrinsic reductants in some deposits (Brewster, 1982). In the Ray Point district and north to the Karnes County district, a number of small deposits formed adjacent to reducing mudstones of the Frio Formation within tuffaceous crevasse splays that were deposited in coastal lacustrine environments (Galloway, 1977; Galloway and Kaiser, 1980). In this area roll fronts are erratic, can be traced for a few hundred meters up about 5 km. They are hosted in gray, pyrite-rich sediments without the reduction/oxidation fronts that typify roll-type deposits (Galloway and Kaiser, 1980). North of the Duval mineral trend in the Casa Blanca deposit cluster, shallow, high-grade uranium (0.1 to 0.2% U_3O_8) forms small deposits ranging from 0.3 to 1 m thick, and 45 to 60 m wide. The strike length can extend up to 1000 m. The uranium is typically

in the Houston embayment is described as a roll-type deposit with tabular ore zones associated with carbonaceous and humate-rich reductants developed at the edge of a large crevasse splay (Galloway and Kaiser, 1979, 1980). These relationships illustrate the importance of interconnected channelized fluid flow and intrinsic reductants in the formation of the deposits. In other areas, deposits are found associated with large faults or faults and associated permeable sands that



introduced reductants, most likely from Oligocene oil and gas fields located to the southeast of uranium occurrences. This is illustrated by deposits in the Duval mineral trend that are located where the Wilcox fault system transects the Rio Grande channel complex.

6.3.3. Preservation and potential

Shallow deposits in the Catahoula Formation are locally being actively oxidized and weathered, but this is limited by the low permeability that now characterizes the host rocks. Uranium deposits formed within portions of the formation that were deposited in ash-rich crevasse splays have been essentially sealed in place by post-mineralization alteration of the ash that has reduced permeability (Galloway, 1977) and made ISR mining difficult. ISR mining of Catahoula Formation deposits was attempted in northern Live Oak County at the Nell deposit, and in northern Duval County at the Brelum and Piedra Lumbre deposits. In each of these areas, low permeability resulting from diagenetic alteration processes inhibited formation of uranium and mining of these

deposits, and uranium recoveries were poor (Kurrus, 2016). In deposits formed by extrinsic reductants and where gas or reducing groundwater continues to move into sandstone host rocks, uranium fronts remain immobile – in places reaching radioactive equilibrium (Galloway and Kaiser, 1980). This is the case at the cluster of deposits associated with the Wilcox fault system in northern Duval County and in the Ray Point district.

Potential mineralization is limited by downdip reducing conditions related to Oligocene oil and gas fields and the transition of transmissive sandstones to impermeable Anahuac Shale and Frio Formation. Also important is the degree to which permeability is reduced by post-depositional alteration of ash. Uranium resource potential could exist along smaller ancestral drainage systems throughout the region that may have retained their permeability in coarser-grained portions of the channels. This potential may be particularly high south and downdip of the Duval mineral trend, and may not have been explored in earlier efforts. Potential of these speculative resources is limited in the Houston

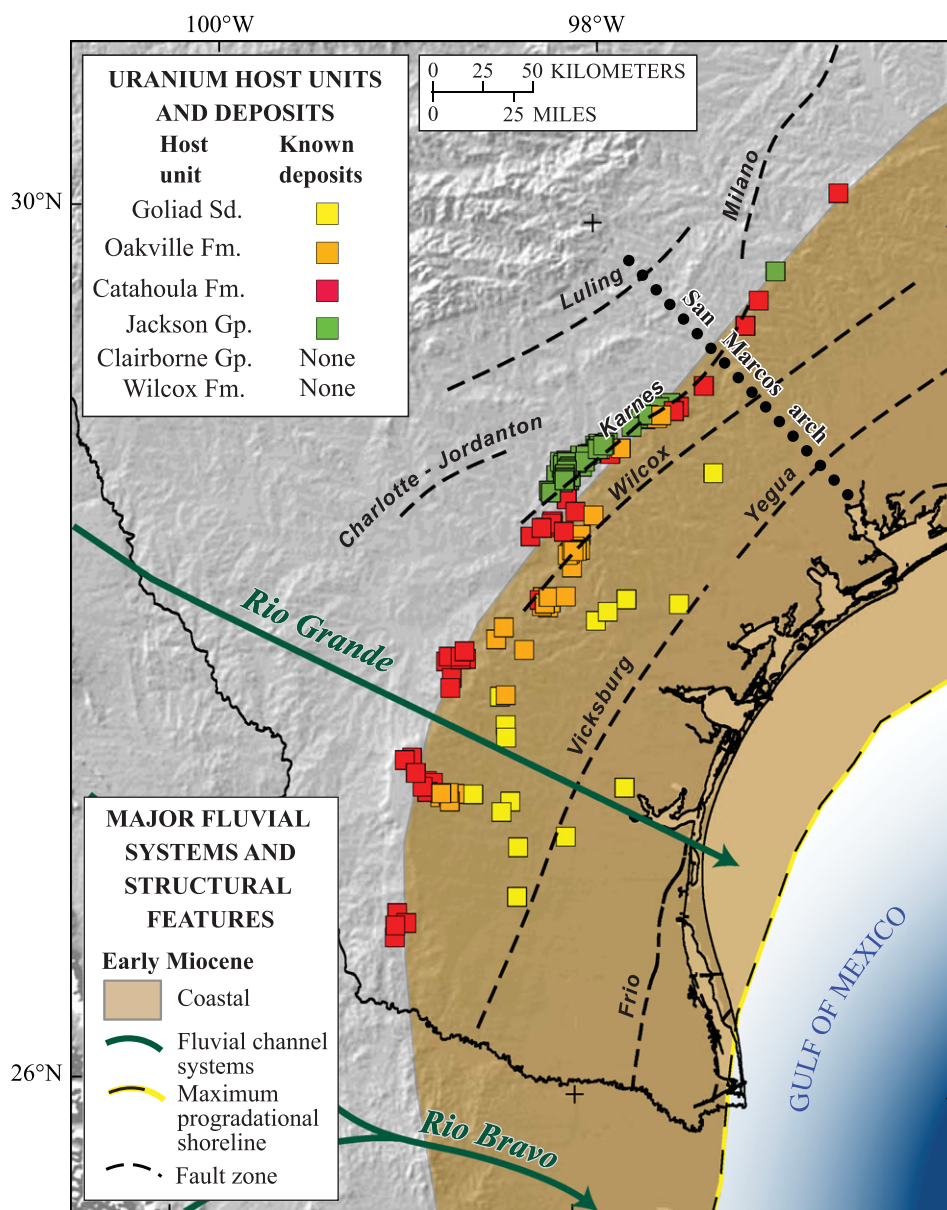


Fig. 14. Uranium occurrences in the Goliad Sand showing the location of occurrences in the Jackson Group, Catahoula Formation and Oakville Formation that may be genetically linked to those in the Goliad.

embayment where transmissive coarse-grained facies and tuffaceous source rocks are not as common.

6.4. Miocene Oakville Formation occurrences

There are 47 uranium occurrences in the Oakville Formation; 36 deposits, 9 prospects and 1 showing, including one tailings facility that has reported production from ore believed to be from the Oakville Formation (Figs. 3 and 12, Appendix 1). Twenty-three deposits produced uranium, four of these contain additional resources, and an additional seven deposits contain identified in-place resources. The resources in these deposits range in total size from 11,000 to almost 7 million lbs U_3O_8 . Most resources are found in the Clay West/Burns and Ray Point districts of Live Oak County. More uranium was produced from the Oakville Formation than from any other geologic unit in the Texas Coastal Plain. Of the 23 deposits that produced uranium, 13 were mined using ISR methods and the rest were open pit mines (Appendix 1). Most producing mines are located within the ancestral Rio Grande channel complex, many down-gradient from deposits in the Catahoula Formation (Fig. 12). Most deposits are found with channel fill and crevasse splays

in the lower Oakville Formation and coarse sand units of the equivalent Fleming Formation where they may have either been reworked from deposits originally formed in the Catahoula Formation, or where the basal Oakville was hydrologically connected with source rocks in the Catahoula.

6.4.1. Source

The most likely source for uranium in Oakville-hosted deposits is tuffs interbedded in the lower Oakville, as well as ash that is voluminous in the underlying Catahoula Formation (Quick et al., 1977). Volcanic rock fragments abundant in the lower Oakville may also have provided a uranium source.

6.4.2. Transport and Trap

The Oakville Formation is a series of medium- to coarse-grained sandstones deposited in a bed-load and mixed-load fluvial system derived largely from weathered portions of the Edwards Plateau and Llano uplift (Eargle et al., 1975). During the early Miocene, the Rio Grande channel complex continued to dominate, bounded by floodplain mudstones and siltstones that transition down-dip to coastal plain rivers

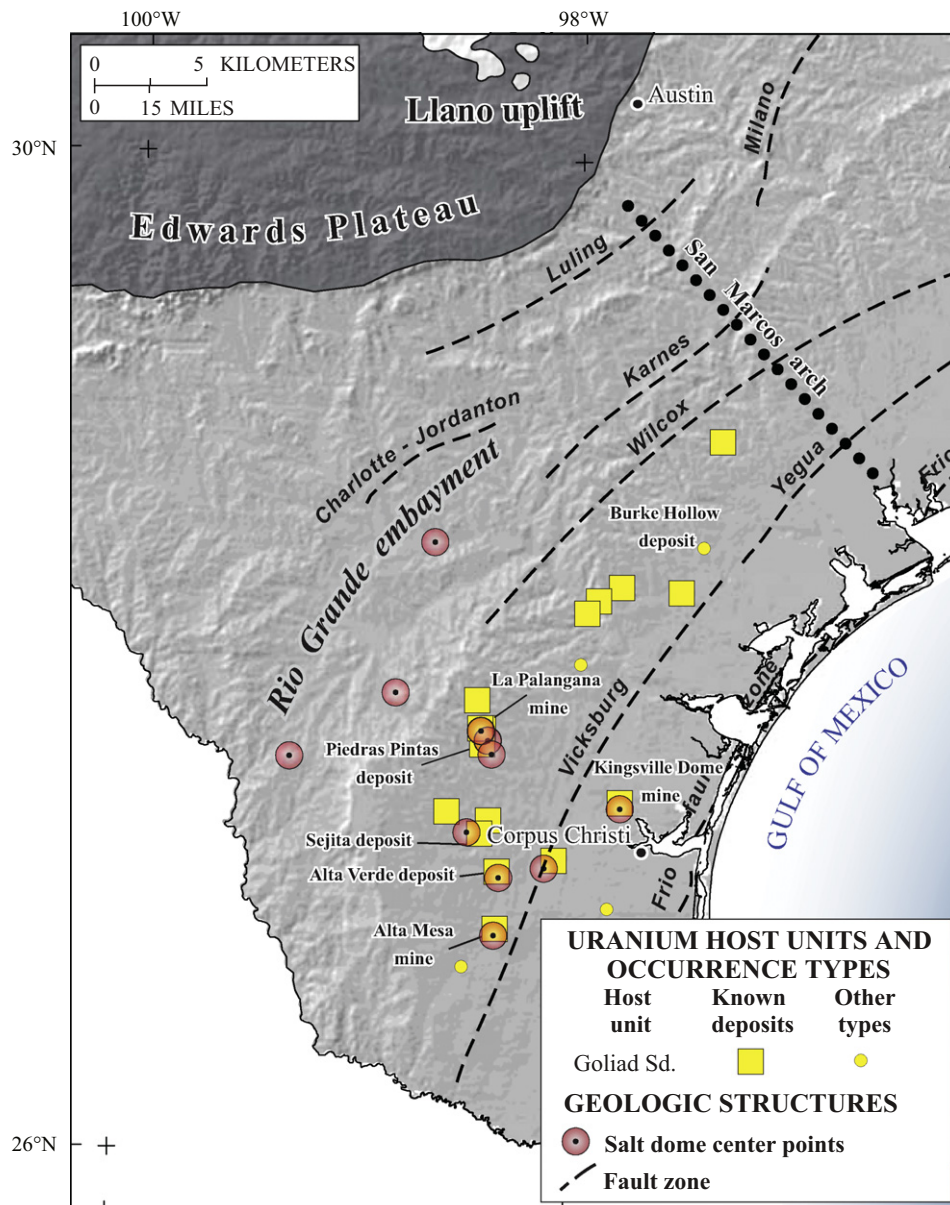


Fig. 15. Positive correlation of salt domes in the Rio Grande Embayment with known uranium occurrences.

