# Devonian Shelf to Basin Facies Distributions and Source Rock Potential, South-central and Southwestern New Mexico

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ABSTRACT

The often poorly exposed Devonian section in southern New Mexico contains complex vertical and lateral ramp-to-basin facies relationships. Ramp environment carbonates and clastics outcrop in the San Andres and Sacramento mountains, and grade southward into the Percha Formation black shale and Canutillo Formation cherty carbonate. Regional facies relationships suggest the Percha shales are of deep water rather than of shallow origin. The Canutillo Formation has variously been interpreted as basin noviculite and shallow shelf.

The Percha Formation (Permian Basin Woodford-equivalent) black shale possesses at least local hydrocarbon source rock potential. The black shale is distributed in a relatively narrow east-west trend extending over 350 km, varying in width from ~30 km near Las Cruces to ~100 km near Deming. It reaches a maximum measured thickness of 76 m. Total organic carbon ranges from less than 1% in southwestern New Mexico to 3.68% in the south-central area. Maturity is highly variable owing to differences in overburden thickness as well as changing heat flow due to local igneous intrusions and regional tectonic rifting, all factors associated with Tertiary Rio Grande Rift tectonism. Type III kerogen is dominant in southwestern New Mexico and Type II/III is present in south-central New Mexico, indicating gas prone to mixed gas/oil prone organic matter. Hydrocarbon expulsion timing is modeled as limited to the Late Paleozoic in southwest New Mexico, but extending variably from Late Paleozoic through Recent in south-central New Mexico. The likelihood of currently active Devonian source rocks in conjunction with numerous potential reservoir units, structural and statigraphic trapping mechanisms, documented hydrocarbon shows, and a recent gas discovery provides encouragement that additional economic hydrocarbon deposits exist within south-central New Mexico.

## Introduction

This study's goal is to provide regional context for Devonian stratigraphic and source rock information in southern New Mexico's Tularosa Basin area, a frontier province for hydrocarbon exploration (Pyron and Grey, 1985; Pyron, 2000; Figures 1 and 2). Major discussion topics include: (1) Devonian facies relationships, including new isopach, lithology type percent, and paleogeography maps, and (2) characterization of Devonian shales for hydrocarbon source rock potential, including thickness, richness, maturity, kerogen types, and burial history/expulsion timing.

The Devonian succession in southern New Mexico has a long history of stratigraphic study (e.g. Nelson, 1940; Stevenson, 1945; Laudon and Bowsher, 1949; Kottlowski et al.,1956; Pray, 1961; Kottlowski, 1963; Rosado, 1970; LeMone, 1982, 1996; Sarouf, 1984; Day, 1988, 1998; Figure 1), however, only a limited number of reports place the complex facies into a regional context (Kottlowski, 1963; Bowsher, 1967; Raatz, 2002) or discuss organic geochemistry and thermal history (Broadhead et al., 1998; Broadhead, 2002). Table 1 lists named well and outcrop locations used in this study, with numbers keyed to locations in Figure 3. A total of 151 data points were used to construct a Devonian isopach map (Figure 4), and from those locations with sufficient information available, a series of lithology maps were generated (% total shale, % black shale, % siltstone, % sandstone, % carbonate) (Figures 5 - 9). Paleogeography and stratigraphic trends are summarized (Figures 10 -12), followed by discussions of Devonian total organic carbon (% TOC) (Figure 13) and maturity and regional heat flow, includeing structural styles (Figures 14 – 17). Burial History models were constructed for two wells, Grim Mobil-32 #1 well in southern Dona Ana County and McGregor GDP 51-8 well in southwestern Otero County (Figures 18 – 23). These wells were selected because they represent end member environments: Grim Mobil is a deep well (22,000') in the center of a Tertiary rift basin that experienced relatively normal regional heat flow, whereas the McGregor well is shallow (4200') but experienced highly elevated heat flow due to local Rio Grande Rift igneous intrusives.

## Stratigraphy

### Overview

The Middle to Late Devonian formations present in southern New Mexico unconformably overlie the Silurian Fusselman Formation and underlie Mississippian units (Figure 2). They are composed of thin-bedded and recessive barren black shales and locally fossiliferous gray to brown shales, siltstones, sandstones, and carbonates. In the San Andres and Sacramento Mountains, Devonian strata representing largely middle ramp or shelf environments can be grossly divided into two major unconformity-bounded packages: the Givetian clastic-dominated Oñate Formation and the upper Frasnian-Famennian mixed clastic/carbonate Sly Gap and Contadero formations (Day, 1988; Figure 2). These ramp/shelf deposits grade southward into a narrow (~30 km) E-W trending elongate band of Percha Formation shales, consisting of lower and middle black, barren shales (Ready Pay Member) and upper gray, calcareous, fossiliferous shales (Box Member) (Kottlowski, 1963; Rosado, 1970; Figures 4 – 11). Further south in the Franklin Mountains, Percha shales grade into and are underlain by the Canutillo Formation, a cherty carbonate (Figures 4 – 11). The Percha Formation widens to the west, extending from northern Grant and Sierra counties southward to Deming and perhaps into Mexico (Figures 5 and 10). To the far west, beginning approximately at Lordsburg, the shaley facies becomes more sandy and carbonate-rich as it approaches the shelf areas of Arizona and the boot heel of New Mexico, correlating to the Portal and Swisshelm formations. Devonian formations are well established within individual mountain ranges, although members continue to undergo revision and correlation between ranges is not always clear (see Kottlowski et al., 1956; Seager, 1981; Sorauf, 1984; Kottlowski and LeMone, 1994).

### Northern Shelf

*Oñate Formation:* The Oñate Formation (Stevenson, 1945; Figure 2) of the Sacramento and San Andres mountains area is of late Givetian age and unconformably overlies the Fusselman, while to the south in the Organ/Franklin Mountains it is age equivalent to portions of the Percha Formation (Figure 11). In the Sacramento Mountains the Oñate consists of open-marine ramp/shelf deposits composed of gray silty dolomite, dolomitic siltstone, and minor sandstone with bryozoans, brachiopods, and local chert (Pray, 1961). It thins from 18 m in the south-central Sacramentos to 6 m in the far northern and southern reaches of the range (Pray, 1961). In the Hueco Mountains, 32 m of sparsely fossiliferous shales, silty shales, and silty limestones may correlate to the Oñate, Sly Gap, and Percha (Kottlowski, 1963). The lower Oñate in the San Andres Mountains is similar to the Sacramento Mountain sections, augmented in the central range by nondolomitized wackestones containing corals, crinoids, brachiopods and bryozoans. The upper Oñate in the San Andres Mountains is clastic-rich, with siltstones, shale, and an upper cross-bedded sandstone unit documented (Kottlowski et al., 1956; Sorauf, 1984). The formation thins to the north and south from its maximum of 26 m in San Andres Canyon, becoming sandier to the north and shalier to the south.

*Sly Gap Formation:* The Sly Gap Formation (Stevenson, 1945; Figure 2), of Frasnian age, disconformably overlies the Oñate (Pray, 1961; Day, 1988). It is present in the northern and central Sacramento Mountains, the entire San Andres Mountains, and is age-equivalent to part of the Percha Formation in the Organ/Franklin Mountains (Pray, 1961; Seager, 1981; Sorauf, 1984; Figure 11). In the Sacramento Mountains the Sly Gap Formation contains interbeds of calcareous shale, thin-to-nodular fossiliferous lime mudstone, and lesser black shale, weathering to a distinctive yellowish color (Pray, 1961). Laudon and Bowsher (1941, 1949), Stevenson (1945), and Pray (1961) considered various upper beds of black shale in the southern Sacramento Mountains as belonging to the Percha Formation, although other workers interpreted them as basin facies of the Sly Gap Formation (Kottlowski et al., 1956). In the San Andres Mountains the Sly Gap Formation consists of nodular interbeds of fossiliferous (colonial and solitary corals, brachiopods, crinoids, ammonoids, gastropods, stromatoporoids), calcareous, silty shale, silty limestone, and calcareous siltstone (Kottlowski et al., 1956; Sorauf, 1984; Kottlowski and LeMone, 1994). In the southern San Andres Mountains the Sly Gap is composed almost completely of dark gray to black shales deposited in anoxic environments (Kottlowski et al., 1956; Day, 1988).

*Contadero Formation:* The Contadero Formation (Stevenson, 1945; Figure 2) is recognized in the northern San Andres Mountains and originally incorporated all strata between the Sly Gap Formation and the Mississippian, but was revised by Flower (in Kottlowski et al., 1956) to include what were originally upper Sly Gap units and also exclude upper dark shales with Fammenian fauna, which were placed in the Percha Formation. Sorauf (1984) revised Flower's member nomenclature to include: the Salinas Peak Member (shale and sandstone, with upper coral-bearing nodular limestone); Thurgood Sandstone Member (fine-grained, well-indurated sandstone with calcareous cement and brachiopod fragments); and Rhodes Canyon Member (Fammenian-aged shales and burrowed siltstones with brachiopods, correlative to the Ready Pay Member of the Percha Formation). The Contadero Formation is not recognized in the Sacramento or Franklin Mountains, and may have formed in a narrow structural re-entrant largely limited to the San Andres Mountains area (Day, 1988).

Basin

*Percha Formation:* In the Organ/Franklin Mountains the Percha Formation includes all Middle-Late Devonian shales above the Canutillo Formation, including strata age-equivalent to the Oñate, Sly Gap, and Contadero Formations (Seager, 1981; Figures 2 and 11). To the north (e.g. Sacramento and San Andres mountains), when used at all, the Percha is constrained to dark shales of Fammenian age. The Percha is divided into two members: the Ready Pay (black, fissile, barren shale) and the Box (shale with nodular limestone concretions and limited fauna). Dark shales in the extreme southern Sacramento Mountains are variously interpreted as Percha or Sly Gap/Oñate basin equivalents (Kottlowski et al., 1956; Pray, 1961). Fammenian-aged shales in the San Andres Mountains are included in the Rhodes Canyon Member of the Contadero Formation (Sorauf, 1984).

In southwestern New Mexico, Devonian strata are composed of dark fissile and carbonaceous shales considered the Percha Formation regardless of age. Barren dark shales of the Ready Pay Member overlie Fusselman carbonates, and in turn are overlain by dark green to black calcareous shale with shaley nodular limestones of the Box Member. Laudon and Bowsher (1949) offer an excellent description of Devonian stratigraphy and paleontology for this facies.

Interpretation of the environment of deposition responsible for the anoxia and subsequent black shale deposition ranges from shallow lagoon with algal mat covering (Seager, 1981; LeMone, 1982, 1996b; Mack et al., 1998), to "deep water" with anoxia resulting from a density-stratified seaway (Kottlowski et al., 1956; Sorauf, 1984; Day, 1988, 1998). The "deep water" model better fits the general basin physiography of the area and is the preferred interpretation of this report (Figure 12). This "black shale problem" is not restricted to southern New Mexico, but is a common interpretive conundrum throughout Devonian epeiric sea deposits in North America (e.g. Grabau, 1915; Brown and Kenig, 2001; Sageman and Arthur, 2001).

### Southern Carbonate

*Canutillo Formation:* The oldest Devonian strata present in south-central New Mexico may be the Canutillo Formation (Nelson, 1940) in the Organ/Franklin Mountains (Figures 2, 10, and 11). It unconformably overlies the Fusselman Formation, and underlies and is a partial lateral facies equivalent to the Percha Formation (Seager, 1981). The Canutillo is composed of a lower dolomitic siltstone and an upper cherty carbonate. The formation thins northward from 26 m in the Franklins to 6 m at Bishop Cap, to 1 m in the southern San Andres Mountains. Published literature does not resolve whether the cherty carbonate represents a deep basin noviculite or a shallower water shelf/slope environment.

## Organic Geochemistry

Organic geochemistry data for Devonian units in south-central and southwestern New Mexico is of varying vintage and quality (Foster, 1978; Thompson, 1981; Leutloff and Curry, 1982; Jacobson et al., 1983; Jacobson et al., 1984; Jacobson et al., 1984; Bayless and Schwarzer, 1988; Mobil Exploration and Producing U.S. Inc. and Core Laboratories, 1988; New Mexico Bureau of Mines and Mineral Resources et al., 1998; Broadhead et al., 1998). Figure 13 contours public domain Devonian TOC values; note that higher values of TOC correlate closely with the Percha black shale facies. Lower TOC values to the west are at least in part the result of over maturity (Figure 14). Kerogen type varies from III to mixed II/III, resulting in a gas to mixed gas/oil prone system. Terrestrially derived type III kerogen is predominant near land areas in the west and north. In addition to kerogen type, the interpretation that this area is largely a gas-prone system is supported by low HI values (50-200), S2/S3 ratios less than 5, and generally high thermal maturities. The Harvey E Yates discovery well in Otero Mesa (Figure 3) is located within the Devonian TOC high making it a likely source rock for this new gas play.

## Burial History and Hydrocarbon Expulsion Timing

Burial history and basin analysis studies are not common for this region due to (1) poor data quality, (2) complex heat flow history, and (3) complex and overprinted structural styles due to Ancestral Rocky Mountain, Laramide, and Rio Grande Rift tectonism (Figure 15).