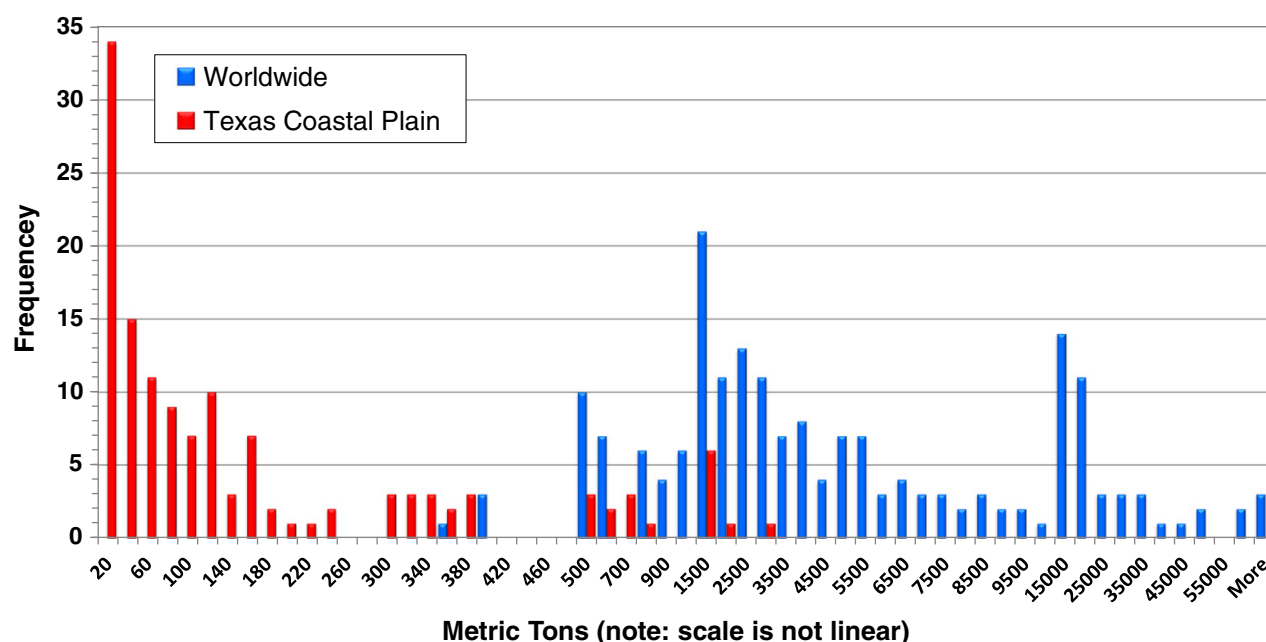


Fig. 16. Histogram comparing contained uranium tonnage of roll-type deposits found worldwide versus those in the Texas Coastal Plain. Worldwide data from the International Atomic Energy Agency (2012).

and barrier-bar systems. In the barrier-bar system, more permeable, sand-rich units host uranium occurrences in both the Catahoula Formation and lower Oakville Formation. In this area, more permeable sand host units may have been interconnected such that the mineralizing system was continuous. In Karnes County, the contact between the lower Catahoula and lower Oakville is transitional and interconnected and it is not clear which stratigraphic unit hosts mineralization. By the middle Miocene, major channels had shifted to the north and uranium mineralization has not been found to date within sandstone deposited during the middle to late Miocene in the Rio Grande embayment. However, results from recent exploration drilling in the early 2000s on several large south Texas ranches may indicate the existence of down-dip Oakville sand deposits in this area at depths greater than 300 m (Kurrus, 2016).

The Oakville Formation is roughly correlative with the Jasper aquifer; fluid flow is confined within the Jasper by the underlying Catahoula aquitard and overlying Burkeville confining system (Lagarto Formation of the Fleming Group). Roll-type deposits form at channel margins within roll front systems that are found in zones of high transmissivity between aquitards in the lower Oakville (Galloway et al., 1982; Klohn and Pickens, 1973). To the north in the Houston embayment, sand content decreases and individual sand bodies are small (Galloway et al., 1982). However, near the modern Brazos River, at the Washington/Fayette County line, conglomerate facies are identified and correspond with small, subeconomic deposits found in the Jackson Group, Catahoula Formation and Oakville Formation. Most deposits within the Oakville are located down-gradient from deposits identified in the Catahoula.

Extrinsic reductants are thought to be the most important type of reductant responsible for creating deposits in the Oakville Formation. Organic carbon, indicative of intrinsic reductants, is rarely associated with deposits (Langmuir and Chatham, 1980). Isotope analyses of carbonates in the Ray Point and George West deposits and sulfides measured in the Felder deposit support the influence of biogenic activity in the Oakville (Galloway et al., 1982; Reynolds et al., 1980b). Occurrences in the Oakville are often associated with large structural features that could have transported reductants as illustrated by the Felder mine found proximal to the Oakville fault (Klohn and Pickens, 1973). In the Ray Point district, highly saline, possibly connate, water and methane are identified within mines. By analogy these components are thought to have moved up portions of the Wilcox fault system, which was intermittently active both during and after deposition of the Oakville (Galloway et al., 1982). Here, H_2S from deep-seated and biogenic sources altered titanium oxide to iron disulfide in the vicinity of major faults, creating pre-ore sulfide lenses that contain from 1 to 10 weight percent sulfur (Goldhaber and Reynolds, 1991; Klohn and Pickens, 1970, 1973; Reynolds et al., 1980b). Pulses of reductant influx are documented by the multiple roll front systems documented within the Oakville that are encased in both reduced rock and sulfides (Adams and Smith, 1981). Deposits are more often re-reduced than in other host units, further evidence that reductants were likely extrinsic and continue to be introduced to the mineralizing system. Some deposits, such as many of those in the Duval mineral trend, do not appear to be associated with northeast-southwest-oriented regional scale faulting (Fig. 13). Local faults that cannot be analyzed at the regional level may be important in the formation of these deposits.

Table 3
Number of mined sandstone-hosted roll-type deposits by host unit and operation type (does not include 2 solution leach operations that produced uranium from ores sourced from the Jackson Group and Oakville Formation). See Appendix 1 for details of individual deposits.

Operation type	Host unit				Total
	Jackson Group (marginal marine)	Catahoula Formation (fluvial)	Oakville Sandstone (fluvial)	Goliad Sand (fluvial)	
Open pit	65	8	13	0	86
ISR	3	16	20	15	54
Unknown	8	17	3	1	29
Total	76	41	36	16	169

6.4.3. Preservation and potential

Re-reduction typical of Oakville deposits also preserves them from remobilization by oxidizing groundwater. Additional undiscovered resources may be found in the Oakville Formation and underlying Catahoula Formation where large, sand-rich paleodrainages are found, and specifically where these drainages intersect large deep-seated fault structures. Potential also exists in large ranches that have been poorly explored and under surface cover south of the Duval mineral trend. Mineral potential is limited in the Houston embayment because transmissive host sandstone channels are smaller and more uncommon.

6.5. Goliad Sand occurrences

There are 21 occurrences in the lower Pliocene/Miocene Goliad Sand, the youngest host unit along the Texas Coastal Plain; 16 deposits and 5 prospects, with current exploration and development expanding these numbers rapidly (Figs. 3 and 14, Appendix 1). The total resource for these deposits ranges from about 400,000 to 10 million lbs U_3O_8 . Historically the Goliad was not explored for a number of reasons including: (1) the difficulty of drilling this unconsolidated sand, (2) oil and gas wells were not logged and cased through this interval therefore missing possible geophysical (gamma) anomalies that might have indicated uranium mineralization, (3) many large, on-trend south Texas ranches were not accessible to mining companies for exploration, (4) the perception that the Goliad had no known uranium source, and (5) exploration was focused on step-out projects adjacent to known mineral clusters. The Goliad Sand is the host of all active uranium mines in the Texas Coastal Plain today, and the focus of most current exploration.

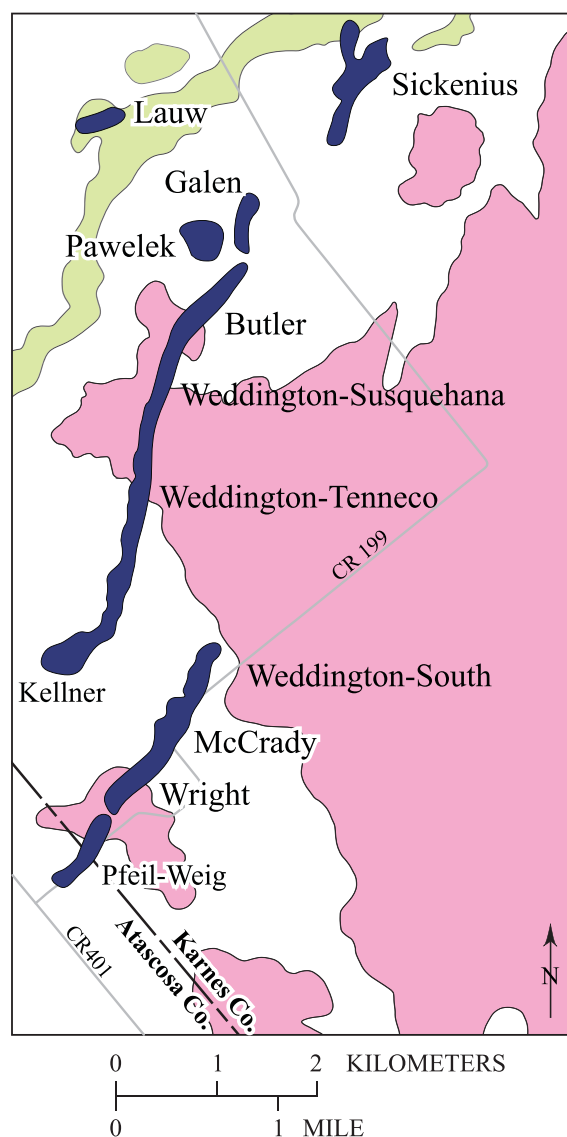
6.5.1. Source

The Goliad uranium source is likely from underlying units and was introduced into the Goliad Sand via groundwater that moves upward along faults or laterally through hydrologically connected deposits. The most likely source of uranium is tuffs in the underlying Catahoula Formation. The Goliad Sand has a significant volcanoclastic component thought to be weathered from tuffs in the upper Rio Grande valley which, when altered, could also provide a source of uranium (Eargle, 1970).

6.5.2. Transport and Trap

During the Pliocene, the principal fluvial input axis shifted from the long-lived Rio Grande paleochannel in the Rio Grande embayment, to the Red and Mississippi River regions of the Houston embayment and eastward (Fig. 4). The Goliad Sand formed in a shallow shelf-coastal bay-lagoon estuarine environment proximal to an active shoreline (Fig. 14) (Arredondo, 1991; Classen, 1981). Sandstones are mostly litharenites composed of mixed sedimentary, volcanic, and metamorphic rock fragments deposited by low-gradient streams on the coastal plain. The Goliad is unconformably deposited on the other uranium-hosting units in the region: the Jackson Group, Catahoula Formation and Oakville Formation. Goliad sediments were likely derived, in part, from the reworking of these underlying units. The Goliad is poorly consolidated, and elevated uranium in groundwater is evidence of active transport (Fig. 5). The climate was arid during deposition of the lower Goliad, supporting the formation of roll-type deposits, but transitioned to a more humid environment during late Goliad time (Adams and Smith, 1981).

Extrinsic reductants are believed to dominate the roll front system in Goliad-hosted deposits. Significant organics are not described at any Goliad-hosted deposits, and hydrogen sulfide is reported at deposits within the Goliad Sand both in the literature and modern drilling programs (Eargle, 1970). Structures are key indicators for mineralization. Salt domes, which emerged during Goliad time, are the primary structural control for deposits in the Rio Grande embayment including the Sejita, Piedras Pintas, La Palangana, and Kingsville Dome deposits (Fig.



EXPLANATION

Uranium Mineralization

■ Ore bodies

Miocene

■ Catahoula Formation

Eocene (Whitsett Formation, Jackson Group)

■ Tordilla Sandstone Member

■ Jackson Group, undivided

Fig. 17. Map showing the distribution of sandstone-hosted uranium deposits in the Jackson and Catahoula Formations in southwestern Karnes County, Texas. Modified from Adams and Smith (1981).

15) (VanHolland, 2011). The Alta Mesa mine and Burke Hollow deposit are associated with a domal structure overlying a shale diapir associated with the Vicksburg fault system (Kurrus, 2016). Shallow gas migrating along parallel, deep-seated structures into conventional traps adjacent to salt domes provides reductant (Adams and Smith, 1981; Arredondo, 1991; Classen, 1981; Kurrus, 1992). At the Kingsville Dome and Alta Mesa mines, methane gas was reported during earliest exploration and subsequent definition drilling. At the La Palangana mine, H_2S was reported during a failed attempt at underground mining (Adams and Smith, 1981). Hydrogen sulfide or CH_4 gas is believed to have formed a reduced “island” immediately around a salt dome at the La Palangana mine, with oxidizing, uranium-bearing groundwater forming rolls at the oxidation/reduction boundary (Kurrus, 2016). Although salt domes are common in the Houston embayment, Goliad-hosted deposits are not found associated with these features likely because of the lack of a uranium source in this region.

6.5.3. Preservation and potential

Deposits in the Goliad Sand generally exhibit positive uranium disequilibrium, and many are actively moving in response to the

movement of oxidizing groundwater (Kunkel, 2013). The Goliad Sand has not been extensively targeted until recently, with large areas remaining relatively unexplored. In the Goliad Sand, exploration guides focus on structures that provide a conduit for uranium-rich groundwater and/or reductants to move into overlying permeable sands (Hoel, 1982).