Although a fair number of well penetrations exist (Table 1, Figure 3), most are of pre-1980 vintage (many significantly older) and contain generally poor log suites. Interpretations of bolson thickness trends and structural styles are poorly constrained, lithologies and lithic percentages can often only be estimated, and formation and age picks are usually performed without the aid of biostratigraphic data or core. Geochemical and thermal data are rare.

Estimation of paleo heat flow curves is a major variable in any burial history model. The Rio Grande Rift area contains one of the more complicated thermal regimes in the world. High-quality regional present-day heat flow maps exist (Reiter et al., 1975; Figure 16), but must smooth some of the natural heterogeneity derived from small intrusions and faults. For example, the regional map (Reiter et al., 1975) illustrates a heat flow range of 1.4 to 4.7 hfu over the study area whereas detailed local measurements reach as high as 17 hfu (equates to over 700 $mWM/m^2$; New Mexico Bureau of Mines and Mineral Resources et al., 1998; Figure 17). The fact that this area has some of the most economic geothermal energy potential in the United States, including a number of existing successful projects, bespeaks to its locally high heat flow.

Due to the data complexities discussed above, any single burial history model is misleading. Two end member models were constructed in an attempt to bracket much of the areas variability (Figures 18 – 23) : (1) Grim Mobil-32 #1, a deep well test below 20,000 feet containing thick Tertiary Rio Grand Rift bolson valley fill but heat flow within regional norms, and (2) McGregor GDP 51-8, with much thinner bolson deposits but anomalously high heat flow.

Model results of hydrocarbon expulsion timing indicate two major periods of activity: the Late Paleozoic and Mid-Tertiary. In general, most Devonian source rocks in the western area probably went from immature to post mature during Late Paleozoic filling of the Ancestral Rocky Mountain Pedregosa basin (Thompson, 1981). Gas-prone sources located in local areas of thinner overburden may have continued to expel hydrocarbons beyond the Paleozoic. No evidence was found during this study to indicate the presence of an active western area hydrocarbon system, however the entire area cannot be condemned due to the limited data set.

The eastern study area contains a broader range of Devonian source rock thermal maturities, with current values ranging from post mature to immature. Devonian source rocks below the Ancestral Rocky Mountain Orogrande basin depocenter reached maturity and expelled hydrocarbons in the Late Paleozoic due to thick sections of Pennsylvanian and Permian overburden. Source rock facies outside of the basin depocenter were not deeply buried and remained immature. It is difficult to ascertain the effects of the Laramide orogeny on the eastern area since little Mesozoic strata is preserved and no detailed vitrinite profiles have been located in the public domain to quantify the extent of Mesozoic deposition and subsequent erosion. The Rio Grande Rift, with its elevated heat flows, igneous intrusions, and graben-centered thick bolson deposits crated another pulse of expulsion. Thick (20,000' plus) graben bolson deposits brought previously immature Paleozoic rocks into the oil and gas window, resulting in minor(?) oil and potentially major gas expulsion beginning ~28 Ma and continuing today. Horst areas vary from immature to post mature depending on the stratigraphic interval, extent of uplift associated with specific blocks, and proximity to igneous intrusions (Figure 15). It is likely that over the large study area hydrocarbons have been continually expulsed from late Paleozoic time until Recent, with pulses centered around the three major orogenic events

## Petroleum System

Numerous oil and gas shows and one significant gas discovery (Harvey E. Yates 1Y Bennett Ranch well, Sec. 14, T.26S., R.12E.) in the study area indicates an active petroleum system exists. Of 83 exploratory wells drilled in the Tularosa Basin, 25 contain hydrocarbon shows. The modern Tularosa Basin area possesses proven potential, large size, multiple source and reservoir facies, and complex structural history offering numerous trapping mechanisms. Despite these factors, few integrated petroleum systems studies have been undertaken (e.g. Broadhead, 2002), leading to the conclusion that this area exists as an understudied frontier basin with hydrocarbon exploration opportunity.

Source Rocks: Source rocks have been documented for Devonian, Mississippian, Pennsylvanian, and Permian strata (Broadhead, 2002), as well as for Cretaceous shales and coals in central New Mexico. This paper has concentrated on Devonian strata, but other units offer viable oil and gas-prone source facies in a wide range of thermal maturities. Regional richness/maturity trends in Devonian strata indicate that the thick black shale deposits in Hidalgo and Luna counties are currently of relatively poor quality and over mature (Thompson, 1981). The area should not be condemned, however, due to the sparse dataset. The most prospective area appears to reside in Dona Ana and southern Otero counties. Here, although black shales are thinner than areas to the southwest, increased organic richness and decreased maturity create a viable, mixed oil/gas-prone source rock.

Reservoirs: Numerous potential reservoir facies exist, including: fractured Precambrian basement, Cambro-Ordovician sandstones (Bliss Formation), karsted Ordovician carbonates (El Paso Formation), Silurian dolomites (Fusselman Formation), Devonian sandstones (northern area), Devonian shales (southern area), Mississippian carbonate bioherms (including large Waulsortian mounds), Pennsylvanian (Morrowan/Atokan) sandstones, Upper Pennsylvanian phylloid-algal mounds (correlative to the Holder Formation outcrops in the Sacramento Mountains), Lower Permian (Wolfcampian) basin margin mounds and breccia debris flows, Upper Permian (San Andres and Yeso Formation) backreef limestones and dolomites, Cretaceous sandstones (Dakota Formation) and coalbed methane, and Tertiary (Eocene) fractured igneous sills (possibly the major reservoir for the Otero Mesa Harvey E. Yates gas discovery).

Traps/seals: The large study area has undergone multiple tectonic episodes and contains numerous stratigraphic pinch-outs creating a wide range of potential trapping styles and mechanisms, many analogous to the neighboring prolific Permian Basin. Ancestral Rocky Mountain block faults, many reactivated during Rio Grande Rift extension, may juxtapose reservoir facies against units with low permeability or fault planes with clay smear/cataclasis effects (Figure 15). Structural roll on horsts near major normal faults also add dip closure. Low angle Laramide thrust faults and rollovers are documented in outcrop (e.g. Pray, 1961) and the subsurface; for example a major thrust fault-induced rollover was encountered in the McGregor 51-8 well. Stratigraphic traps include Devonian shale gas, large biohermal mounds in the Mississippian, Pennsylvanian, and Permian section, carbonate debris flows off basin margins sealed (and potentially sourced) with basin shales, Pennsylvanian and Permian stratigraphic pinch-outs onlapping Ancestral Rocky Mountain uplifts, lower Paleozoic pinch-outs of strata onlapping the Transcontinental Arch, Cretaceous coalbed methane, and fractured Eocene igneous sills intruded into tight carbonates and shales.

Seal integrity is a concern in the eastern Sacramento Mountain uplift area. Major fracture systems have breached some horst block units, flushing reservoirs with fresh water. This negative does create an opportunity, however, for fresh water exploration in this growing, water-starved area.

Comments on most prospective areas: Integrating previous studies and new work, the most prospective area for Devonian-sourced hydrocarbons appears to be the south-central portion of the study area, bounded approximately by the latitudes of Hatch to the north and El Paso to the south, and longitudes of Deming to the west and extending eastward beyond the study area. This area has adequate organic richness, thermal maturity, reservoir facies, and trapping mechanisms to create a viable petroleum (predominantly gas) system. To the north, Devonian organic richness lessens due to the influx of shelf clastics, to the west source rock richness decreases and maturities increase to post mature. To the south richness decreases due to a facies change into the cherty carbonate Canutillo Formation.

## Conclusions

South-central New Mexico contains the necessary ingredients for economic discoveries of hydrocarbons sourced by Devonian black shales. Poor data and a complicated geologic history pose challenges, but continued studies that focus on quantifying and high-grading local and regional aspects of the petroleum system will reduce risks and lead to more exploration activity. Available well and outcrop data have not yet been fully synthesized to create a robust petroleum systems model.

Major conclusions of this study include:

(1). Devonian black shales with sufficient richness (up to 3.68% TOC) and thermal maturity exist in south-central New Mexico to source an active hydrocarbon system. However, documented viable source rock is limited to a relatively narrow band.

(2) Thermal maturity within this area varies widely from overmature to immature due to complex heat flow patterns and drastic changes in bolson fill thickness.

(3) The most prospective play appears to be located around Otero Mesa due to documented active source rock, numerous traps (both stratigraphic and structural), numerous potential reservoir horizons, relatively shallow drilling depths, and a proven discovery well.

(3) Risks are still large and include uncertainties in source rock thermal maturity, migration pathways, reservoir quality, and seal integrity.

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## Figure Captions

Figure 1 Map of New Mexico with approximate study area in box.

Figure 2 Paleozoic stratigraphic chart for southern New Mexico.

Figure 3 Data source location map, with numbers corresponding to outcrop or well locations listed in Table 1.

Figure 4 Devonian isopach map for south-central and southwestern New Mexico. Data points, in meters, are provided with a range of values where studies disagree. Contour interval is 10 meters except where noted.

Figure 5 Percent black shale lithology map for south-central and southwestern New Mexico. Data points are provided with a range of values where studies disagree. Contour interval is 20%.

Figure 6 Percent total shale lithology map.

Figure 7 Percent total siltstone lithology map.

Figure 8 Percent total sandstone lithology map.

Figure 9 Percent total carbonate lithology map.

Figure 10  General Devonian paleogeography map based on lithologies and paleoenvironmental interpretations.  The line of cross section is presented in Figure 11.

Figure 11 General north  to south cross section illustrating major Devonian facies relationships.  See Figure 10 for location of section line.

Figure 12  Depositional profiles from the Sacramento/San Andres mountains shelf area in the north to the basin area to the south.

Figure 13  Data points and contours of Devonian total organic carbon (TOC) in southern New Mexico.  Note how the high TOC trend largely tracks the high %black shale trend.

Figure 14 General Devonian source rock maturity provinces in osuthern New Mexico.

Figure 15  Schematic representation of the complex and overprinted structural styles in southern New Mexico.  The area illustrated represents Otero Mesa and the edge of the Tularosa Basin.

Figure 16 Regional heat flow map for New Mexico.  A magnified view of the area within the dashed box near the extreme southern boundary is illustrated in Figure 17.

Figure 17 Heat flow map for a small area within the McGregor military range in southern New Mexico (see Figure 16 for basemap) providing an example of extremely high local heat flow.  The McGregor GDP 51-8 well is located on one of the heat flow high points (Figures 21 – 23).

Figure 18  Location map for well Grim Mobil-32 #1.

Figure 19  Burial history plot for the Grim Mobil-32 #1 well in south-central Dona Ana County.  This well experienced deep burial (22,000') but relatively low heat flow.  Time scale is 450 Ma to present.  The color scale is:  Yellow = Early Mature (oil) 0.5 – 0.7 %Ro;  Green = Mid Mature (oil) 0.7 – 1.0 % Ro;  Red = Late Mature (oil) 1.0 – 1.3 % Ro;  Stippled red = Main Gas Generation 1.3 – 2.6 % Ro.

Figure 20 Close up burial history plot for Grim Mobil-32 #1 representing only 40 Ma - Present.  See Figure 19 caption for scale description.

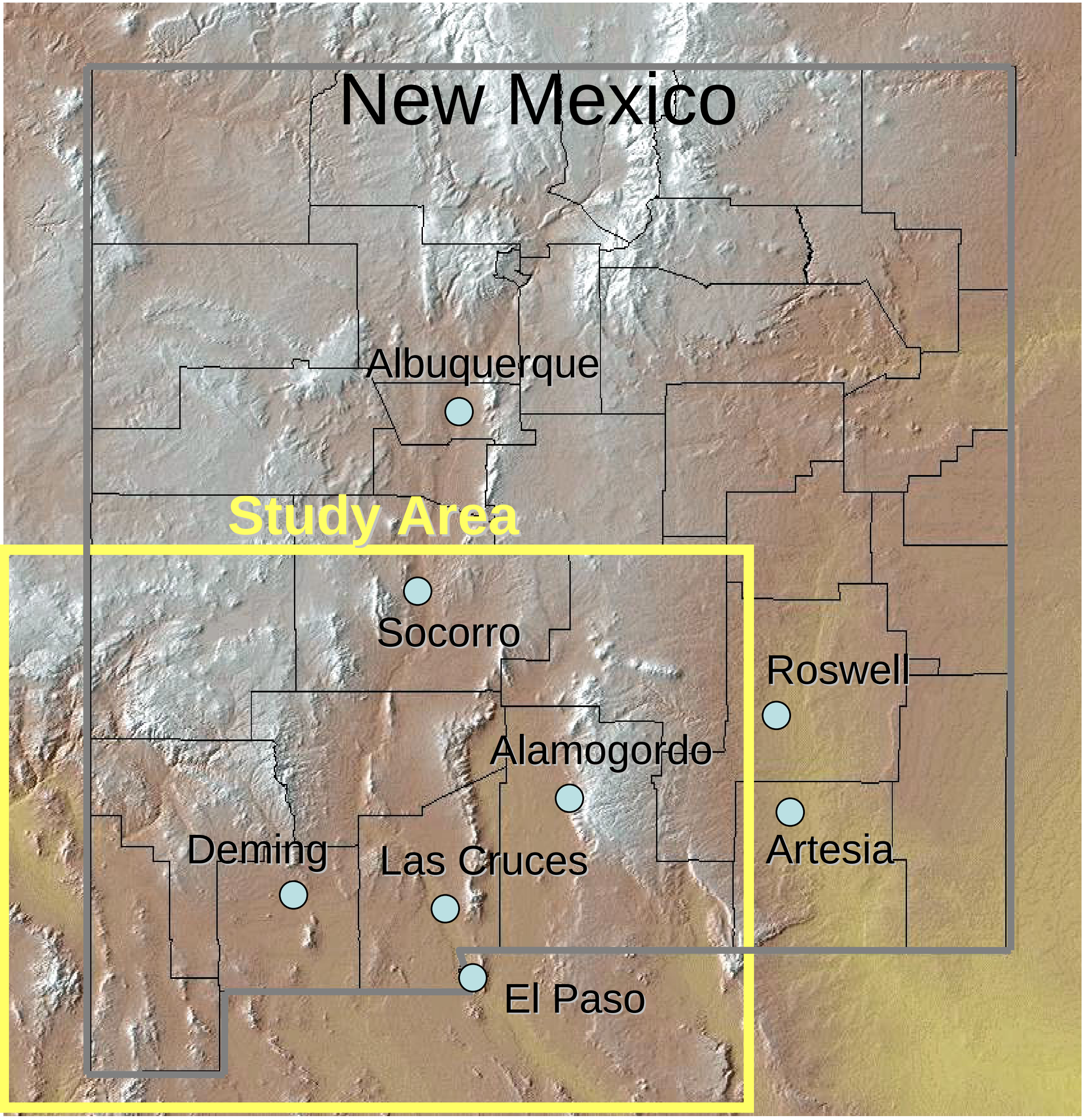
Figure 21 Location map for well McGregor GDP 51-8.

Figure 22  Burial history plot for McGregor GDP 51-8 well in southwestern Otero County.  This well experienced relatively little burial (4200') but high heat flows.  Time is from 450 MA to present.  Color scale same as Figure 19.

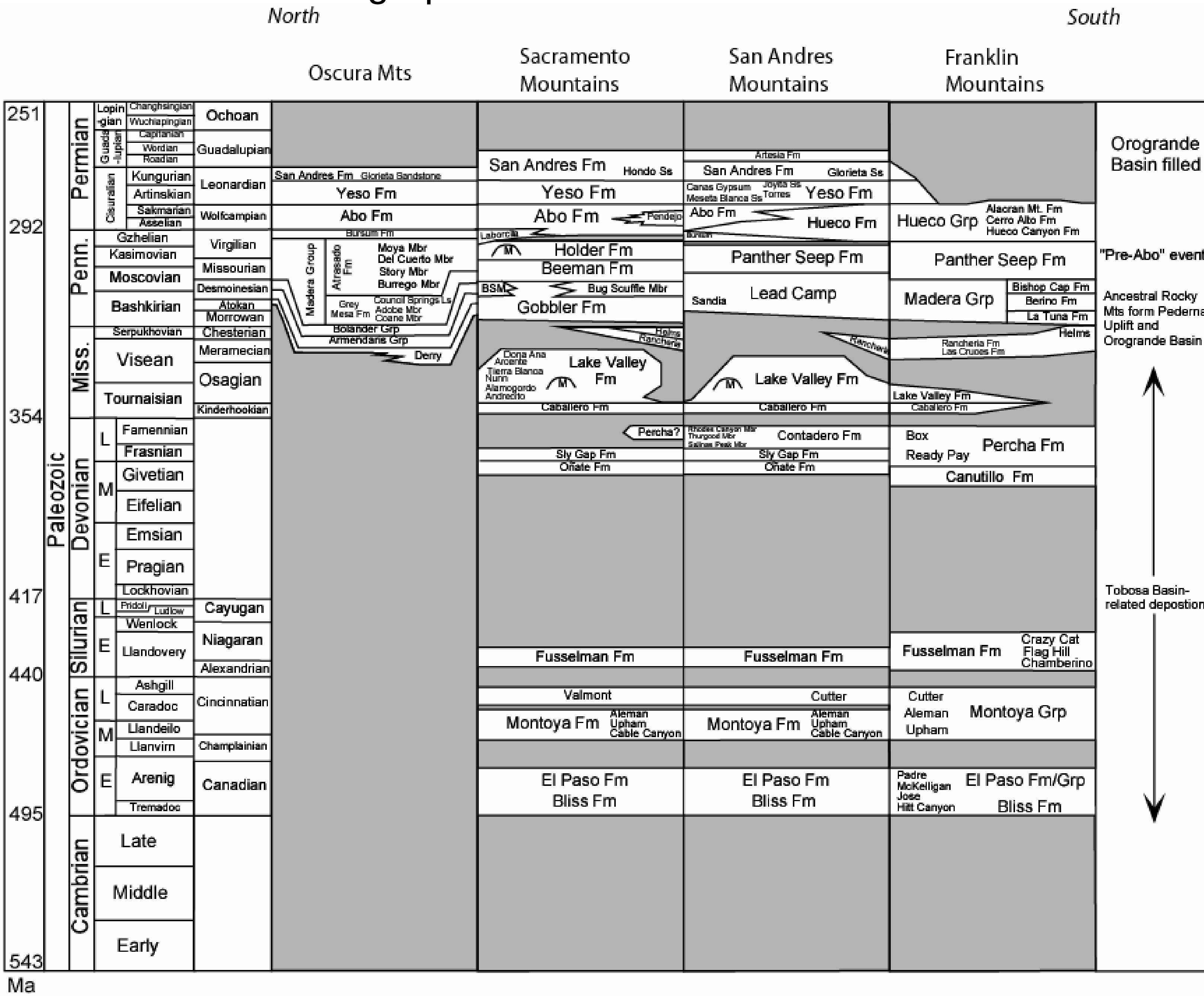
Figure 23  Close up burial history plot for McGregor GDP 51-8 representing only 40 Ma - Present.  See Figure 19 caption for scale description.

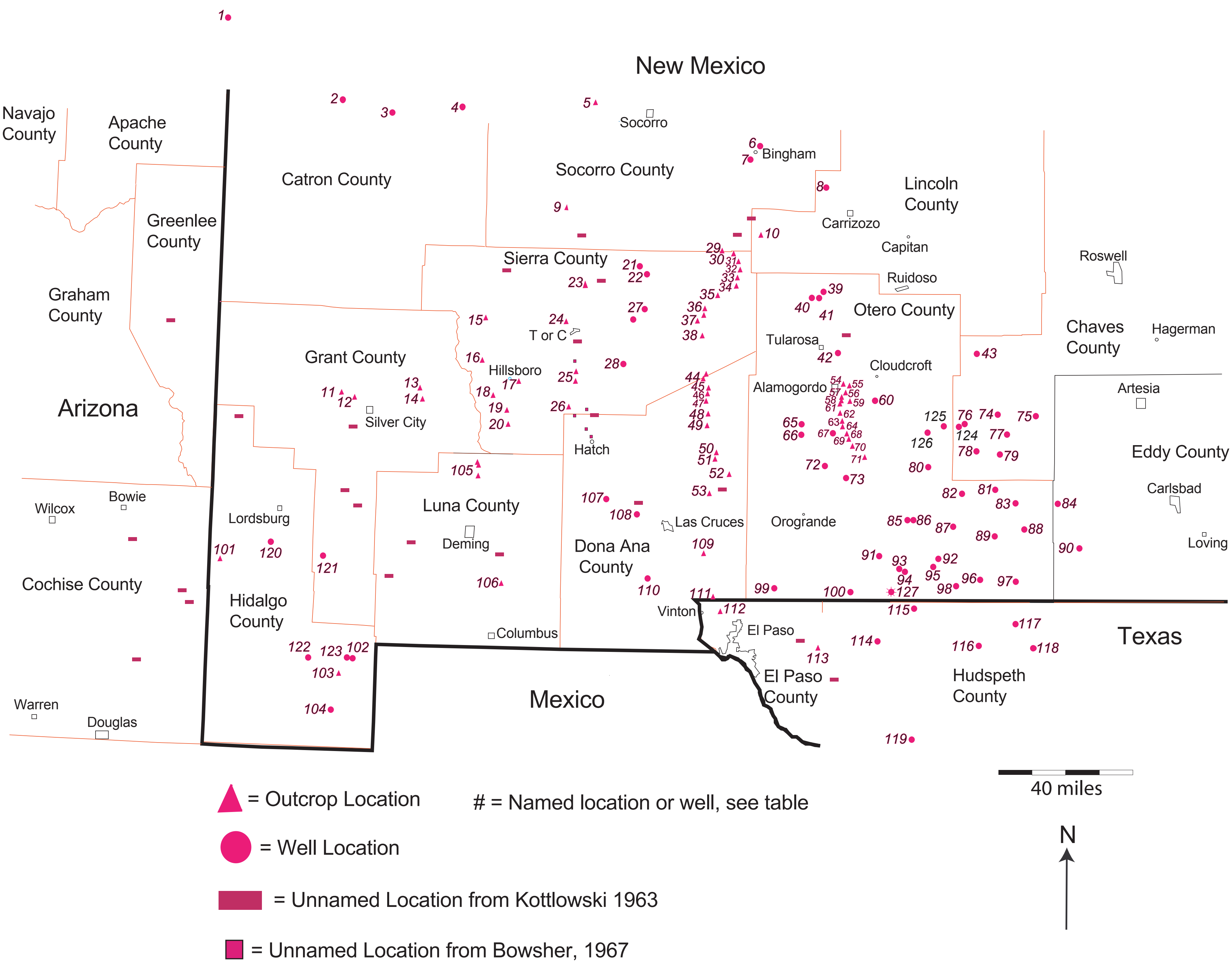
Table Caption

Table 1  List of named data points used in this study.  Numbers correspond to location map of Figure 3.

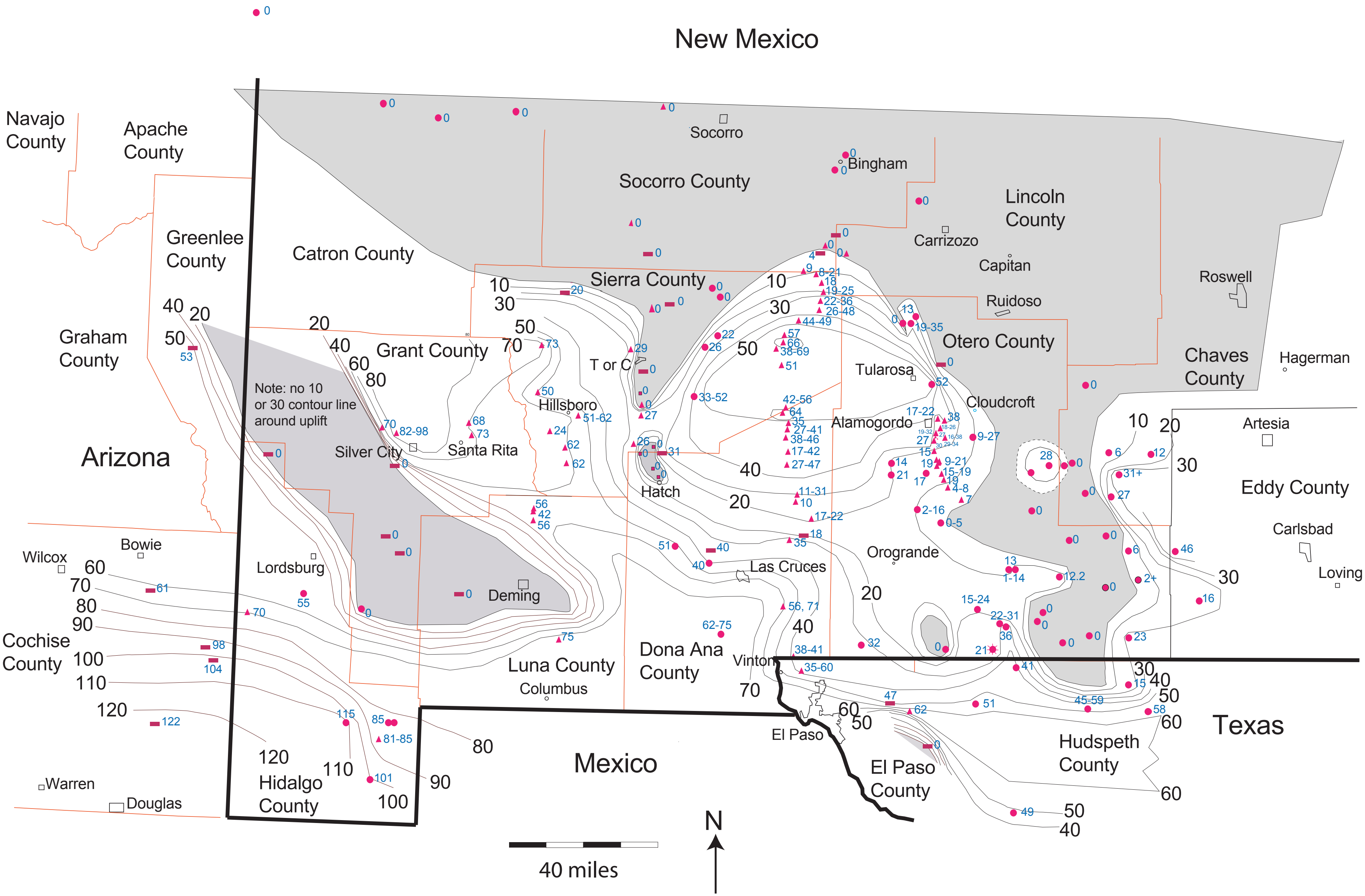

New Mexico
Albuquerque
Study Area
Socorro
Roswell
Alamogordo
Artesia
Deming
Las Cruces
El Paso