There is recent exploration activity in Pleistocene sands overlying the Goliad. This may indicate Goliad-hosted deposits continue to migrate into connected sandstones. At the Mt. Lucas deposit in Live Oak County, where several lower Goliad sands were mined using ISR methods, a sand unit within the Lagarto was also productive in one well field. This is the only known uranium production from the Lagarto. However, petroleum well logs from several south Texas counties often display gamma ray anomalies in Lagarto sands, and these may be a target for future exploration (Kurrus, 2016).

7. Grade and tonnage model

Grade and tonnage models are frequency distributions of tonnages and average grades of thoroughly explored mineral deposits of a given

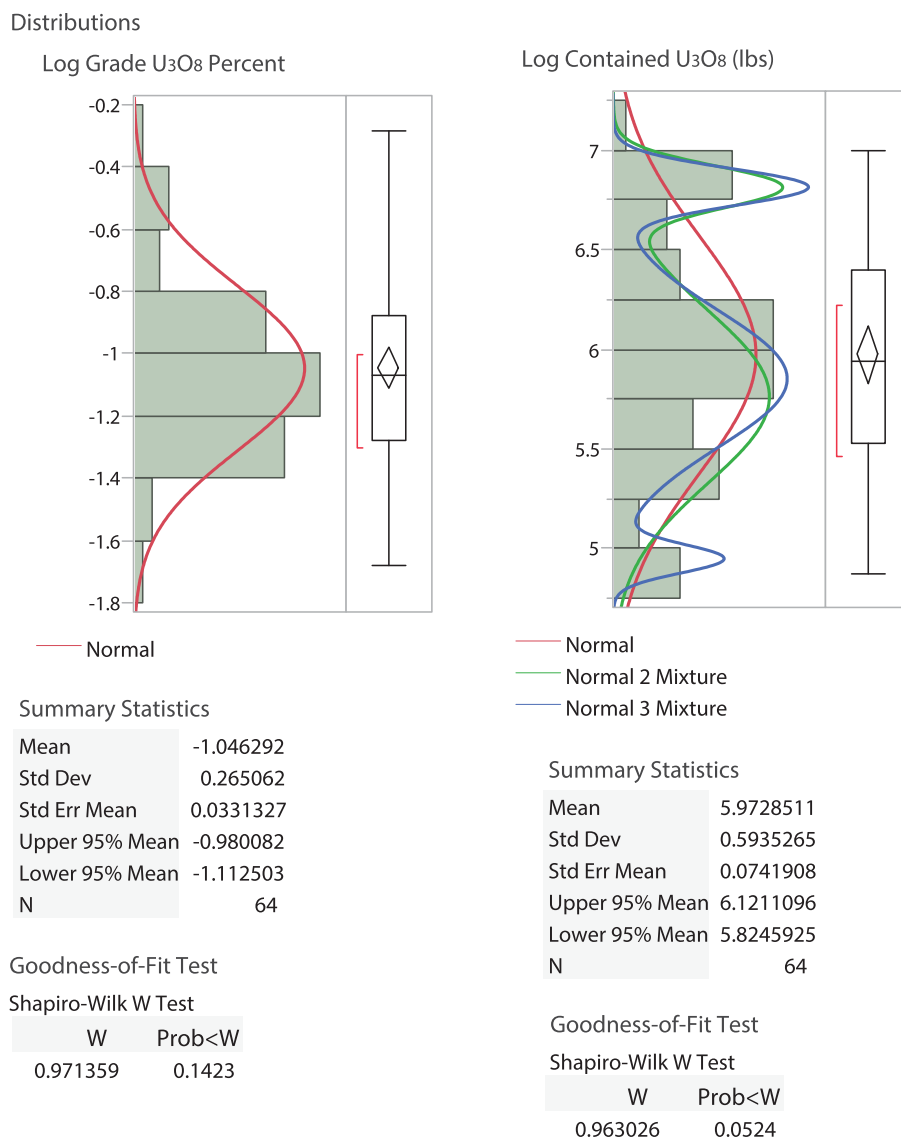


Fig. 18. Distributions of log-transformed average uranium grades and contained uranium for 64 groups of deposits in the South Texas uranium province.

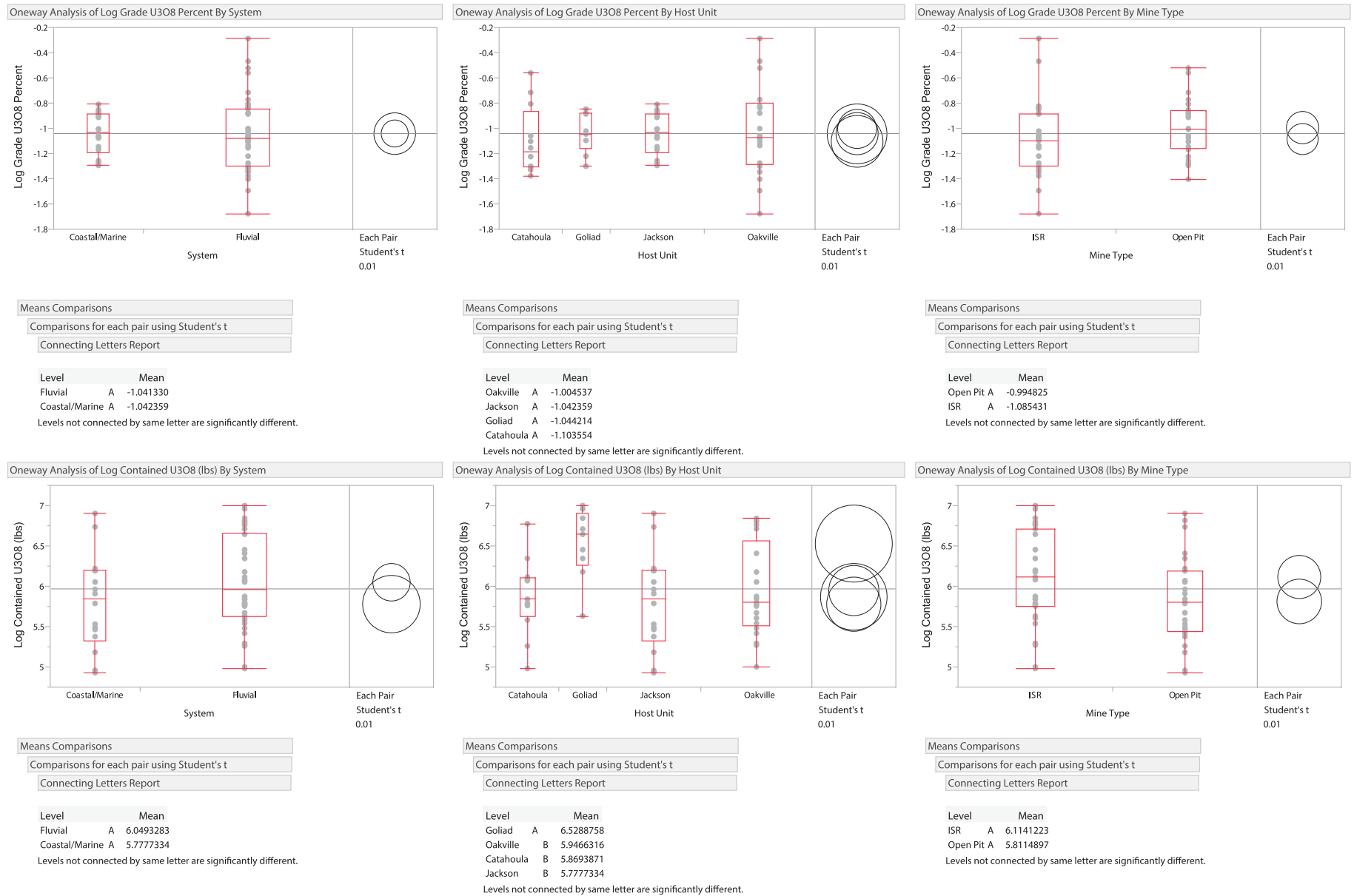


Fig. 19. Distributions of log-transformed average uranium grades and contained uranium for deposits in the South Texas uranium province as a function of environment of deposition, host lithology, and mining method.

type. Grade and tonnage models, along with descriptive and genetic models, provide a conceptual framework for mineral deposit classification and exploration. The distributions also provide models for predicting mineral endowment of undiscovered deposits of the same type in geologically similar settings.

Comparisons of the total uranium content of Texas Coastal Plain deposits with other roll-type uranium districts in the U.S. (Table 1) and with roll-type uranium deposits around the world show that the Texas deposits represent a distinct, lower tonnage subset of roll-type deposits (Fig. 16). Therefore, the resource data compiled for this study (Appendix 1) were analyzed to construct models that could be used for characterization and assessment of undiscovered uranium resources in the Texas Coastal Plain.

Data are available for total uranium content (pounds of U_3O_8) and an average uranium grade (percent U_3O_8) for a subset of the South Texas uranium deposits listed in Appendix 1. Only the deposits with reported grades, tonnages of contained uranium, and known locations and host units are included in the data set of 106 deposits selected for statistical analysis. After converting pounds to metric tons (1 pound = 0.00045359 metric tons), a total equivalent ore tonnage for each deposit

Table 4

Statistical summary for grade and tonnage data for sandstone hosted deposits of the Texas Coastal Plain.

Groups (N = 64)	U_3O_8 Grade, in percent	Contained U_3O_8 , in pounds	Contained U_3O_8 , in metric tons	Equivalent ore tonnage, in pounds	Equivalent ore tonnage, in metric tons
Quantiles					
100% (maximum)	0.516	10,000,000	4536	14,000,000,000	6,329,172
99.5%	0.516	10,000,000	4536	14,000,000,000	6,329,172
97.5%	0.406	9,436,875	4281	12,000,000,000	5,413,522
90.0%	0.182	6,739,471	3057	6,520,000,000	2,958,805
75% (quartile)	0.132	2,495,108	1132	2,870,000,000	1,302,601
50% (median)	0.085	861,778	391	1,180,000,000	536,992
25% (quartile)	0.053	340,194	154	351,000,000	159,427
10.0%	0.046	125,946	57	155,000,000	70,208
2.5%	0.028	80,979	37	56,500,000	25,646
0.50%	0.021	75,000	34	54,600,000	24,777
0% (minimum)	0.021	75,000	34	54,600,000	24,777
Summary statistics					
Mean	0.110	2,105,661	955	2,325,800,000	1,054,997
Std dev	0.085	2,601,433	1180	2,930,800,000	1,329,408
Std err mean	0.011	325,179	148	366,349,222	166,176
Upper 95% mean	0.131	2,755,480	1250	3,057,900,000	1,387,073
Lower 95% mean	0.089	1,455,842	660	1,593,700,000	722,920
N	64	64	64	64	64

was calculated as:

$$\text{Equivalent ore tonnage, in metric tons} = \text{Contained total } U_3O_8, \text{ in metric tons} / (\text{percent } U_3O_8 \times 0.01) \quad (1)$$

These calculated equivalent tonnages are not necessarily based on current reporting standards that depend on drill-indicated measured parameters such as strike length, depth, width, and specific gravity of ore that allow calculation of ore volume, which is then converted to tonnage. Drill densities are available for some, but not all of the sites included in the data set. Cutoff grades are not reported. The deposits include operating mines and past producers as well as unmined deposits. Both open pit and ISR operations are represented in the data set (Table 3). Guidelines for reporting uranium resource evaluations that meet international standards (for example, Canadian Institute of Mining, Metallurgy, and Petroleum, 2016) are not always available. Deposits hosted in the Jackson Group primarily represent open pit mines whereas all of the deposits in the Goliad Sand were mined by ISR. Although most of the deposits and occurrences are hosted in the Jackson Group, most of the historical production is from the Oakville Formation and the largest identified resource as of 2013 is in the Goliad Sand (Tables 1 and 3).

Tonnage and uranium grade data for the 106 deposits provided the basis for the constructing a custom grade and tonnage model for South Texas sandstone-hosted uranium deposits (Table 3, Appendix 1). Ideally, data used for models include the average grade and associated tonnage for total production, and resources at the lowest possible cutoff grade (Singer and Menzie, 2010). Additionally, the data used in the model should represent a consistent sampling unit and avoid mixing different geologic environments and/or mining methods. Selection of a consistent sampling unit for sandstone-hosted uranium deposits is challenging because multiple deposits may be developed on a single ore body (Fig. 17). Therefore, each site does not necessarily represent a single ore body as a geologic entity. In addition, available data represent both coastal marine (Jackson) and fluvial (Catahoula, Oakville, Goliad) depositional environments and a mix of mining methods. Thus, the South Texas data pose many challenges for constructing and applying grade and tonnage models in mineral resource assessment

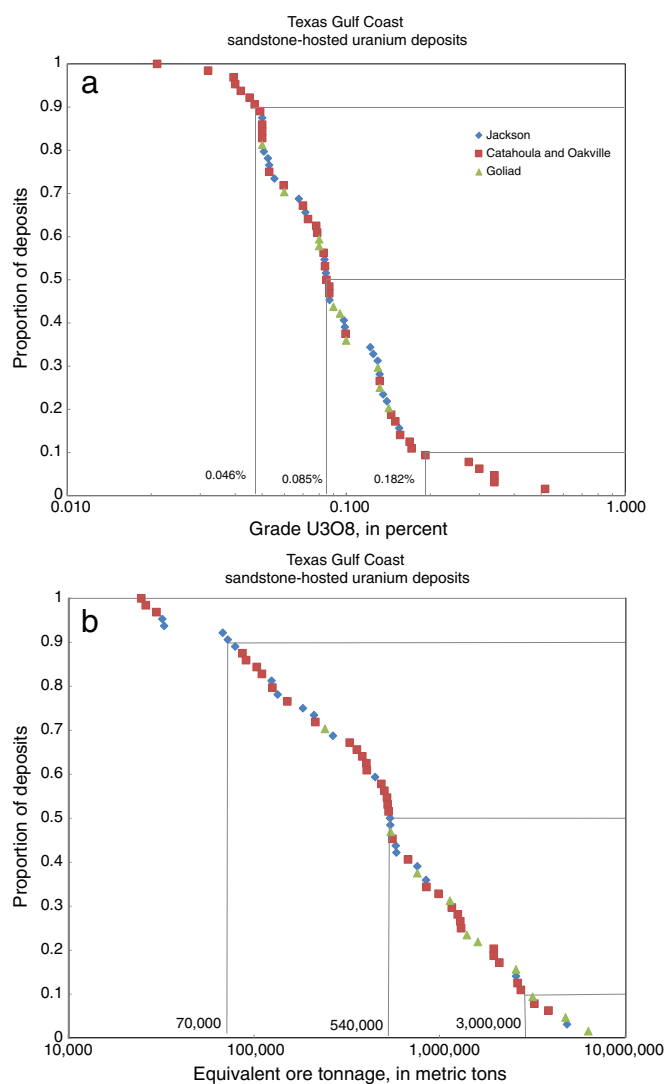


Fig. 20. Models for grade and equivalent ore tonnage for south Texas sandstone-hosted uranium deposits. Quantile intercepts from Table 4; tonnage intercepts rounded to two significant figures.

because of the nature of the sandstone-hosted deposits and paucity of appropriate data, as noted previously by Finch et al. (1992).

7.1. Sampling unit

Operational rules for defining consistent sampling units are arbitrary, typically spatial guidelines for defining a deposit as a geologic entity (Mosier, 1986). For example, the operational rule used for a model of unconformity type uranium-gold deposits defines individual deposits as those separated by 100 m stratigraphically and along strike (Mosier, 1986). For some deposit types, all mineralized rock or altered rock within a distance of 2 km is combined as a single deposit, or a minimum of 500 m separating adjacent sites is used (Singer and Menzie, 2010). For undiscovered mineral resource assessments, the key point is that estimates of numbers of undiscovered deposits that are combined with grade and tonnage models to estimate undiscovered resources should be made in accord with the operational rule used to develop the model.

In the South Texas uranium province, resource information is available for multiple deposits on single ore bodies as well as for discrete ore bodies. Ore bodies typically are narrow and long, with strike lengths ranging from meters to kilometers. In addition, the size and orientations of deposits mined by in situ methods are not well constrained. In order to define a deposit as a consistent geologic entity in a grade and tonnage model, individual sites within the same host lithology were grouped on the basis of (1) close proximity, (2) previous studies that showed a relationship to a single ore body, and (3) expert judgment.

Deposit locations (Appendix 1) were plotted in a geographic information system to facilitate spatial analysis. The resulting map shows that deposits hosted within the Goliad Sand are discrete, and have been mined by ISR exclusively to date. In contrast, many of the deposits hosted in the older host rocks represent closely spaced open pits or a mix of open pit and ISR mining methods. The grouping approach resulted in data set of 64 deposits, including 20 groups and 44 discrete deposits. The Weddington Group, for example, includes the Kellner, Weddington-Tenneco, Weddington-Susquehanna, Butler, Pawelek, and Galen deposits (Fig. 17); conversely, the Sickenius deposit is treated as discrete. Site spacing within groups ranges from a few hundred meters to 2 km and represents polygonal areas of about 1 to 16 km². Other assumptions about grouping uranium deposits as geologic entities can be made, such as the cluster approach promulgated by Finch (Finch et al., 1992) as long as the same criteria are used to define deposits in making estimates of undiscovered deposits.

7.2. Data analysis

Models are likely to be stable if the following criteria are met: (1) tonnages and grades are not significantly different from a lognormal distribution, (2) at least 20 deposits are used, (3) standard deviations for log-transformed tonnages are less than 1.0, and (4) there are no significant correlations between tonnage and grade (Singer and Menzie, 2010). To analyze the South Texas data, the grade, contained U₃O₈ and equivalent tonnages were log-transformed and plotted as normal quantile plots to test for lognormality, population statistics, and correlations.

Tests of various distributions for the log-transformed data show that the grade and contained uranium data for the South Texas deposits are poorly described by a lognormal distribution (Fig. 18), as indicated by the shapes of the distributions and goodness-of-fit tests. Analysis of variance tests were done to look for possible subpopulations that could explain the multimodality suggested by the histogram of contained uranium distributions (Fig. 16). Data for log-transformed average grades and contained uranium contents were evaluated by predominant depositional environment (coastal/barrier island or fluvial), mining method (open pit or ISR), and host lithology (Fig. 19). At a statistical significance level of 1 percent, differences in average grades are not significantly distinct as a function of these attributes. Differences

in depositional setting and mining method do not distinguish subsets of deposits in terms of contained uranium content (shown in terms of log-transformed data in pounds). Deposits hosted in the Goliad Sand, however have significantly higher tonnages of contained uranium than deposits hosted in the Jackson Group, Catahoula Formation, and Oakville Formation (Fig. 19). This is probably because all of the deposits in the Goliad Sand are mined using ISR, whereas the other deposits are mined by open pit or by both methods. There are too few deposits (10) in the Goliad to develop a valid separate model. Deposits in the Oakville Formation represent both mining methods and overlap data for deposits in the Catahoula Formation and Jackson Group. Therefore, we adopted a single data set based on 64 deposit groups to construct a grade and equivalent tonnage model for sandstone-hosted uranium deposits in the Texas Coastal Plain.

7.3. Grade and tonnage model for Texas Coastal Plain deposits

Quantiles and summary statistics for the South Texas uranium deposits show that average grades range from 0.021 to 0.051 percent U₃O₈ and contained U₃O₈ ranges from 75,000 to 10,000,000 pounds (Appendix 1). Calculated equivalent ore tonnages range from 54.6 million to 14 billion pounds. Contained U₃O₈ and equivalent tonnage data are reported here in pounds as well as metric tons.

The conventional format for grade and tonnage models is a cumulative frequency plot of grade in percent and tonnage in metric tons, where each point represents a singled deposit, as defined by the spatial rules adopted for the study. Intercepts for the 90th, 50th (median), and 10th percentiles are plotted (Singer and Menzie, 2010). The grade model for the Texas Coastal Plain deposits shows the deposits plotted by host rocks on a logarithmic scale (Fig. 20), along with selected quantile values from Table 4. Note that some deposits from each geologic formation plot above and below the median grade value of 0.085 percent U₃O₈. Equivalent tonnages are derived from reported contained U₃O₈ reported in pounds, therefore the ore tonnages and contained uranium metal data are co-dependent and models based on either parameter have the same shape. Similarly, the equivalent ore tonnage model shows that deposits within different host rocks plot above and below the median ore tonnage for the data set (Fig. 19). This indicates that using the model for the entire uranium province is a viable option for conducting a mineral resource assessment given the limitations of the available data. These models are not applicable to assessments of other regions or other types of uranium deposits.

8. Conclusions

Geology, geochemistry and deposit locations were compiled and integrated with regional analysis of the Cenozoic depositional environments of the Texas Coastal Plain to produce an updated comprehensive deposit model for uranium. Both spatial and temporal distribution of the most prolific deposits supports a volcanogenic source that provided uranium as ash from active volcanic systems west of the area in the Trans-Pecos region. However, weathering of uranium-rich highland areas may also be important. The uranium source for some deposits that cluster around the San Marcos arch may be uranium-rich Mesoproterozoic rocks of the Llano uplift exposed at the core of the arch. Additional uranium may also have been supplied to the region in the Paleogene from weathering of uranium-rich source rocks in the Sierra Madre Occidental and southern Rocky Mountains. In the Neogene, sediment was derived from weathering in the Great Plains, southern Rocky Mountains and Appalachian Mountains, areas that do not contain a large component of fertile source rocks. Sediments from these regions were eventually deposited into the Houston embayment which contains few uranium occurrences.

Transport of uranium was in groundwater that travelled through sandstone channels, crevasse splays, and strandline deposits that were deposited in the Texas Coastal Plain. Thick, interconnected and stacked

transmissive sands were formed by the Rio Grande and Rio Bravo paleochannel systems in the Rio Grande embayment and provided a conduit for uranium-rich groundwater. Uranium was transported in solution within these paleochannel systems, and associated interconnected permeable coastal barrier–bar systems. The largest deposits formed in the Rio Grande embayment where arid conditions dominated. In this area, organic debris was not as voluminous as in the Houston embayment because biologic productivity was low. Therefore, uranium was not entrained in organic facies, but concentrated in oxidizing groundwater that mobilized sufficient metal to form economic deposits. Deposits formed at the interface between oxidizing groundwater and plumes of reductants related to the well-developed oil and gas system in the region, or near organic-rich facies adjacent to sandstone channels or barrier bars.

Analysis of grade and tonnage of deposits in the Texas Coastal Plain shows that most uranium was produced from the Oakville Formation in the Rio Grande embayment. Deposits formed mostly within basal permeable portions of the Oakville, adjacent to abundant volcanic tuff source rock in the underlying Catahoula Formation. The greatest number of deposits is in the Jackson Group, which probably is related to mining of outcropping mineralization by discrete open pit mines developed within transport distance of an operating uranium mill. The largest deposits are found in the Goliad Sand, which is probably related to mining by successive ISR well-fields that extract uranium from mineralized portions of a larger roll front in an ongoing fashion. Most of the production came from deposits in the Duval mineral trend which corresponds to the Rio Grande paleochannel system. This association emphasizes the importance of the long-lived river systems and their associated transmissive sand facies to productive mineral trends in this region. This analysis provides a framework for more detailed studies that may lead to deeper understanding of mechanisms required for genesis of individual deposits in the Texas Coastal Plain.

Funding

This work was supported through U.S. Geological Survey programmatic funding. This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Acknowledgements

Helpful reviews by Andrew Kurrus (Uranium Energy Corporation), several reviewers at the U.S. Geological Survey (Janet Slate, David Ferderer, Julie Herrick), and an anonymous reviewer for *Ore Geology Reviews* were very helpful. The figures were expertly drafted by John Wallis (Serrano IT Services). Deborah Briggs (Serrano IT Services) assisted with compilation and clean-up of the uranium occurrences

database. The groundwater geochemistry for the region was compiled and analyzed by Ray Johnson (U.S. Geological Survey).

Appendix 1

Appendix 1 tabulates the location, type of occurrence, U_3O_8 production and remaining in-place resources, host unit, and age of sandstone roll-type uranium occurrences found in the Texas Coastal Plain. Uranium occurrences are categorized as (1) mined deposits, (2) unmined deposits (sites with a reported in-place resource), (3) prospects (sites that have some level of exploration, where something was removed to evaluate the mineral potential, such as drill holes or prospect pits), (4) showings (sites of interest that have been recorded in the literature, a database, or which is a significant anomaly), or (5) anomalies (sites with indications that mineralizing processes may have taken place as evidenced by a geochemical anomaly defined by a cluster of soil, water, rock, or stream sediment samples containing elevated uranium, or a geophysical anomaly such as prominent anomalous gamma peak on a flight line) (Mihalasky, 2014).

Most of the uranium production data came from the proprietary U.S. Department of Energy's (DOE) producing uranium mines database (DOE, 2009). In-place resource data are compiled both from published reports and from the DOE database. Data identifying individual production centers in the DOE database are protected, so a range of production and resources is assigned to each property to alias property specific information. Most of the grade information for the Texas Coastal Plain is calculated using reported U_3O_8 production (lbs) and tonnage data, and is so identified. Calculated grades should be used with caution. The location of mines was deleted from DOE's database; these were added based on spatial imagery and published deposit data. Other occurrence data were compiled from a number of sources, a great deal from the original DOE NURE geologic quadrangle report series in which geochemical, geophysical, occurrence and geologic data were summarized for each quadrangle assessed by the program.