# Paleozoic Stratigraphic Column for Southern New Mexico





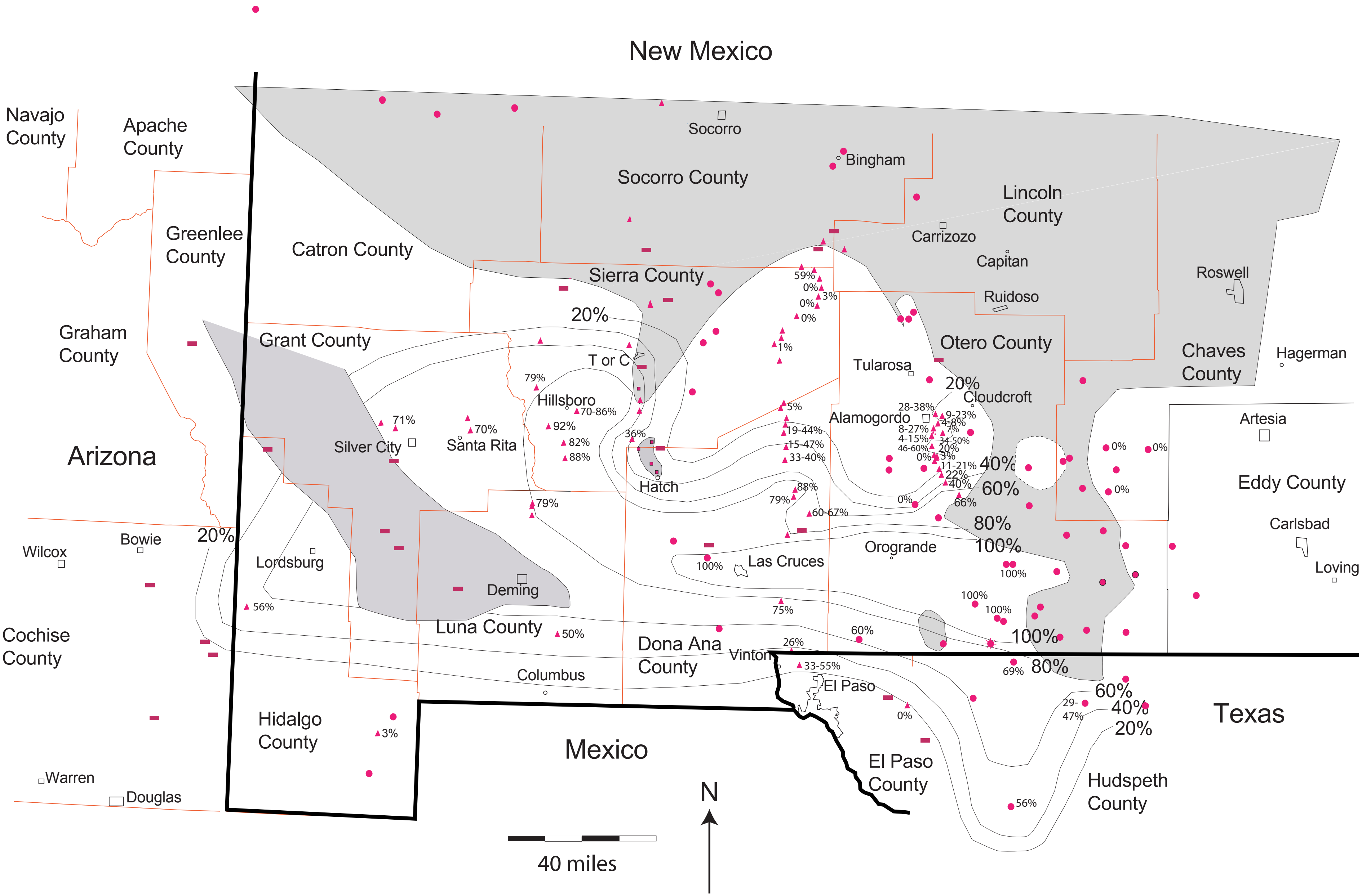
New Mexico
Arizona
Texas
Mexico
Navajo County
Apache County
Greenlee County
Graham County
Cochise County
Catron County
Socorro County
Sierra County
Grant County
Hidalgo County
Luna County
Dona Ana County
Lincoln County
Otero County
Chaves County
Eddy County
El Paso County
Hudspeth County
Socorro
Bingham
Carrizozo
Capitan
Ruidoso
Roswell
Hagerman
Artesia
Carlsbad
Loving
T or C
Hillsboro
Silver City
Hatch
Tularosa
Alamogordo
Cloudcroft
Orogrande
Las Cruces
Vinton
El Paso
Deming
Columbus
Lordsburg
Bowie
Wilcox
Warren
Douglas
40 miles
N
= Outcrop Location
= Well Location
= Unnamed Location from Kottlowski 1963
= Unnamed Location from Bowsher, 1967
# = Named location or well, see table



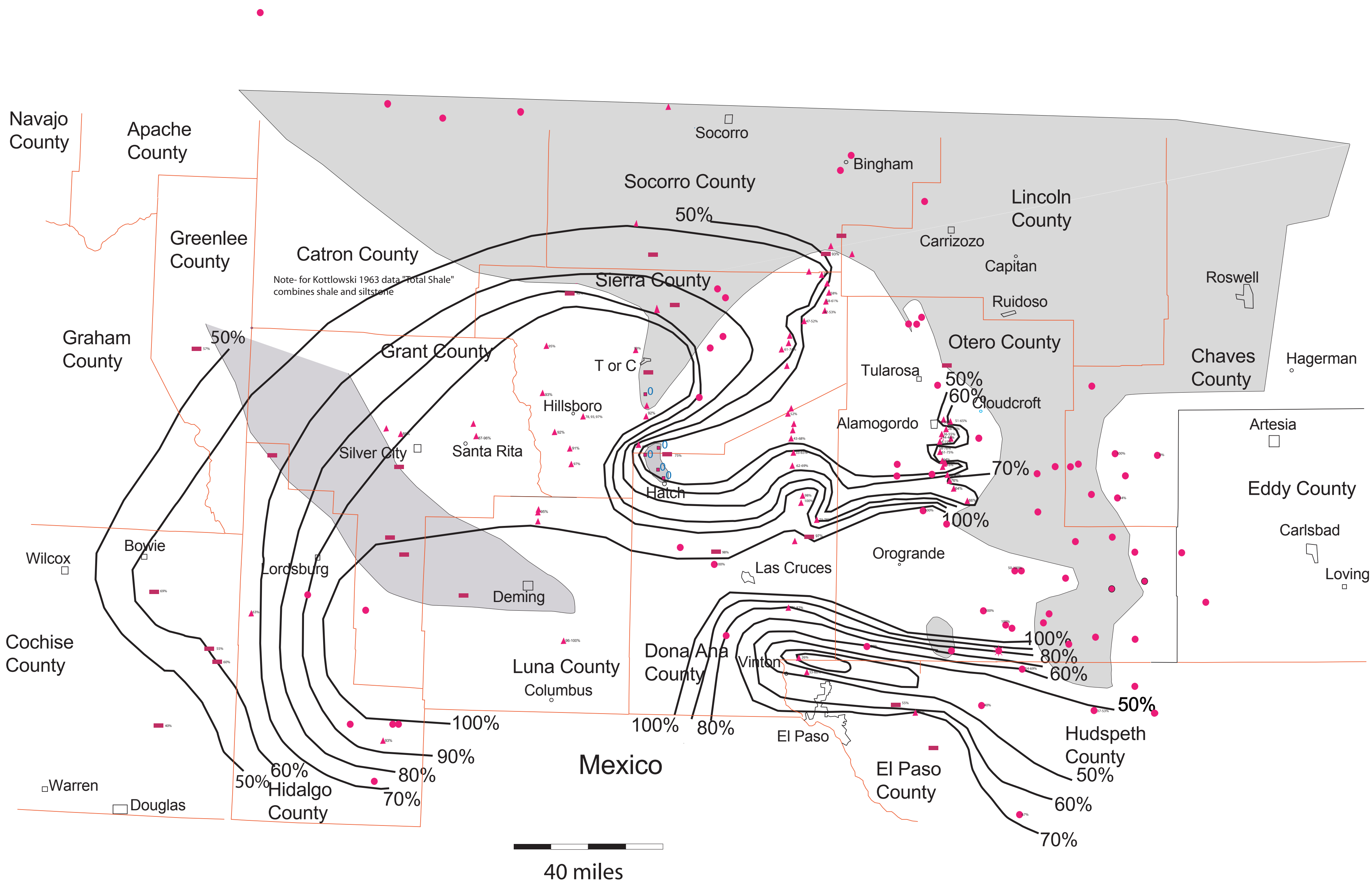

# Devonian Isopach Map

Isopach in meters, Contour Interval = 10 meters except where noted

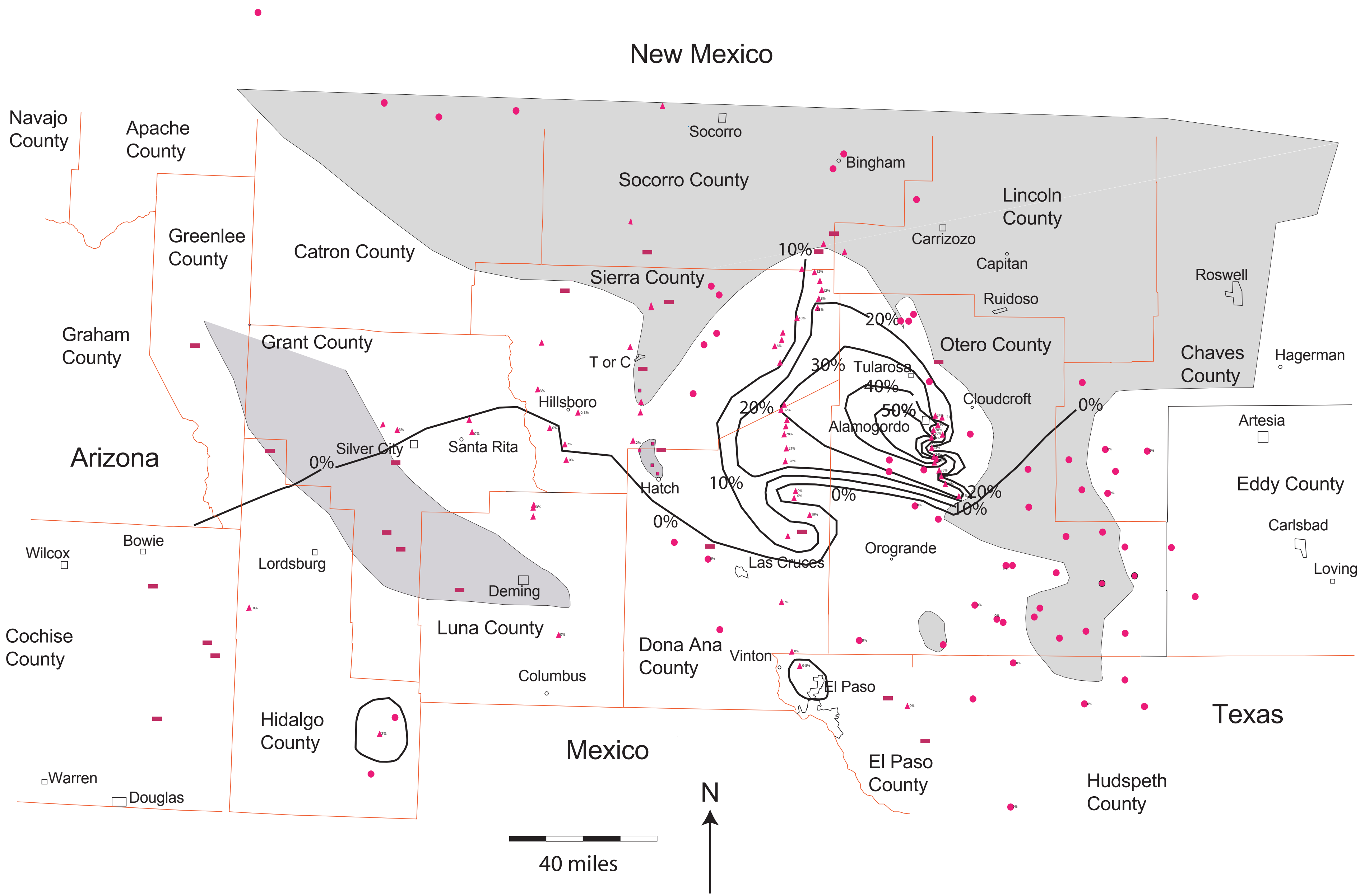
Where overlapping studies disagree on unit thickness, a range is given




Devonian % Black Shale control points and contours



Devonian % Total Shale



New Mexico
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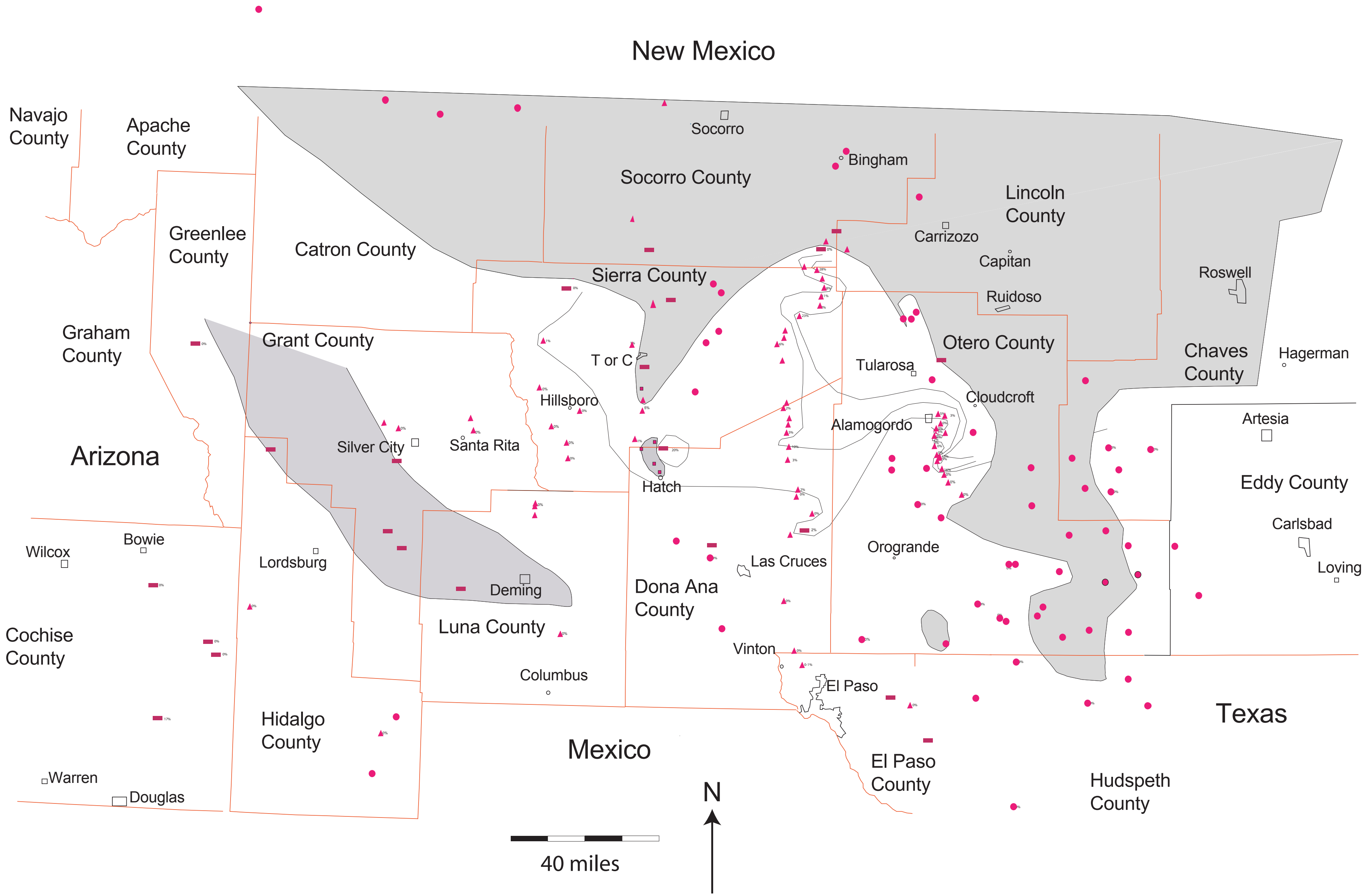
Apache County
Greenlee County
Catron County
Socorro
Socorro County
Bingham
Lincoln County
Carrizozo
Capitan
Roswell
Ruidoso
Sierra County
Graham County
Grant County
T or C
Hillsboro
Otero County
Chaves County
Hagerman
Tularosa
Cloudcroft
Alamogordo
Artesia
Arizona
Silver City
Santa Rita
Hatch
Eddy County
Carlsbad
Wilcox
Bowie
Lordsburg
Deming
Orogrande
Las Cruces
Loving
Cochise County
Luna County
Dona Ana County
Vinton
Columbus
El Paso
Hidalgo County
Mexico
Texas
El Paso County
Hudspeth County
Warren
Douglas
N
40 miles
0%
10%
20%
30%
40%
50%


New Mexico
Navajo County
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Greenlee County
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Socorro
Socorro County
Bingham
Lincoln County
Carrizozo
Capitan
Ruidoso
Roswell
Sierra County
Graham County
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Tularosa
Otero County
Chaves County
Hagerman
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Cloudcroft
Artesia
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Silver City
Santa Rita
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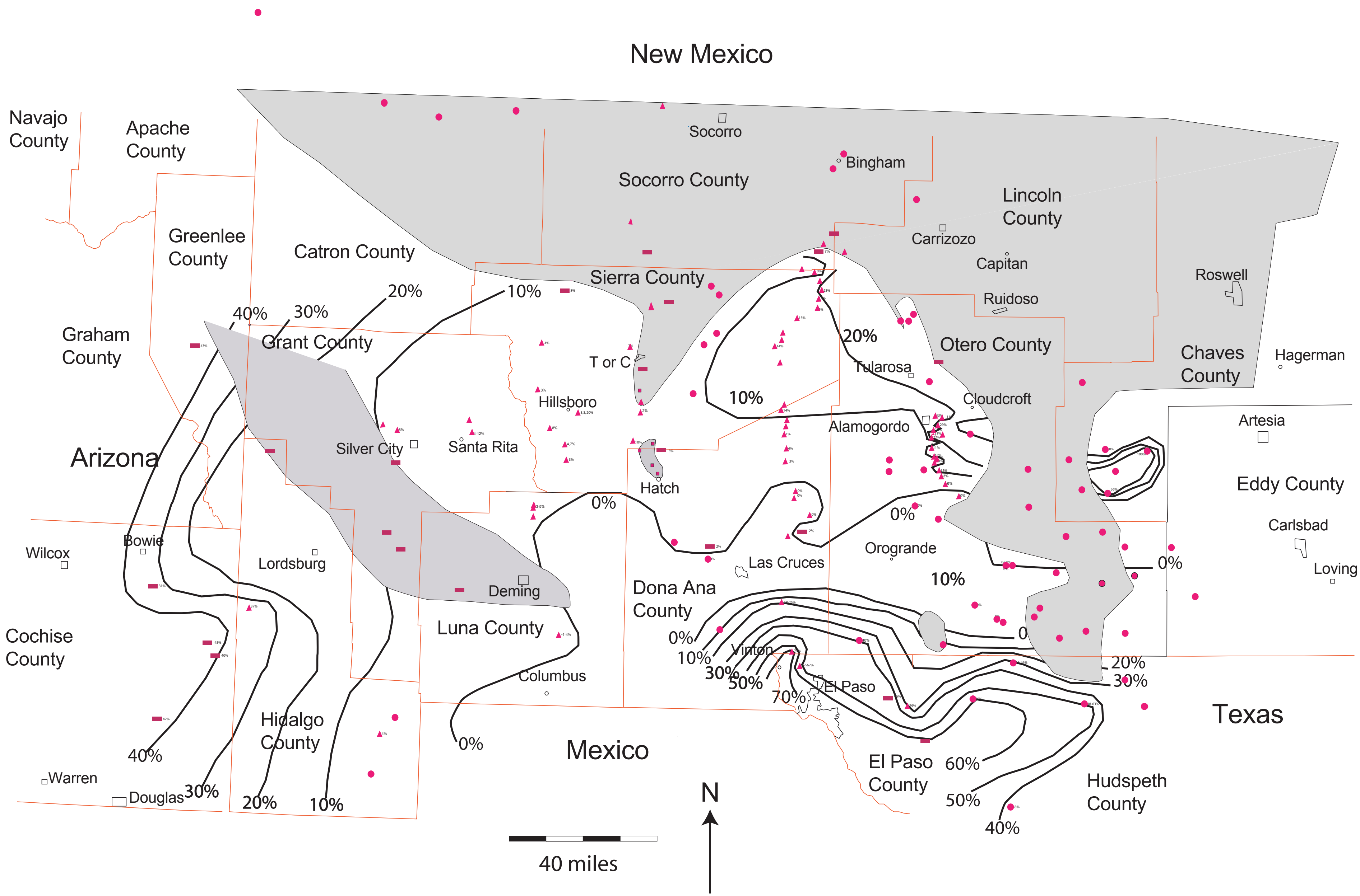
Eddy County
Carlsbad
Bowie
Wilcox
Lordsburg
Orogrande
Las Cruces
Loving
Deming
Dona Ana County
Cochise County
Luna County
Vinton
Columbus
El Paso
Hidalgo County
Texas
Mexico
El Paso County
Hudspeth County
Warren
Douglas
N
40 miles

% Carbonate



New Mexico
Navajo County
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Greenlee County
Catron County
Socorro
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Lincoln County
Carrizozo
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Ruidoso
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Silver City
Santa Rita
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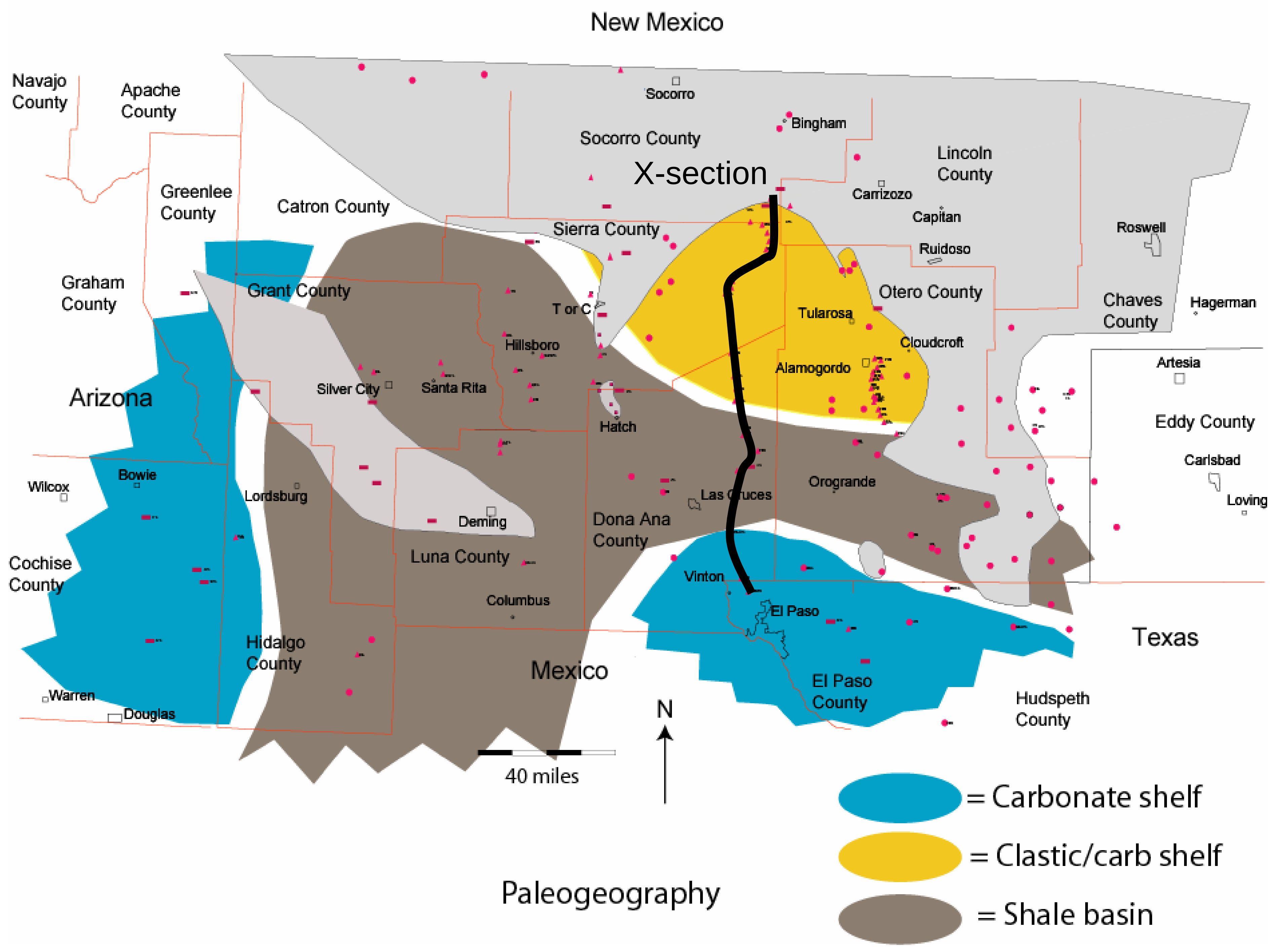
Bowie
Wilcox
Lordsburg
Orogrande
Las Cruces
Loving
Deming
Dona Ana County
Luna County
Cochise County
Vinton
El Paso
Columbus
Hidalgo County
Mexico
Texas
El Paso County
Hudspeth County
Warren
Douglas
40%
30%
20%
10%
0%
50%
60%
70%
N
40 miles