References used to compile this information were: (Adams and Smith, 1981; Ambrose, 2007; Barnes, 1976; Brandt, 2010; Brewster, 1982; Brown et al., 1961; Bunker and Mackallor, 1973; Carothers, 2008, 2009, 2010; Carothers et al., 2013; Cherepon and Stauber, 1982a, 1982b; Crook, 1979; Dahlkamp, 2010; Dickinson, 1976, 1978; Dickinson and Duval, 1977; Dickinson and Sullivan, 1976; DOE, 2009; Drodgy and Hovorka, 1982a, 1982b; Eargle et al., 1961a, 1961b, 1975; Eargle and Moxham, 1961; Eargle and Snider, 1956; Finch, 1967; Galloway, 1977; Galloway et al., 1979, 1982; Galloway and Kaiser, 1979, 1980; Goldhaber and Reynolds, 1977; Goldhaber et al., 1978, 1983; Greimel, 1982; Greimel and Ambrose, 1982; Henke et al., 1982; McNeill, 2010; Pool, 2013; Reynolds et al., 1980b; Rigby et al., 2010; Smith, 1982; Stauber and Rogers, 1982; TCEQ, 2013; UEC, 2010; URI, 2010; URI, 2015; Weinzapfel, 1981).

Occurrence Name	Includes	Latitude	Longitude	County	Occurrence Type	Operation Type	Status in 2014	Total U ₃ O ₈ (lbs.)	Produced U ₃ O ₈ (lbs.)	In Situ U ₃ O ₈ resource (lbs.)	Grade (% U ₃ O ₈)	Date of reported resource and/or production	Host Unit	Reference
A. HERNANDEZ SURV.		29.0061	-97.9933	Karnes	Prospect	N.A.	N.A.					1982	Jackson Group	Droddy and Hovorka, 1982a
ALTA MESA ESTE		26.9356	-98.2781	Brooks	Prospect	N.A.	Exploration					2015	Goliad Sand	URI, 2015
ALTA MESA MINE		26.9028	-98.3147	Brooks	Deposit	ISR	Operating	>1,000,000	>1,000,000	>1,000,000	0.09	2013	Goliad Sand	Dahlkamp, 2010; McNeill, 2010
ALTA VERDE DOME		27.1319	-98.3144	Brooks	Deposit	ISR	Unmined	>1,000,000		>1,000,000	0.13	2010	Goliad Sand	Dahlkamp, 2010
BANDUCH-COCHRAN		29.1082	-97.7079	Karnes	Deposit	Open Pit	Unmined	100,000-1,000,000		100,000-1,000,000	0.06*	1982	Jackson Group	Dickinson, 1976
BARGMANN		28.8774	-98.1380	Karnes	Deposit	Open Pit	Past Producer	10,000-25,000	10,000-25,000			1982	Jackson Group	Bunker and MacKallor, 1973
BAUMBACH		Unknown	Unknown	Fayette	Deposit	Unknown	Unmined	100,000-1,000,000		100,000-1,000,000	0.05*	2009	Catahoula Formation?	DOE, 2009
BEICKER URANIUM PIT		28.8728	-98.1139	Karnes	Prospect	N.A.	N.A.					1982	Jackson Group	Greimel, 1982
BEICKER-ZAMZOW MINE		28.8843	-98.1059	Karnes	Deposit	Open Pit	Past Producer	100,000-1,000,000	100,000-1,000,000		0.09*	1985	Jackson Group	Dickinson and Duval, 1977
BEN A. PAWELEK PROPERTY		29.0167	-97.8858	Karnes	Prospect	N.A.	N.A.					1982	Jackson Group	Droddy and Hovorka, 1982a
BENAVIDES MINE		27.4255	-98.7885	Duval	Deposit	ISR	Past Producer	100,000-1,000,000	100,000-1,000,000		0.09*	1988	Catahoula Formation	DOE, 2009
BENHAM		28.5702	-98.0315	Bee	Deposit	ISR	Unmined	100,000-1,000,000		100,000-1,000,000	0.03*	2009	Oakville Formation	TCEQ, 2013
BLASHKE		29.1580	-97.6501	Gonzales	Deposit	Open Pit	Unmined					2010	Jackson Group	Brandt, 2010
BOOTS-BROWN EXPL		28.2853	-98.2153	Live Oak	Prospect	N.A.	Exploration					2012	Oakville Formation	TCEQ, 2013
BOOTS-BROWN MINE		28.2830	-98.2180	Live Oak	Deposit	ISR	Past Producer					2012	Oakville Formation	TCEQ, 2013
BOSO-HACKNEY 2		28.8665	-98.1473	Karnes	Deposit	Open Pit	Past Producer	10,000-25,000	10,000-25,000		0.13*	1981	Jackson Group	Bunker and MacKallor, 1973
BOSO-PLLBG		28.8806	-98.1198	Karnes	Deposit	Open Pit	Unknown					2010	Jackson Group	Dickinson, 1976
BRAZIL (UL1408)		Unknown	Unknown	Karnes	Deposit	Unknown	Unmined	100,000-1,000,000		100,000-1,000,000	0.06*	1981	Jackson Group	DOE, 2009
BRELUM 106-200 MINE		28.0000	-98.6333	Duval	Deposit	ISR	Unmined	>1,000,000		>1,000,000	0.54	1986	Catahoula Formation	Crook, 1979
BRELUM 199 MINE		28.0250	-98.6140	Duval	Deposit	ISR	Unmined	>1,000,000		>1,000,000	0.54	1986	Catahoula Formation	Crook, 1979
BRENNHAM DOME		30.0667	-96.4739	Washington	Prospect	N.A.	N.A.					1982	Oakville Formation	Stauber and Rogers, 1982
BREVARD		28.5740	-98.0270	Bee	Prospect	N.A.	Exploration					2012	Oakville Formation	TCEQ, 2013
BRUNI MINE		27.5295	-98.8653	Webb	Deposit	ISR	Past Producer	100,000-1,000,000	100,000-1,000,000		0.05*	1985	Catahoula Formation	Goldhaber et al., 1978
BURKE HOLLOW		28.2638	-97.5176	Bee	Deposit	ISR	Exploration	>1,000,000		>1,000,000	0.05	2013	Goliad Sand	Carothers et al., 2013
BURNS MINE	BURNS, BOOTS-BROWN, PAWLK BUTLER RANCH	28.2354	-98.1899	Live Oak	Deposit	ISR	Past Producer	>1,000,000	>1,000,000		0.08	1990	Oakville Formation	TCEQ, 2013; Galloway et al., 1982
BUTLER PIT		28.8587	-98.1157	Karnes	Deposit	Open Pit	Past Producer	>1,000,000	>1,000,000		0.14*	2009	Jackson Group	Dickinson, 1976
CADENA		27.8210	-98.4260	Duval	Deposit	ISR	Unmined	>1,000,000		>1,000,000		1982	Goliad Sand	Smith, 1982
CAMPANA 101 + 103		28.0834	-98.4542	McMullen	Deposit	Unknown	Unmined	>1,000,000		>1,000,000	0.02*	1976	Oakville Formation	Adams and Smith, 1981
CASA BLANCA 293		27.9850	-98.6940	Duval	Deposit	ISR	Unmined	100,000-1,000,000		100,000-1,000,000	0.34	1982	Catahoula Formation	Adams and Smith, 1981; Pool, 2013
CASA BLANCA 297		27.9763	-98.7082	Duval	Deposit	ISR	Unmined	100,000-1,000,000		100,000-1,000,000	0.34	1982	Catahoula Formation	Adams and Smith, 1981; Pool, 2013
CASTRANO PROPERTY		29.4411	-98.2167	Bexar	Prospect	N.A.	N.A.					1982	Wilcox Formation	Greimel, 1982
CEDRO HILL		27.7578	-98.7008	Duval	Prospect	N.A.	N.A.					1982	Catahoula Formation	Cherepon and Stauber, 1982a
CHANNEN		28.4590	-97.4230	Goliad	Prospect	N.A.	Exploration					2012	Goliad Sand	UEC, 2012
CHAPMAN PIT		28.6006	-98.2321	Live Oak	Deposit	Open Pit	Past Producer	100,000-1,000,000	100,000-1,000,000		0.07*	1985	Catahoula Formation	Adams and Smith, 1981
CHEAPSIDE		29.2638	-97.4078	Gonzales	Deposit	Unknown	Unknown					1981	Catahoula Formation	Adams and Smith, 1981

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Occurrence Name	Includes	Latitude	Longitude	County	Occurrence Type	Operation Type	Status in 2014	Total U ₃ O ₈ (lbs.)	Produced U ₃ O ₈ (lbs.)	In Situ U ₃ O ₈ resource (lbs.)	Grade (% U ₃ O ₈)	Date of reported resource and/or production	Host Unit	Reference
CHEVRON PROPOSED LEACH MINE		27.3417	-98.3583	Duval	Deposit	ISR	Unmined					1982	Goliad Sand	Cherepon and Stauber, 1982b
CLAY CREEK		30.2997	-96.4261	Washington	Prospect	N.A.	N.A.					1982	Catahoula Formation	Stauber and Rogers, 1982
CLAY WEST MINE	CLAY WEST DEEP, PROPER SLURRY, and WEST WSW	28.2408	-98.2228	Live Oak	Deposit	ISR	Past Producer	>1,000,000	>1,000,000		0.15*	1990	Oakville Formation	Ambrose, 2007
CLINTON MANGES RANCH		27.7606	-98.7367	Duval	Prospect	N.A.	N.A.					1982	Catahoula Formation	Cherepon and Stauber, 1982a
COCHRAN MINE		29.1108	-97.7300	Karnes	Deposit	Open Pit	Unmined	100,000-1,000,000		100,000-1,000,000	0.04*	2009	Jackson Group	Brandt, 2010
COLONEL WEDDINGTON		28.8594	-98.1533	Karnes	Prospect	N.A.	N.A.					1982	Jackson Group	Greimel, 1982
CONRAD SWBIC		28.9661	-98.0383	Karnes	Prospect	N.A.	N.A.					1982	Jackson Group	Greimel, 1982
COX LEASE		29.8225	-97.0000	Fayette	Prospect	N.A.	N.A.					1982	Jackson Group	Droddy and Hovorka, 1982a
CRESTONIA CUEVITAS		27.3683	-98.5489	Duval	Deposit	Unknown	Unmined					1981	Goliad Sand	Dahlkamp, 2010
		26.8141	-98.9184	Jim Hogg	Deposit	Unknown	Unknown					1981	Catahoula Formation	Adams and Smith, 1981
DAVID MARTIN DCRC	DCRC 572, DCRC UL 541	28.9925	-97.9497	Karnes	Deposit	Unknown	Unknown			100,000-1,000,000	0.07*	2010	Jackson Group	Brandt, 2010
		28.0000	-98.6940	Duval	Deposit	Unknown	Unmined					1981	Catahoula Formation	Cherepon and Stauber, 1982a
DICKSON-BROWN (BROWN)		28.9043	-98.0572	Karnes	Deposit	Open Pit	Past Producer	100,000-1,000,000	100,000-1,000,000		0.07*	1981	Jackson Group	Dickinson and Duval, 1977
DICKSON-PAWELEK		28.9009	-98.0629	Karnes	Deposit	Open Pit	Past Producer	>1,000,000	>1,000,000		0.10*	1981	Jackson Group	Dickinson, 1976
DOBIE VAUGHN PITS	DOBIE SE ALE	28.6024	-98.2128	Live Oak	Deposit	Open Pit	Past Producer	100,000-1,000,000	100,000-1,000,000		0.10*	2009	Catahoula Formation	Adams and Smith, 1981; Weinzapfel, 1981
DRAGON-JANYSEK PIT DUBOSE		29.1399	-97.6755	Karnes	Deposit	Open Pit	Unmined	5,000-10,000		5,000-10,000	0.06*	1981	Jackson Group	Brandt, 2010
		29.1670	-97.5340	DeWitt	Deposit	Unknown	Unknown					1981	Catahoula Formation	Adams and Smith, 1981
DUDERSTADT		29.1845	-97.5794	Gonzales	Deposit	Open Pit	Past Producer	300-1,000	300-1,000		0.12*	1973	Jackson Group	Adams and Smith, 1981
DZUIK-LYSE		28.8202	-98.0965	Karnes	Deposit	Open Pit	Unmined					2010	Jackson Group	Brandt, 2010
EAST PIT-PANNA MARIA OPERATIONS		28.9878	-97.9189	Karnes	Deposit	Open Pit	Past Producer					2010	Jackson Group	Weinzapfel, 1981
EAST WARD, OWL CREEK		30.0436	-96.8928	Fayette	Prospect	N.A.	N.A.					1982	Jackson Group	Stauber and Rogers, 1982
ESSE-SPOONAMOORE MINE		28.7332	-98.1063	Live Oak	Deposit	Open Pit	Past Producer	100,000-1,000,000	100,000-1,000,000		0.16*	1991	Catahoula Formation	Adams and Smith, 1981
F. BRYSCH MINE		28.9824	-97.9665	Karnes	Deposit	Open Pit	Past Producer	10,000-25,000	10,000-25,000		0.08*	2009	Jackson Group	Dickinson and Sullivan, 1976
FALLS CITY TAILINGS		28.9056	-98.1320	Karnes	Processing Facility / Tailings Deposit	Solution Leach	Past Producer	100,000-1,000,000	100,000-1,000,000		0.01*	1981	Jackson Group-sourced ore presumed	DOE, 2009
FELDER MINE		28.4943	-98.0776	Live Oak	Deposit	Open Pit	Past Producer	>1,000,000	>1,000,000		0.23*	1985	Oakville Formation	Goldhaber et al., 1983
FORT WORTH NATIONAL BANK MINE		28.9822	-97.9445	Karnes	Deposit	Open Pit	Past Producer	50,000-100,000	50,000-100,000		0.05*	1981	Jackson Group	DOE, 2009
FOSTER RANCH		28.0050	-98.5953	Duval	Prospect	N.A.	N.A.					1982	Catahoula Formation	Greimel, 1982
FRANKLIN-SWIERC (UL1754)		28.9056	-98.0476	Karnes	Deposit	Open Pit	Past Producer	100,000-1,000,000	100,000-1,000,000		0.10*	1983	Jackson Group	Cherepon and Stauber, 1982b
G. E. GRADY		28.7653	-98.0358	Karnes	Prospect	N.A.	N.A.					1982	Catahoula Formation	Greimel, 1982
GALEN PIT		28.8728	-98.1094	Karnes	Deposit	Open Pit	Past Producer	100,000-1,000,000	100,000-1,000,000		0.20*	1975	Jackson Group	Dickinson, 1976, 1978
GARBYSCH-THANE		28.8447	-98.1650	Atascosa	Deposit	Open Pit	Past Producer	50,000-100,000	25,000-50,000	25,000-50,000	0.05	1983	Jackson Group	Eargle and Snider, 1956