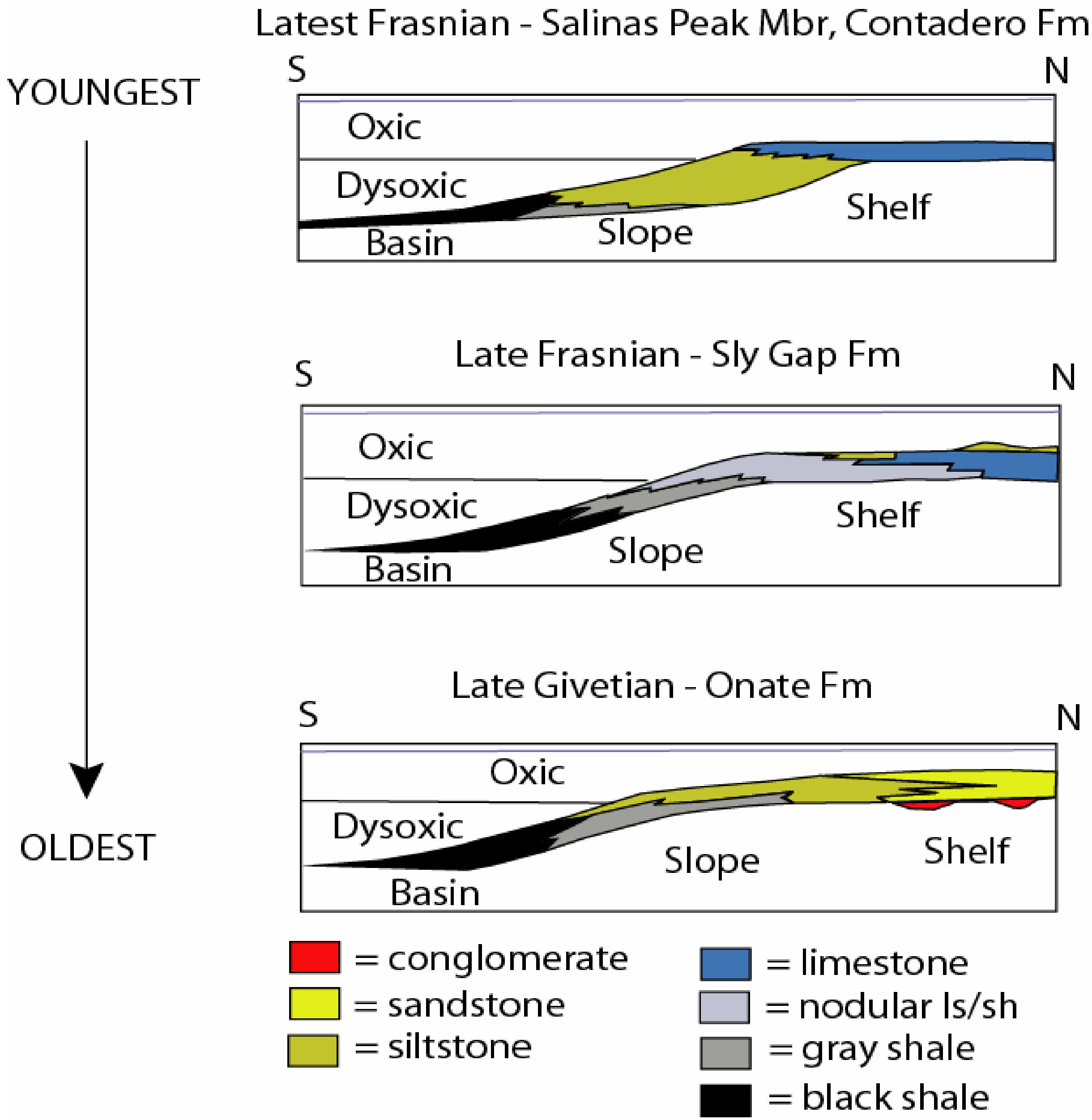

% Carbonate



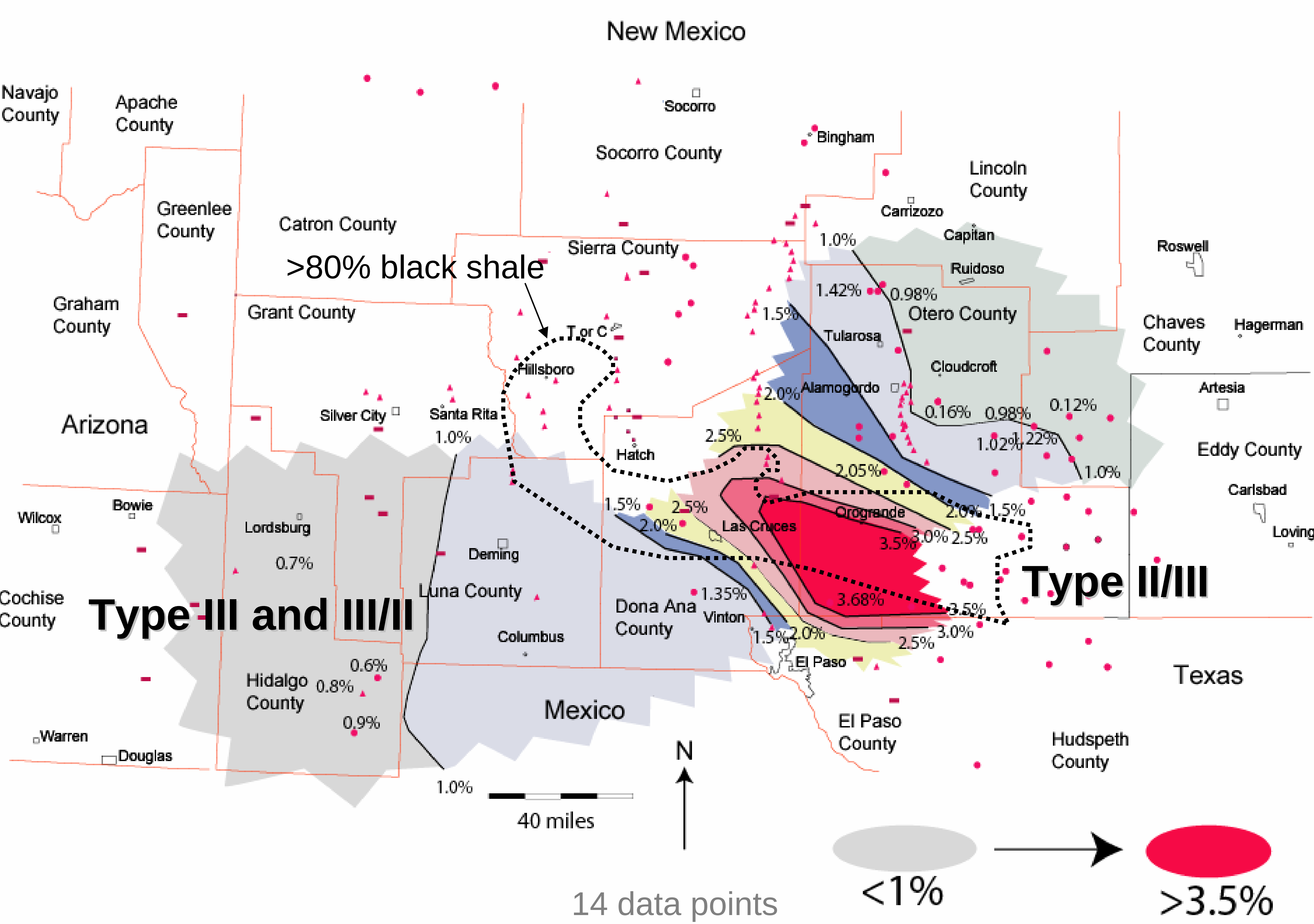

Paleogeography


North
South
Northern San Andres Mts
Southern San Andres Mts
Franklin Mts
Latitude of : Carrizozo
Alamogordo
Las Cruces
El Paso
Mixed
clastic/carbonate
shelf
Onate, Sly Gap,
Contadero fms
Black shale
Percha Fm
Limestone
Canutillo Fm
30 m
30 miles
Modified from Sorauf, 1984 and Rosado, 1970

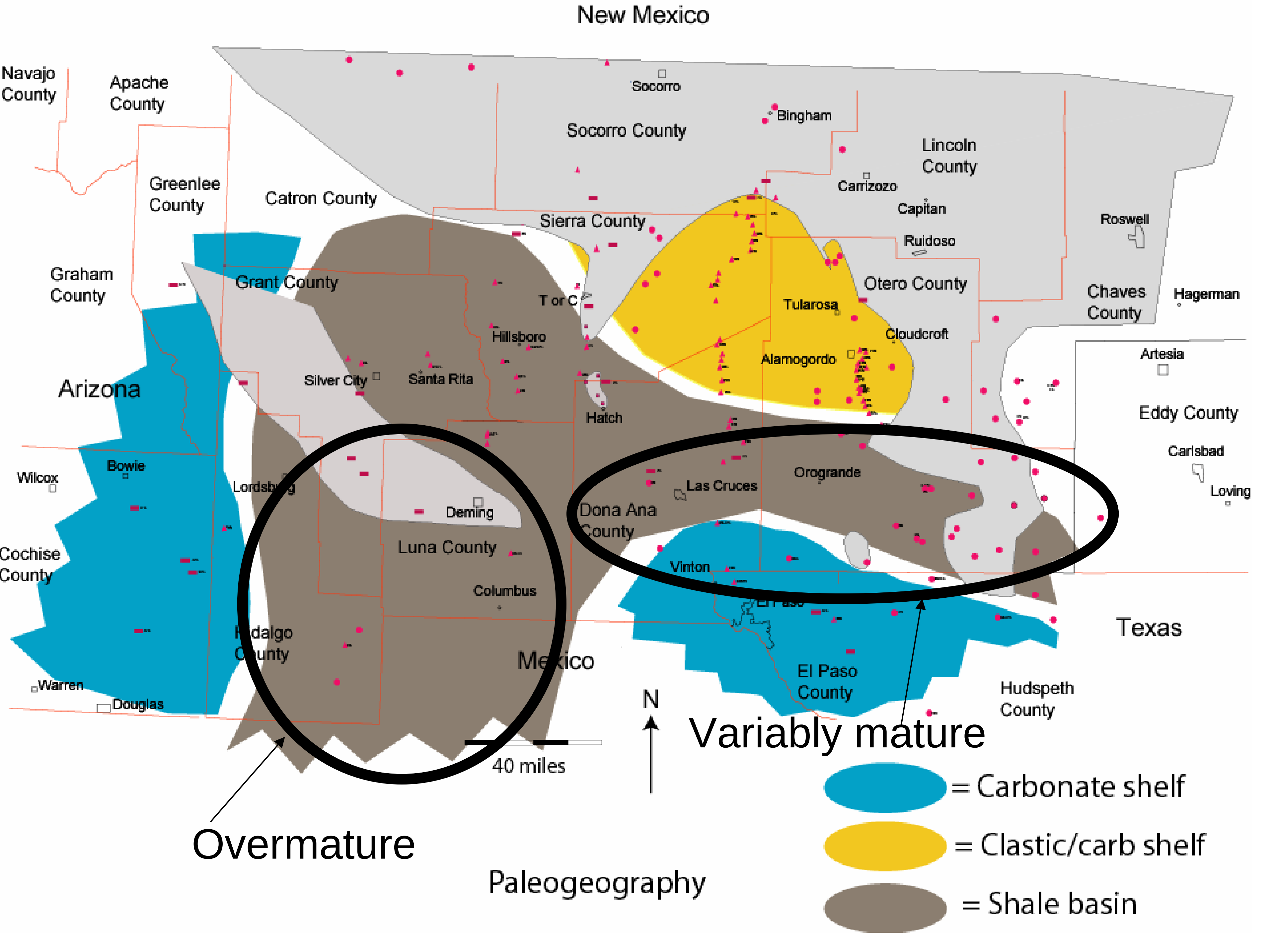
# Depositional models, northern shelf-to-basin




Modified from Day, 1988




% Total Organic Carbon


New Mexico
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Socorro
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Alamogordo
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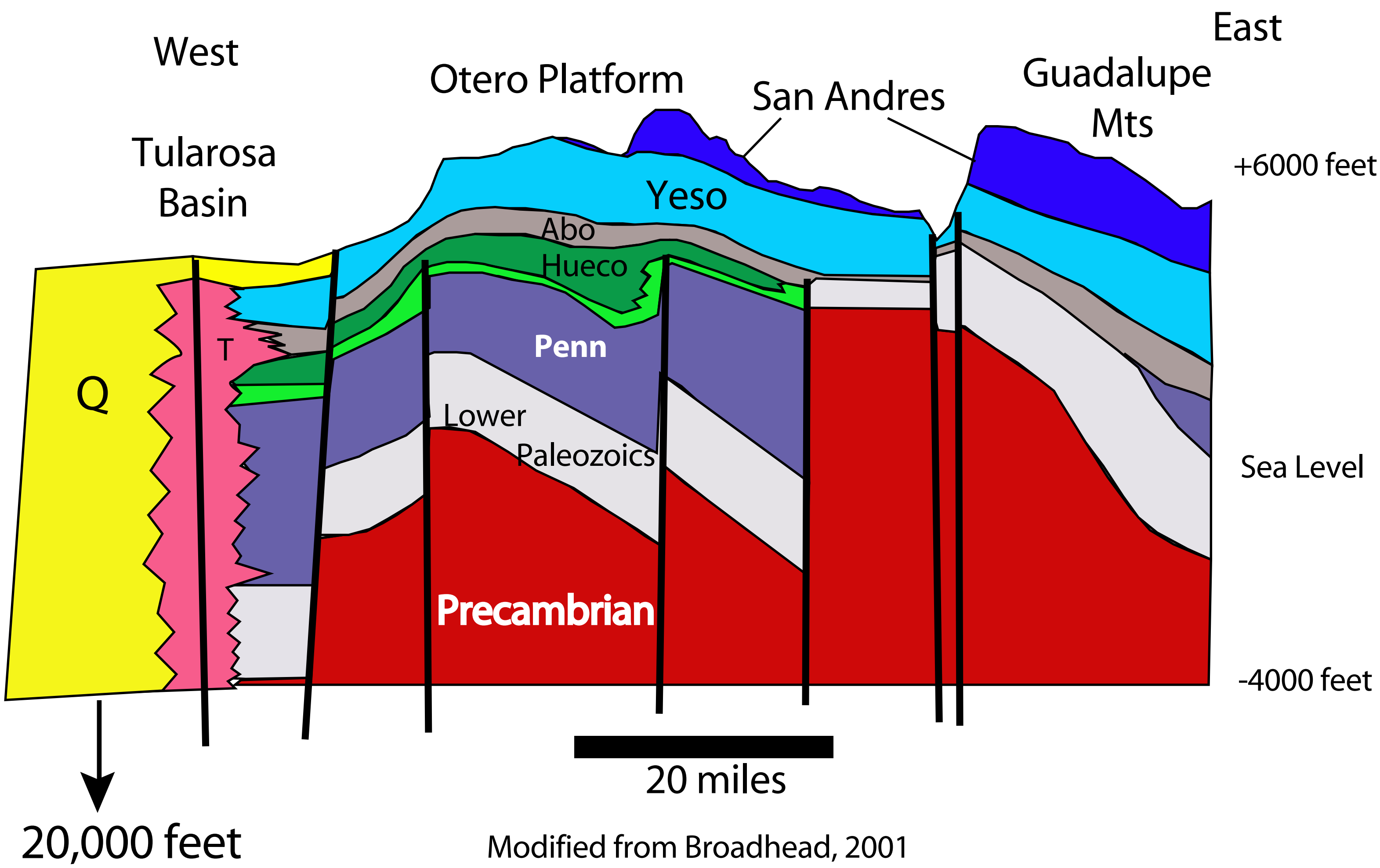
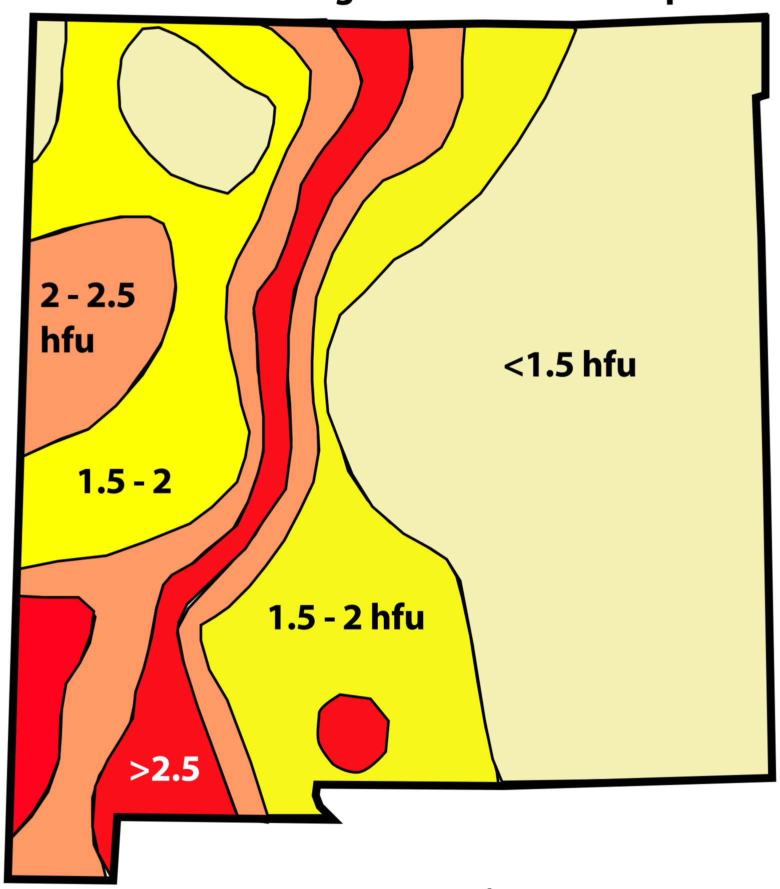
Arizona
Hatch
Eddy County
Carlsbad
Wilcox
Bowie
Lordsburg
Las Cruces
Orogrande
Loving
Deming
Dona Ana County
Cochise County
Luna County
Vinton
Columbus
El Paso
Hidalgo County
Texas
Mexico
Warren
Douglas
El Paso County
Hudspeth County
N
40 miles
Variably mature
= Carbonate shelf
Overmature
= Clastic/carb shelf
Paleogeography
= Shale basin