GARCIA GARZA	28.8954 26.7021	-98.0684 -98.9265	Karnes Starr	Deposit Deposit	Open Pit Unknown	Unmined Unknown				2010 1981	Jackson Group Catahoula Formation Oakville Formation?	Dickinson, 1978 Adams and Smith, 1981 DOE, 2009
GEFFERT ISL	Unknown	Unknown	Bee	Deposit	ISR	Past	100,000-1,000,000	100,000-1,000,000	0.05	1987	Oakville Formation?	DOE, 2009
GEMBLER-LYSSY	28.9007	-98.1311	Karnes	Deposit	Open Pit	Producer Past				2010	Jackson Group	Bunker and Mackallor, 1973
GOLIAD MINE	28.8659	-97.3501	Goliad	Deposit	ISR	Development Unmined	>1,000,000	>1,000,000	0.05	2008	Goliad Sand	Carothers, 2008
GRIFFIN	29.1505	-97.6610	Karnes	Deposit	Open Pit	Unmined				2010	Jackson Group	Brandt, 2010
GRIFFIN PIT	29.1548	-97.6558	Gonzales	Deposit	Open Pit	Past	100,000-1,000,000	100,000-1,000,000	0.05*	1979	Jackson Group	Droddy and Hovorka, 1982a
GRUY MINE	27.3527	-98.7158	Jim Hogg	Deposit	ISR	Producer Unmined	100,000-1,000,000	100,000-1,000,000	0.09	2012	Oakville Formation	TCEQ, 2013
GUERRA	26.7690	-98.8699	Starr	Deposit	Unknown	Unmined				1981	Catahoula Formation	Adams and Smith, 1981
GUERRA-GARZA-CONZALES RANCH	26.4694	-98.8197	Starr	Prospect	N.A.	N.A.				1982	Catahoula Formation	Cherepon and Staubert, 1982a
GYP HILL	27.1847	-98.0732	Brooks	Deposit	ISR	Unmined				1981	Goliad Sand	Adams and Smith, 1981
H.V. JUSTICE FARM	30.0558	-96.8403	Fayette	Prospect	N.A.	N.A.				1982	Jackson Group	Staubert and Rogers, 1982
HAASE-MOY-WIATREK MINE	29.1217	-97.7035	Karnes	Deposit	Open Pit	Past	100,000-1,000,000	100,000-1,000,000	0.09*	1991	Jackson Group	DOE, 2009
HACKNEY, J.M. MINE	28.8761	-98.1374	Karnes	Deposit	Open Pit	Producer Past	50,000-100,000	50,000-100,000	0.12*	2009	Jackson Group	Bunker and Mackallor, 1973
HAHN LEASE 240 (ZAMZOW)	28.4975	-98.0628	Live Oak	Deposit	ISR	Past	10,000-25,000	10,000-25,000	0.05*	1989	Oakville Formation	Galloway et. al., 1982
HAIRLI, HARPER RANCH	Unknown 29.0464	Unknown -97.8458	Karnes Karnes	Deposit Prospect	Unknown N.A.	Producer Unmined N.A.	100,000-1,000,000	100,000-1,000,000	0.03*	1981 1982	Jackson Group Jackson Group	DOE, 2009 Droddy and Hovorka, 1982a, Eargle and Snider, 1956
HOBSON MINE	28.9453	-97.9889	Karnes	Deposit	ISR	Past	50,000-100,000	50,000-100,000	0.13	1983	Jackson Group	TCEQ, 2013
HOFFMAN PROSPECT	28.7703	-98.0000	Karnes	Prospect	N.A.	Producer				1982	Oakville Formation	Finch, 1967
HOFFMAN PROSPECT	28.7647	-97.9983	Karnes	Showing	N.A.	N.A.				1982	Oakville Formation	Droddy and Hovorka, 1982b
HOLIDAY, EL MESQUITE	27.4165	-98.7547	Duval	Deposit	ISR	Past	>1,000,000	>1,000,000	0.07*	2009	Catahoula Formation	Galloway and Kaiser, 1979
HOUSE	28.6127	-98.1766	Live Oak	Deposit	Open Pit	Producer Unmined	100,000-1,000,000	100,000-1,000,000	0.04*	1981	Catahoula Formation	Galloway and Kaiser, 1980
HOUSE-SEALE-TAYLOR PIT	28.6314	-98.1797	Live Oak	Deposit	Open Pit	Past	100,000-1,000,000	100,000-1,000,000	0.08*	2009	Catahoula Formation	Galloway and Kaiser, 1980
HURT MINE	28.7712	-98.1984	Atascosa	Deposit	Open Pit	Producer Past	100,000-1,000,000	100,000-1,000,000	0.06*	2009	Jackson Group	Dickinson, 1976
I.M. BRYSCH MINE (SOUTH BRYSCH)	28.9068	-98.0766	Karnes	Deposit	Open Pit	Producer Past	50,000-100,000	50,000-100,000	0.14*	2009	Jackson Group	Brandt, 2010
JACKPUMP	29.1750	-97.6880	Karnes	Deposit	Open Pit	Producer Past				1997	Jackson Group	Adams and Smith, 1981
JACOBS RANCH	29.1872	-97.5442	Gonzales	Prospect	N.A.	N.A.				1982	Catahoula Formation	Finch, 1967
JAMES PEYTON RANCH	28.8742	-98.1125	Karnes	Prospect	N.A.	N.A.				1982	Jackson Group	Greimel, 1982
JASKINIA TRACT	28.9667	-97.9667	Karnes	Prospect	N.A.	N.A.				1982	Jackson Group	Greimel, 1982 Eargle and Snider, 1956
KELLNER PIT	28.8323	-98.1276	Karnes	Deposit	Open Pit	Past	100,000-1,000,000	100,000-1,000,000	0.09*	2009	Jackson Group	Dickinson, 1976
KINGSVILLE DOME MINE	27.4158	-97.7801	Kleberg	Deposit	ISR	Producer Past	>1,000,000	>1,000,000	0.14	2013	Goliad Sand	TCEQ, 2013
KITTIE BURNS RANCH LEACH MINE KNIPSEL	28.2569 28.6200	-98.1783 -98.1840	Live Oak Live Oak	Deposit Deposit	ISR ISR	Unknown Unmined	100,000-1,000,000	100,000-1,000,000		1982 1982	Oakville Formation Catahoula Formation	Greimel, 1982 Adams and Smith, 1981, Smith, 1982
KOLAR LEASE	29.6586	-97.1261	Fayette	Deposit	Unknown	Past				2009	Catahoula Formation	Adams and Smith, 1981
KOPPLIN PIT	28.5181	-98.0625	Live Oak	Deposit	Open Pit	Producer Past	100,000-1,000,000	100,000-1,000,000	0.17*	2009	Oakville Formation	Galloway et. al., 1982

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Occurrence Name	Includes	Latitude	Longitude	County	Occurrence Type	Operation Type	Status in 2014	Total U ₃ O ₈ (lbs.)	Produced U ₃ O ₈ (lbs.)	In Situ U ₃ O ₈ resource (lbs.)	Grade (% U ₃ O ₈)	Date of reported resource and/or production	Host Unit	Reference
KORTH-HARTMAN-FINCH-OTTON		29.1116	-97.6473	Karnes	Deposit	Open Pit	Past Producer	> 1,000,000		> 1,000,000	0.13*	2009	Oakville Formation	Droddy and Hovorka, 1982a
KORZEKWA (CLIMAX) PIT		28.8956	-98.1293	Karnes	Deposit	Open Pit	Past Producer					2010	Jackson Group	Bunker and Mackallor, 1973
KORZEWA-NIESCHWITZ-725		28.9050	-98.1451	Karnes	Deposit	Open Pit	Past Producer	5,000–10,000	5,000–10,000		0.07*	1991	Jackson Group	DOE, 2009
KOTZLUR PIT		28.9968	-97.9008	Karnes	Deposit	Open Pit	Past Producer	100,000–1,000,000	100,000–1,000,000		0.05*	1976	Jackson Group	Bunker and Mackallor, 1973
KRAEJEIK		29.6483	-97.1311	Fayette	Prospect	N.A.	N.A.					1982	Jackson Group	Droddy and Hovorka, 1982a
KUNSCHIK STEINMANN		29.0703	-97.7775	Karnes	Deposit	Unknown	Unknown					1981	Jackson Group	Adams and Smith, 1981
L. SZEPANIK & SONS		28.8817	-98.1214	Karnes	Prospect	N.A.	N.A.					1982	Jackson Group	Greimel, 1982
LA PALANGANA MINE		27.6915	-98.3927	Duval	Deposit	ISR	Operating	> 1,000,000	100,000–1,000,000	> 1,000,000	0.13	2010	Goliad Sand	Rigby et al., 2010
LABUS MINE		28.9673	-97.9606	Karnes	Deposit	Open Pit	Past Producer	100,000–1,000,000	100,000–1,000,000		0.08*	1983	Jackson Group	Weinzapfel, 1981
LABUS-HOFFMAN PIT		28.9400	-98.0046	Karnes	Deposit	Open Pit	Past Producer					2010	Jackson Group	Greimel, 1982
LAMPRECHT MINE		28.5060	-98.0520	Live Oak	Deposit	ISR	Past Producer	> 1,000,000	> 1,000,000		0.07*	1989	Oakville Formation	Ludwig et al., 1982
LANDELL		27.9583	-98.6408	Duval	Prospect	N.A.	N.A.					1982	Catahoula Formation	Cherepon and Stauber, 1982b
LAS PALMAS MINE		27.3701	-98.6452	Duval	Deposit	ISR	Past Producer	100,000–1,000,000	100,000–1,000,000		0.05*	1985	Oakville Formation	TCEQ, 2013
LAUW PIT		28.8786	-98.1275	Karnes	Deposit	Open Pit	Past Producer	50,000–100,000	50,000–100,000		0.12*	1974	Jackson Group	Dickinson and Duval, 1977
LEDBETTER, NORTH SCHMIDT FARM		30.1631	-96.7500	Washington	Prospect	N.A.	N.A.					1982	Jackson Group	Stauber and Rogers, 1982
LONGORIA MINE		27.3749	-98.7822	Duval	Deposit	ISR	Past Producer	50,000–100,000	50,000–100,000		0.05*	2009	Catahoula Formation	TCEQ, 2013
LOS FINADOS		27.0100	-97.8270	Kendry	Prospect	N.A.	Exploration					2012	Goliad Sand	URI, 2013
LOVELACE		28.9440	-97.8880	Karnes	Deposit	Open Pit	Past Producer	10,000–25,000	10,000–25,000		0.07*	1980	Catahoula Formation	Eargle et al., 1961b
LUCKETT PIT		28.9095	-98.1146	Karnes	Deposit	Open Pit	Past Producer	100,000–1,000,000	100,000–1,000,000		0.20*	1973	Jackson Group	Bunker and Mackallor, 1973
LUCKY		29.4847	-97.8931	Guadalupe	Prospect	N.A.	N.A.					1982	Claiborne Group	Droddy and Hovorka, 1982a
LYNE 171		28.4215	-98.0716	Live Oak	Deposit	Open Pit	Past Producer	> 1,000,000	> 1,000,000		0.04*	1988	Oakville Formation	Adams and Smith, 1981
LYSSY NIESTORY MINE		28.8980	-98.1285	Karnes	Deposit	Open Pit	Past Producer	100,000–1,000,000	100,000–1,000,000		0.21*	1972	Jackson Group	Bunker and Mackallor, 1973
M. SICKENIUS		28.8989	-98.0811	Karnes	Prospect	N.A.	N.A.					1982	Jackson Group	Greimel, 1982
MABEL NEW SUPERIOR PIT		28.5584	-98.2900	Live Oak	Deposit	Open Pit	Past Producer	100,000–1,000,000	100,000–1,000,000		0.27*	2009	Catahoula Formation	Eargle et al., 1975
MALONEY RANCH		29.8183	-97.0128	Fayette	Prospect	N.A.	N.A.					1982	Jackson Group	Droddy and Hovorka, 1982a
MANKA PIT		28.9343	-98.0328	Karnes	Deposit	Open Pit	Past Producer	100,000–1,000,000	100,000–1,000,000		0.16*	2009	Jackson Group	Dickinson, 1976
MANUEL RAMIREZ-REFUGIO GUTIERREZ RANCH MARSHALL		26.9583	-99.3000	Zapata	Prospect	N.A.	N.A.					1982	Claiborne Group	Cherepon and Stauber, 1982b
MARTIN		28.0000	-98.3771	Duval, McMullen	Prospect	N.A.	Exploration					2012	Oakville Formation (and Goliad Sand?)	URI, 2013
MARTIN		28.5018	-98.0674	Live Oak	Deposit	Open Pit	Past Producer	100,000–1,000,000	5,000–10,000	100,000–1,000,000	0.09*	1989, 1982	Oakville Formation	Galloway et al., 1982
MARTIN EXPLORATION		28.5000	-98.0700	Live Oak	Prospect	N.A.	Exploration					2012	Oakville Formation	Galloway et al., 1982

MARVIN HACKNEY MC CRADY MINE	28.8600 28.8252	-98.1506 -98.1212	Karnes Karnes	Prospect Deposit	N.A. Open Pit	N.A. Past	100,000-1,000,000	100,000-1,000,000	0.14*	1982 1991	Jackson Group Jackson Group	Greimel, 1982 Dickinson, 1976
MC LEAN (MARRES) 1 + 2 (MCLEAN 2)	28.4847	-98.0864	Live Oak	Deposit	Open Pit	Past	>1,000,000	>1,000,000	0.18*	1991	Oakville Formation	Galloway et al., 1982
MC LEAN-BOWMAN (MCLEAN)	28.4884	-98.0842	Live Oak	Deposit	Open Pit	Past	100,000-1,000,000	100,000-1,000,000	0.23*	1985	Oakville Formation	Galloway et al., 1982
MCBRYDE MINE	27.3592	-98.6739	Jim Hogg	Deposit	ISR	Past	50,000-100,000	50,000-100,000	0.05*	2009	Oakville Formation	TCEQ, 2013
MCGILLIE PROPERTY MCCRIF	30.5806 28.4780	-95.8806 -98.0952	Grimes Live Oak	Prospect Deposit	N.A. Open Pit	N.A. Unmined	100,000-1,000,000	100,000-1,000,000	0.04*	1982 1981	Oakville Formation Oakville Formation	Henke et al., 1982 Galloway et al., 1979
MOZCYGEMBA PIT	28.9351	-98.0429	Karnes	Deposit	Open Pit	Past	50,000-100,000	50,000-100,000	0.07*	1981	Jackson Group	Dickinson, 1976
MORREL MINE	28.2700	-98.2344	Live Oak	Deposit	Unknown	Unknown				1982	Catahoula Formation	Greimel, 1982
MOSER MINE	28.2530	-98.2080	Live Oak	Deposit	ISR	Past	>1,000,000	100,000-1,000,000		2013, 1982	Oakville Formation	TCEQ, 2013, Galloway et al., 1982
MOSSER EXPLORATION MT. LUCAS MINE	27.9834 28.1801	-97.9678 -97.9448	Jim Wells Live Oak	Prospect Deposit	N.A. ISR	Exploration Past	>1,000,000	>1,000,000	0.06*	2013 1989	Goliad Sand Goliad Sand	URI, 2013 Dahlkamp, 2010
NDC SURFACE MINE	27.9883	-98.6981	Duval	Prospect	N.A.	N.A.				1982	Catahoula Formation	Cherepon and Stauber, 1982a
NELL PROJECT	28.6777	-98.0620	Live Oak	Deposit	ISR	Past	>1,000,000	>1,000,000	0.05*	2010	Catahoula Formation	Adams and Smith, 1981
NICHOLS NIESCHWITZ	28.8844 28.9036	-98.0328 -98.0831	Karnes Karnes	Deposit Deposit	ISR Open Pit	Exploration Unmined	>1,000,000	>1,000,000	0.07	2009 2010	Jackson Group Jackson Group	Carothers, 2009 Dickinson, 1978
NO. GOVERNMENT WELLS	27.9007	-98.6759	Duval	Deposit	Unknown	Unknown				1981	Catahoula Formation	Adams and Smith, 1981
NUHN-KORZEKWA MINE	28.8914	-98.1308	Karnes	Deposit	Open Pit	Past	100,000-1,000,000	100,000-1,000,000	0.13*	1981	Jackson Group	Bunker and Mackallor, 1973
OEHL-LUK-BUNTING	Unknown	Unknown	Gonzales	Deposit	Unknown	Unmined	100,000-1,000,000	100,000-1,000,000	0.06*	1981	Catahoula Formation?	DOE, 2009
O'HERN MINE	27.3976	-98.8077	Webb	Deposit	ISR	Past	>1,000,000	>1,000,000	0.04*	2009	Catahoula Formation	TCEQ, 2013
OLD KELSEY RANCH	26.4564	-98.8531	Starr	Prospect	N.A.	N.A.				1982	Catahoula Formation	Cherepon and Stauber, 1982b
OLIVARES #5, SUN FIELD	26.7620	-98.4667	Starr	Prospect	N.A.	N.A.				1982	Goliad Sand	Cherepon and Stauber, 1982b
OTTO GAWLIC PALANGANA DOME	28.9708 27.6915	-98.0486 -98.3927	Karnes Duval	Prospect Deposit	N.A. ISR	N.A. Past	100,000-1,000,000	100,000-1,000,000	0.08	1982 1988	Jackson Group Goliad Sand	Greimel, 1982 Rigby et al., 2010; Pool, 2013
PANNA MARIA MINE	28.9661	-97.9430	Karnes	Deposit	Open Pit	Past	>1,000,000	>1,000,000	0.05*	1986	Jackson Group	Doddy and Hovorka, 1982a; Weinzapfel, 1981
PAWLEK D.B. 763	28.8679	-98.1137	Karnes	Deposit	Open Pit	Past	100,000-1,000,000	100,000-1,000,000	0.08*	1991	Jackson Group	Dickinson, 1976
PAWLEK-LYSSY-LAUW	28.8679	-98.1137	Karnes	Deposit	Open Pit	Past	100,000-1,000,000	100,000-1,000,000	0.08*	1991	Jackson Group	Dickinson, 1976
PAWLUK MINE	28.2848	-98.1903	Live Oak	Deposit	ISR	Past				1990	Oakville Formation	TCEQ, 2013
PAWNEE MINE	28.6613	-97.9676	Bee	Deposit	ISR	Past	50,000-100,000	50,000-100,000		2013	Oakville Formation	TCEQ, 2013
PERKINS PETER'S RANCH NO. 1	28.2887 27.7033	-98.0997 -98.7481	Live Oak Duval	Deposit Prospect	Unknown N.A.	Unmined N.A.	>1,000,000	>1,000,000	0.04*	1982 1981	Oakville Formation Catahoula Formation	Smith, 1982 Cherepon and Stauber, 1982a
PETER'S RANCH NO. 2	27.6983	-98.7514	Duval	Prospect	N.A.	N.A.				1981	Catahoula Formation	Cherepon and Stauber, 1982a
PFEIL-WEIG MINE	28.8124	-98.1284	Atascosa	Deposit	Open Pit	Past	100,000-1,000,000	100,000-1,000,000	0.09*	1981	Jackson Group	Dickinson and Duval, 1977
PIEDRAS PINTAS PIEDRE LUMBRE 201 (201-205)	27.6350 27.9910	-98.3903 -98.6050	Duval Duval	Deposit Deposit	ISR ISR	Unmined Past	>1,000,000	100,000-1,000,000	0.48	1982 1986	Goliad Sand Catahoula Formation	Dahlkamp, 2010 Crook, 1979
PIEDRE LUMBRE 202	27.9880	-98.6310	Duval	Deposit	ISR	Unmined	100,000-1,000,000	100,000-1,000,000	0.48	1986	Catahoula Formation	Crook, 1979

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Occurrence Name	Includes	Latitude	Longitude	County	Occurrence Type	Operation Type	Status in 2014	Total U ₃ O ₈ (lbs.)	Produced U ₃ O ₈ (lbs.)	In Situ U ₃ O ₈ resource (lbs.)	Grade (% U ₃ O ₈)	Date of reported resource and/or production	Host Unit	Reference
PIERZYCA A.		Unknown	Unknown	Karnes	Deposit	Unknown	Unmined	25,000–50,000		25,000–50,000	0.04*	1981	Jackson Group	DOE, 2009
PROBST		28.5007	-98.0735	Live Oak	Deposit	Open Pit	Unmined					2010	Oakville Formation	Galloway et al., 1979
RAY POINT-SUSQUEHANNA TAILINGS		28.5244	-98.1006	Live Oak	Processing Facility / Tailings	Solution Leach	Past Producer	10,000–25,000	10,000–25,000		0.05*	1981	Oakville Formation-sourced ore presumed	DOE, 2009
RHODE RANCH PROJECT		28.1397	-98.4156	McMullen	Deposit	Open Pit	Past Producer	>1,000,000	>1,000,000		0.3	2013	Oakville Formation	Dahlkamp, 2010; Barnes, 1976
RICHARD RUDOLF RING PROTOTYPE		28.7411	-98.1486	Live Oak	Prospect	N.A.	N.A.					1982	Jackson Group	Greimel, 1982
		29.6989	-97.1325	Fayette	Prospect	N.A.	N.A.					1982	Jackson Group	Droddy and Hovorka, 1982a
ROSANSKY RANCH		29.9861	-97.2508	Bastrop	Prospect	N.A.	N.A.					1982	Claiborne Group	Droddy and Hovorka, 1982a; Weinzaepfel, 1981
ROSENBROCK/CARMODY PIT	ROSENBROCK	28.8355	-98.0900	Karnes	Deposit	Open Pit	Past Producer	100,000–1,000,000	100,000–1,000,000		0.09*	1985	Jackson Group	Dickinson and Duval, 1977
ROSITA MINE		27.8281	-98.3975	Duval	Deposit	ISR	Past Producer	>1,000,000	>1,000,000	>1,000,000	0.15	2009, 1994	Oakville Formation	Ambrose, 2007
ROSITA SOUTH RYAN PIT		27.7951	-98.4430	Duval	Prospect	N.A.	Exploration				0.07*	2012	Oakville Formation	URI, 2013
		28.5990	-98.2354	Live Oak	Deposit	Open Pit	Past Producer	25,000–50,000	25,000–50,000			1981	Catahoula Formation	Adams and Smith, 1981
SALVADOR SALINAS		26.6606	-98.8767	Starr	Prospect	N.A.	N.A.					1982	Catahoula Formation	Cherepon and Stauber, 1982b
SALVO		28.2794	-97.7883	Bee	Deposit	ISR	Exploration	>1,000,000		>1,000,000	0.08	2011	Goliad Sand	Carothers, 2010
SAN CARLOS		26.7562	-98.9238	Starr	Deposit	Unknown	Unknown					1981	Catahoula Formation	Adams and Smith, 1981
SANTONIO		27.5180	-98.9030	Webb	Deposit	Unknown	Unmined					1981	Catahoula Formation	Dahlkamp, 2010
SAWYER URANIUM PROSPECT		28.5850	-98.1170	Live Oak	Deposit	ISR	Unmined					1982	Catahoula Formation	Brewster, 1982
SCHNITZER FARM, RIGHTMER		29.8183	-97.0492	Fayette	Prospect	N.A.	N.A.					1982	Jackson Group	Droddy and Hovorka, 1982a
SEABOARD LEASE		28.9919	-97.9761	Karnes	Showing	N.A.	N.A.					1982	Jackson Group	Droddy and Hovorka, 1982b
SEARCY-PAWELEK PIT		28.9039	-98.1123	Karnes	Deposit	Open Pit	Past Producer	100,000–1,000,000	100,000–1,000,000		0.09*	1974	Jackson Group	Dickinson and Duval, 1977
SEJITA	SEJITA DOME	27.3238	-98.4327	Duval	Deposit	ISR	Unmined					1981	Goliad Sand	Dahlkamp, 2010
SICKENIUS PIT		28.8852	-98.0956	Karnes	Deposit	Open Pit	Past Producer	>1,000,000	>1,000,000		0.09*	2009	Jackson Group	Dickinson and Duval, 1977
SICKENIUS WEST		28.8766	-98.1013	Karnes	Deposit	Open Pit	Past Producer					2010	Jackson Group	Dickinson and Duval, 1977
SIKES RANCH		29.5369	-97.2372	Gonzales	Prospect	N.A.	N.A.					1982	Jackson Group	Droddy and Hovorka, 1982a
SILVER LAKE		27.3330	-98.6680	Jim Hogg	Deposit	ISR	Unmined	100,000–1,000,000		100,000–1,000,000		1982	Oakville Formation	TCEQ, 2013
SKYLES MANSION		28.9506	-98.0231	Karnes	Prospect	N.A.	N.A.					1982	Catahoula Formation	Greimel, 1982
SMITH E.E. URANIUM PIT		28.5045	-98.0334	Live Oak	Deposit	Open Pit	Past Producer	100,000–1,000,000	100,000–1,000,000		0.13*	2009	Oakville Formation	Galloway et al., 1982
SMITH, W.A. 2-670		29.1628	-97.6368	Gonzales	Deposit	Open Pit	Past Producer	100,000–1,000,000	100,000–1,000,000		0.05*	2009	Jackson Group	Droddy and Hovorka, 1982a
SOILZ		28.7636	-98.1089	Live Oak	Prospect	N.A.	N.A.					1982	Jackson Group	Greimel, 1982
SPEED LEASE		29.7917	-97.0417	Fayette	Deposit	Unknown	Unmined	50,000–100,000		50,000–100,000	0.05*	2009	Jackson Group	Droddy and Hovorka, 1982a
SPOELSTRA, M.-673		Unknown	Unknown	Fayette	Deposit	Unknown	Unmined	100,000–1,000,000		100,000–1,000,000	0.06*	2009	Jackson Group	DOE, 2009
STEINMAN-LATTA-SWANSON-HAASE		29.1281	-97.6964	Karnes	Deposit	Open Pit	Past Producer	100,000–1,000,000	100,000–1,000,000		0.07*	2009	Jackson Group	Adams and Smith, 1981
STOELTJE MINE		28.9368	-98.0162	Karnes	Deposit	Open Pit	Past Producer	100,000–1,000,000	100,000–1,000,000		0.13*	1991	Jackson Group	Dickinson, 1976; Dickinson and Duval, 1977

STRAKE	Unknown	Unknown	Duval	Deposit	Unknown	Unknown	100,000–1,000,000	100,000–1,000,000	0.06*	1978	Catahoula Formation	DOE, 2009
STRICKHAUSEN 1762	Unknown	Unknown	Karnes	Deposit	Unknown	Unmined	100,000–1,000,000	100,000–1,000,000	0.05*	2009	Jackson Group	DOE, 2009
STUELETJE URANIUM PIT	28.9364	-98.0142	Karnes	Deposit	Open Pit	Producer				2005	Jackson Group	Greimel, 1982
SULFUR CREEK LEACH MINE	28.4989	-98.0503	Live Oak	Deposit	ISR	Past				1982	Oakville Formation	Greimel, 1982
SUPERIOR OIL LEASE	28.8919	-98.1269	Karnes	Prospect	N.A.	Producer				1982	Jackson Group	Greimel, 1982
SWENNEY SWITCH	28.2214	-97.8834	Live Oak	Deposit	ISR	Unmined			0.1	1982	Goliad Sand	Dahlkamp, 2010
SWIENTEK MINE-PANNA MARIA OPERATIONS	28.9830	-97.9253	Karnes	Deposit	Open Pit	Producer	>1,000,000			2010	Jackson Group	Weinzapfel, 1981
T. D. SMITH	28.0069	-98.5358	Duval	Prospect	N.A.	N.A.				1982	Catahoula Formation	Greimel, 1982
TAYLOR	29.1460	-97.5612	DeWitt	Deposit	Unknown	Unknown				1981	Catahoula Formation	Adams and Smith, 1981
TEX-1 MINE	28.9076	-98.0168	Karnes	Deposit	ISR	Past	100,000–1,000,000	100,000–1,000,000	0.14*	1990	Jackson Group	TCEQ, 2013
THOMAS-KVANDEL-DYBOWSKI	29.1251	-97.6270	Karnes	Deposit	Open Pit	Producer	>1,000,000		0.07*	1976	Oakville Formation	Droddy and Hovorka, 1982a
TOM-RETZLOF	28.7616	-98.1887	Atascosa	Deposit	Open Pit	Producer	100,000–1,000,000		0.08*	2009	Jackson Group	Brandt, 2010
TREVINO MINE	27.3739	-98.6775	Duval	Deposit	ISR	Unmined	100,000–1,000,000	100,000–1,000,000	0.04*	1986	Oakville Formation	TCEQ, 2013
TRIAL PIT	28.9469	-97.9822	Karnes	Prospect	N.A.	N.A.				1988	Jackson Group	Adams and Smith, 1981
TRICOUNTY	28.0385	-98.3075	Duval	Deposit	Unknown	Unknown				1981	Oakville Formation	Adams and Smith, 1981
TURNER MINE	28.8675	-98.1108	Karnes	Deposit	Open Pit	Past	10,000–25,000			1982	Jackson Group	Dickinson, 1976, 1978
UNKNOWN	27.8719	-98.7722	Duval	Showing	N.A.	N.A.				1982	Catahoula Formation	Cherepon and Stauber, 1982b
UNKNOWN	27.9400	-98.6514	Duval	Showing	N.A.	N.A.				1982	Catahoula Formation	Cherepon and Stauber, 1982b
UNKNOWN	27.9750	-98.6958	Duval	Showing	N.A.	N.A.				1982	Catahoula Formation	Cherepon and Stauber, 1982b
UNNAMED RADIOACTIVE ANOMALY	29.1653	-98.6981	Atascosa	Anomaly	N.A.	N.A.				1982	Claiborne Group	Greimel, 1982
UNNAMED RADIOACTIVE ANOMALY	29.2631	-98.3022	Bexar	Anomaly	N.A.	N.A.				1982	Claiborne Group	Greimel, 1982
UNNAMED RADIOACTIVE ANOMALY	29.0242	-98.8733	Frio	Anomaly	N.A.	N.A.				1982	Claiborne Group	Greimel, 1982
UNNAMED RADIOACTIVE ANOMALY	29.0281	-98.8644	Frio	Anomaly	N.A.	N.A.				1982	Claiborne Group	Greimel, 1982
UNNAMED RADIOACTIVE ANOMALY	29.3297	-98.1922	Wilson	Anomaly	N.A.	N.A.				1982	Wilcox Formation	Greimel and Ambrose, 1982
USGS GP-247_28	29.0239	-97.8768	Karnes	Prospect	N.A.	N.A.				1961	Jackson Group	Trumbull et al., 1961
USGS GP-250_11	28.8888	-98.1006	Karnes	Prospect	N.A.	N.A.				1961	Jackson Group	Brown et al., 1961
USGS GP-250_17	28.8858	-98.1121	Karnes	Prospect	N.A.	N.A.				1961	Jackson Group	Brown et al., 1961
USGS GP-250_18	28.9201	-98.0713	Karnes	Prospect	N.A.	N.A.				1961	Jackson Group	Brown et al., 1961
USGS GP-250_21	28.8975	-98.1141	Karnes	Prospect	N.A.	N.A.				1961	Jackson Group	Brown et al., 1961
USGS GP-250_8	28.9379	-98.0435	Karnes	Prospect	N.A.	N.A.				1961	Jackson Group	Brown et al., 1961
USGS GP-250_9	28.9387	-98.0411	Karnes	Prospect	N.A.	N.A.				1961	Jackson Group	Brown et al., 1961
USGS GP-251-6	28.9834	-97.9810	Karnes	Prospect	N.A.	N.A.				1961	Jackson Group	Eagle and Moxham, 1961
USGS GP-252_2	28.8613	-98.1507	Karnes	Prospect	N.A.	N.A.				1961	Jackson Group	Eagle et al., 1961a
USGS GP-252_29	28.8407	-98.1634	Karnes	Prospect	N.A.	N.A.				1961	Jackson Group	Eagle et al., 1961a
USGS GP-252-4	28.8607	-98.1252	Karnes	Prospect	N.A.	N.A.				1961	Jackson Group	Eagle et al., 1961a
USGS GP-253_1	28.7609	-97.9982	Karnes	Prospect	N.A.	N.A.				1961	Oakville Formation	Eagle and Moxham, 1961
VASQUEZ MINE	27.3699	-98.7116	Duval	Deposit	ISR	Past	100,000–1,000,000	50,000–100,000	0.08	2009	Oakville Formation	Ambrose, 2007
W. DZUIK UL-1798	28.8232	-98.1058	Karnes	Deposit	Open Pit	Producer	25,000–50,000		0.08*	2009	Jackson Group	Brandt, 2010
W. SARANOSA	27.8549	-98.6810	Duval	Deposit	Unknown	Producer				1981	Catahoula Formation	Adams and Smith, 1981
WALDECK, COOPER FARM	30.0517	-96.8258	Fayette	Prospect	N.A.	N.A.				1982	Jackson Group	Stauber and Rogers, 1982
WASHINGTON-FAYETTE	30.1510	-96.7140	Washington	Deposit	ISR	Unknown				1979	Catahoula Formation	Galloway and Kaiser, 1979

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Occurrence Name	Includes	Latitude	Longitude	County	Occurrence Type	Operation Type	Status in 2014	Total U ₃ O ₈ (lbs.)	Produced U ₃ O ₈ (lbs.)	In Situ U ₃ O ₈ resource (lbs.)	Grade (% U ₃ O ₈)	Date of reported resource and/or production	Host Unit	Reference
WEDDINGTON URANIUM PIT		28.7986	-98.0964	Karnes	Prospect	N.A.	N.A.					1982	Jackson Group	Greimel, 1982
WEDDINGTON-NORTH		28.8420	-98.1232	Karnes	Deposit	Open Pit	Past Producer					2010	Jackson Group	Brandt, 2010
WEDDINGTON-SOUTH (CONOCO)		28.8291	-98.1157	Karnes	Deposit	Open Pit	Past Producer					2010	Jackson Group	Dickinson, 1976, 1978
WEDDINGTON-SUSQUEHANA		28.8494	-98.1198	Karnes	Deposit	Open Pit	Past Producer	>1,000,000	>1,000,000		0.19*	2009	Jackson Group	Dickinson, 1976, 1978
WEDDINGTON-TENNECO		28.8370	-98.1226	Karnes	Deposit	Open Pit	Past Producer	>1,000,000	>1,000,000		0.13*	1991	Jackson Group	Dickinson, 1976, 1978
WEIDERKEHR LEASE		27.9272	-98.6325	Duval	Prospect	N.A.	N.A.					1982	Catahoula Formation	Cherepon and Stauber, 1982a
WEST COLE MINE		27.4616	-98.8452	Webb	Deposit	ISR	Past Producer	100,000-1,000,000	100,000-1,000,000		0.05*	2009	Catahoula Formation	TCEQ, 2013
WEST PIT-PANNA MARIA OPERATIONS		28.9664	-97.9521	Karnes	Deposit	Open Pit	Past Producer					2010	Jackson Group	Weinzapfel, 1981
WILLIE GABRISH		28.8667	-98.1681	Atascosa	Prospect	N.A.	N.A.					1982	Jackson Group	Greimel, 1982
WINERICH MINE		28.9716	-97.8343	Karnes	Deposit	Open Pit	Past Producer	100,000-1,000,000	100,000-1,000,000		0.08*	2009	Oakville Formation	Droddy and Hovobka, 1982a
WOODY PURSCH		28.0536	-98.5408	McMullen	Prospect	N.A.	N.A.					1982	Catahoula Formation	Greimel, 1982
WRIGHT PIT		28.8200	-98.1228	Karnes	Deposit	Open Pit	Past Producer	100,000-1,000,000	100,000-1,000,000		0.14*	1974	Jackson Group	Dickinson, 1976
WURZBACH		Unknown	Unknown	Karnes	Deposit	Open Pit	Past Producer	25,000-50,000	25,000-50,000		0.15*	1972	Jackson Group	DOE, 2009
ZAMZOW (ALL)		28.4969	-98.0675	Live Oak	Deposit	ISR	Past Producer	>1,000,000	>1,000,000		0.06*	1989	Oakville Formation	Reynolds et al., 1980b
ZIDEN		29.5420	-97.1960	Lavaca	Deposit	Unknown	Unknown					1981	Catahoula Formation	Adams and Smith, 1981
ZINK AND JOYCE CLAIMS		27.9792	-98.6792	Duval	Showing	N.A.	N.A.					1982	Catahoula Formation	Cherepon and Stauber, 1982b

* Indicates grade was calculated using tonnage and produced U₃O₈ information.

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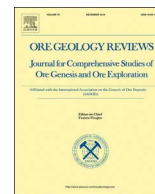
DOI: <https://doi.org/10.1016/j.oregeorev.2017.07.022>



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Corrigendum

Corrigendum to “Genetic and grade and tonnage models for sandstone-hosted roll-type uranium deposits, Texas Coastal Plain, USA” [Ore Geol. Rev. 80 (2017) 716–753]



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The authors regret to report that a mistake was found in the article after its availability online. We kindly request that you correct the following mistake:

On page 724, Fig. 5, in the explanation box on the lower right, the groundwater concentration should read “ppb”, not “ppm”.

DOI of original article: <http://dx.doi.org/10.1016/j.oregeorev.2016.06.013>

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<http://dx.doi.org/10.1016/j.oregeorev.2017.07.022>

Available online 01 August 2017

0169-1368/ Published by Elsevier B.V.