Example of tectonic style in southern NM



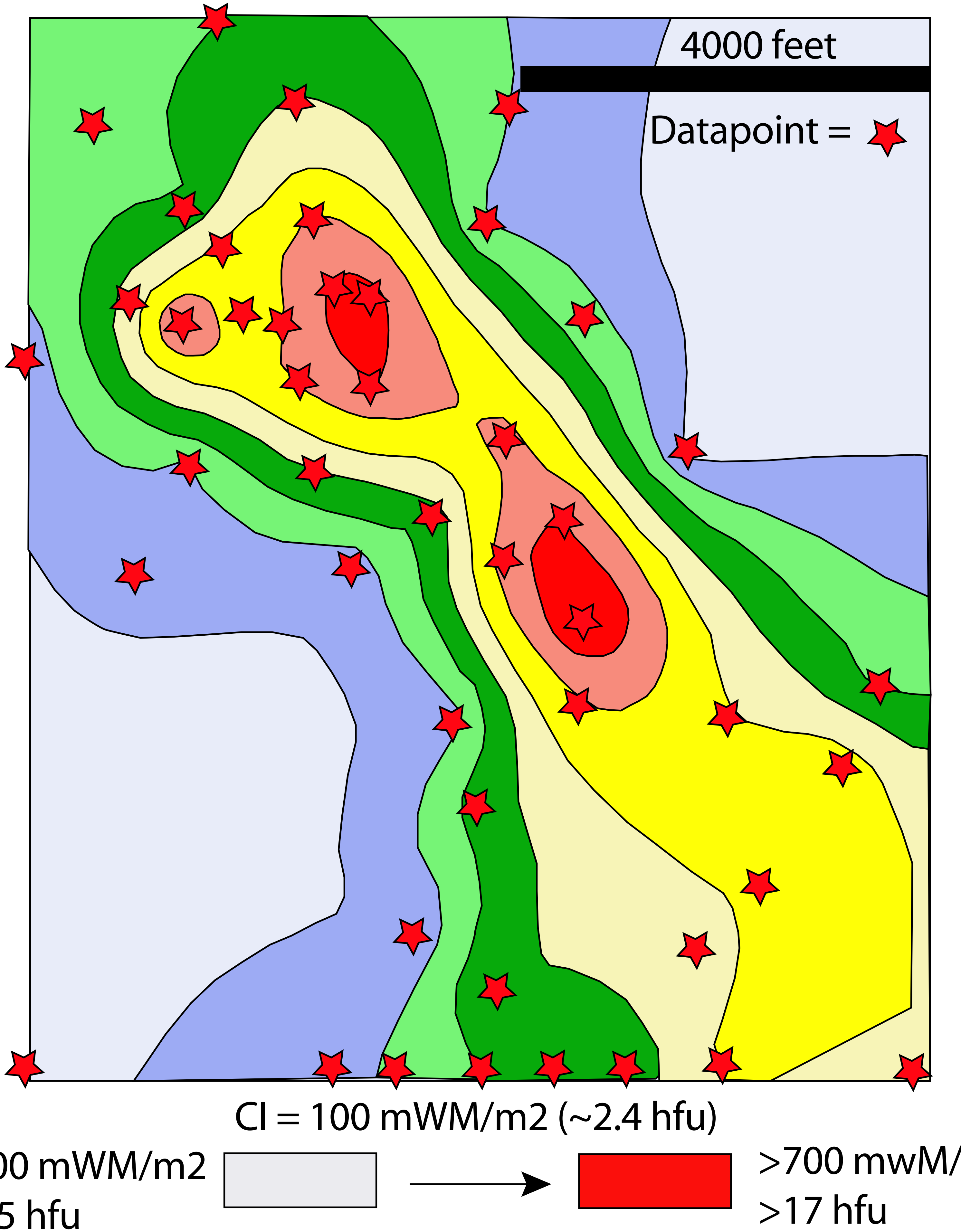

Modified from Broadhead, 2001

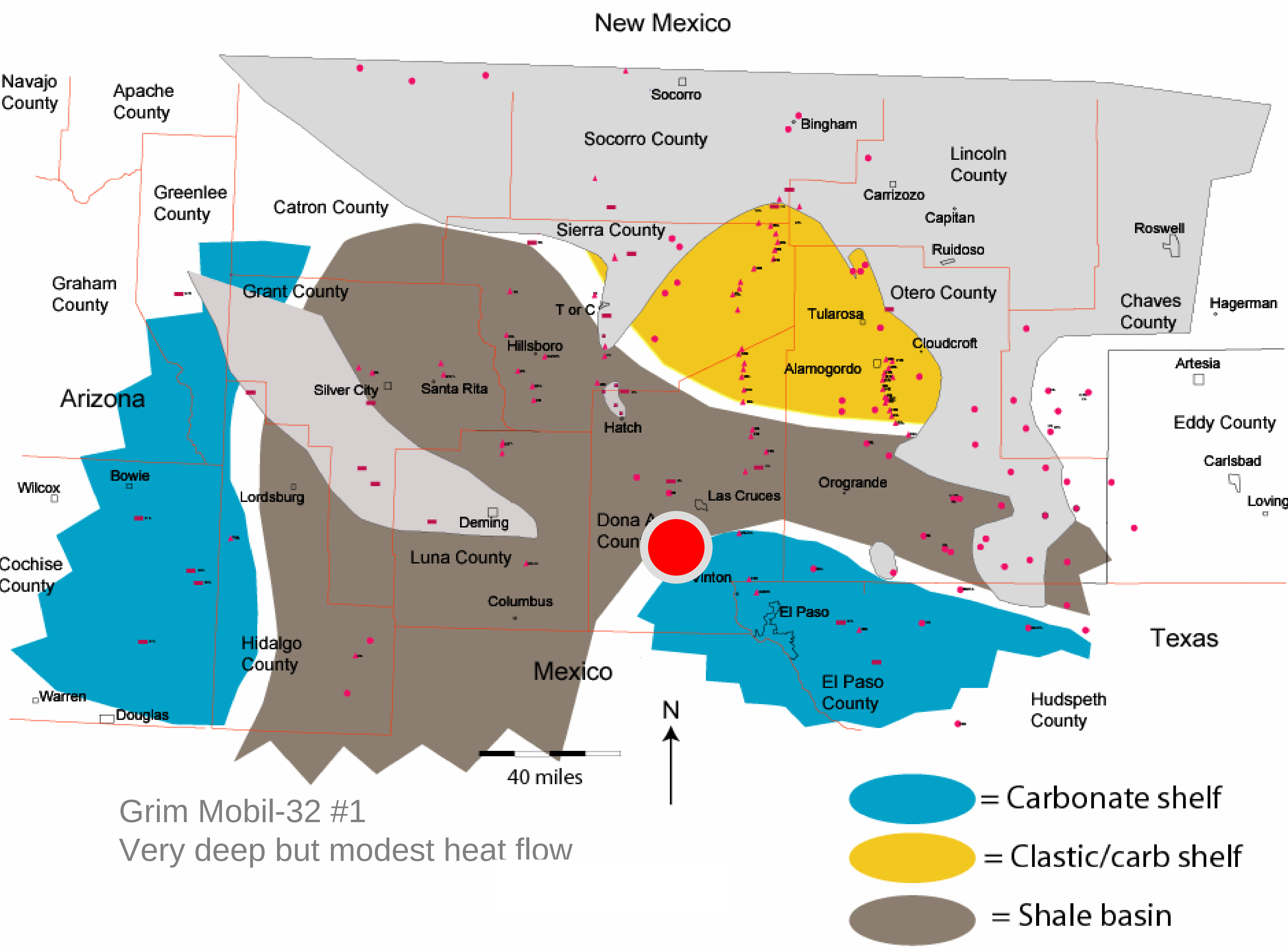
## New Mexico Regional Heat Flow Map




From Reiter et al., 1975

# Local McGregor Range (Fort Bliss) Heat Flow

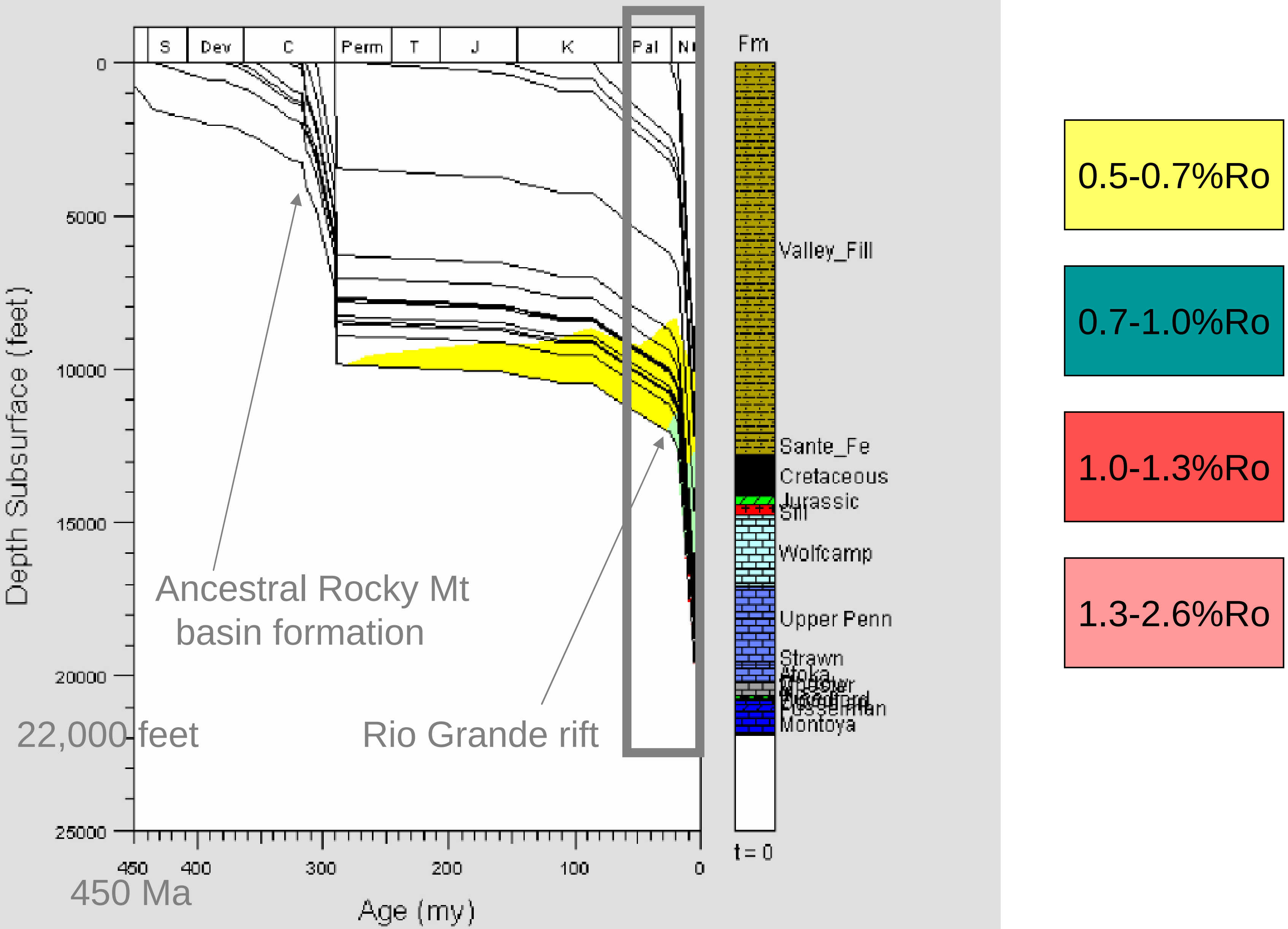




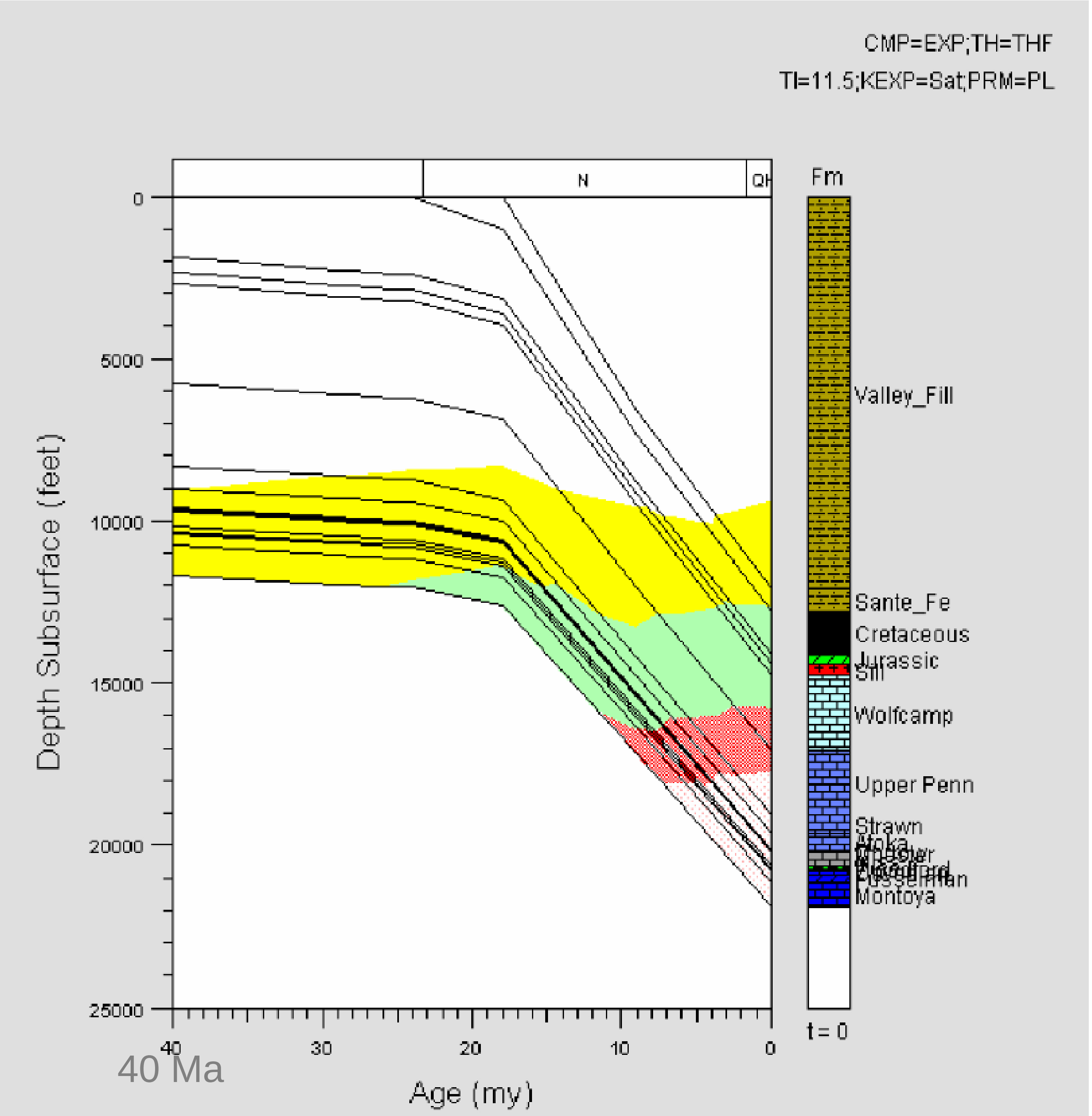

Grim Mobil-32 #1

Very deep but modest heat flow

# Grim Mobil



S
Dev
C
Perm
T
J
K
Pal
Fm
0
5000
10000
15000
20000
25000
Depth Subsurface (feet)
450
400
300
200
100
0
Age (my)
t = 0
Valley_Fill
Sante_Fe
Cretaceous
Jurassic
Sill
Wolfcamp
Upper Penn
Strawn
Montoya
Ancestral Rocky Mt basin formation
Rio Grande rift
22,000 feet
450 Ma
0.5-0.7%Ro
0.7-1.0%Ro
1.0-1.3%Ro
1.3-2.6%Ro



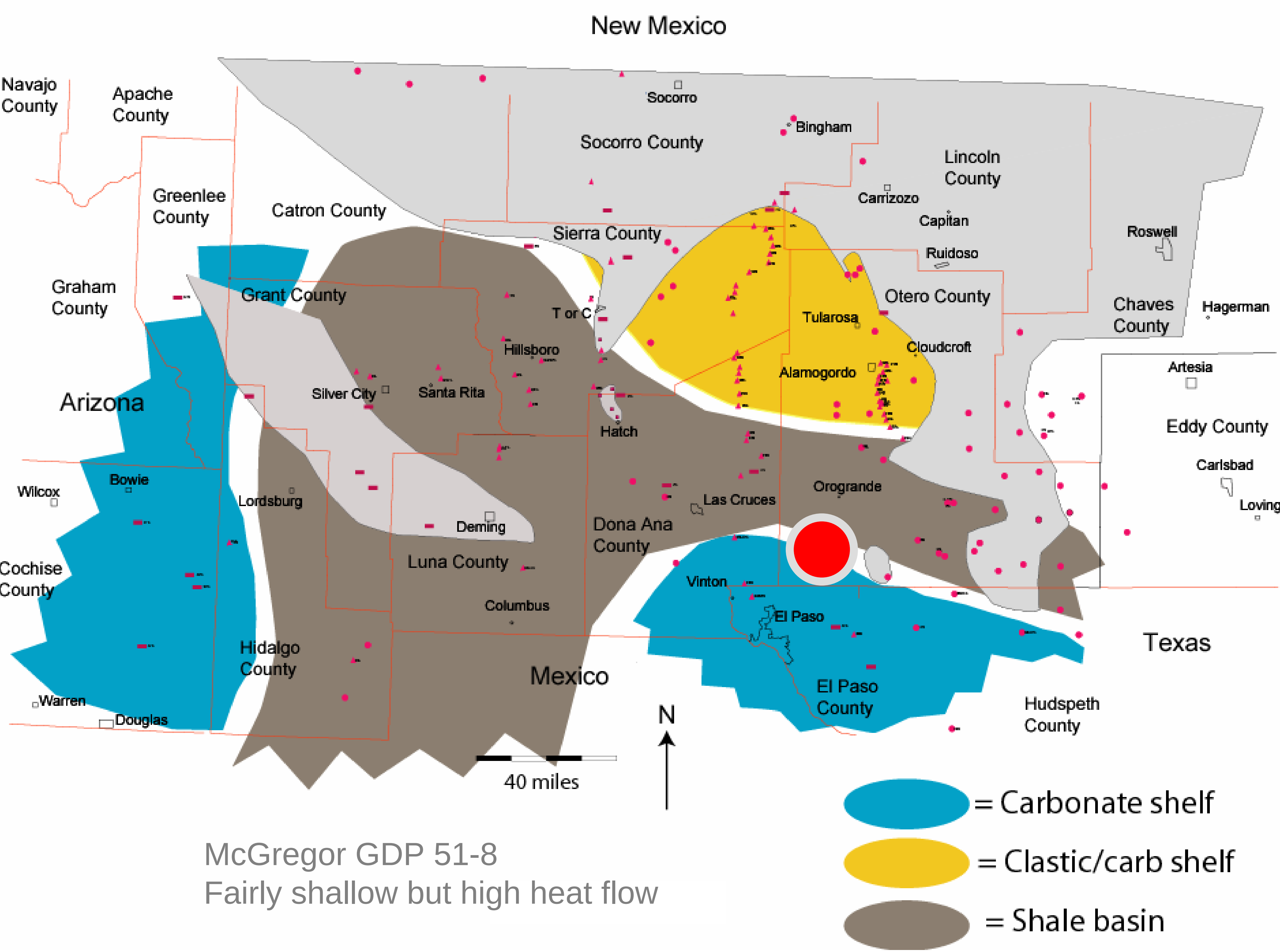

40 Ma

0.5-0.7%Ro

0.7-1.0%Ro

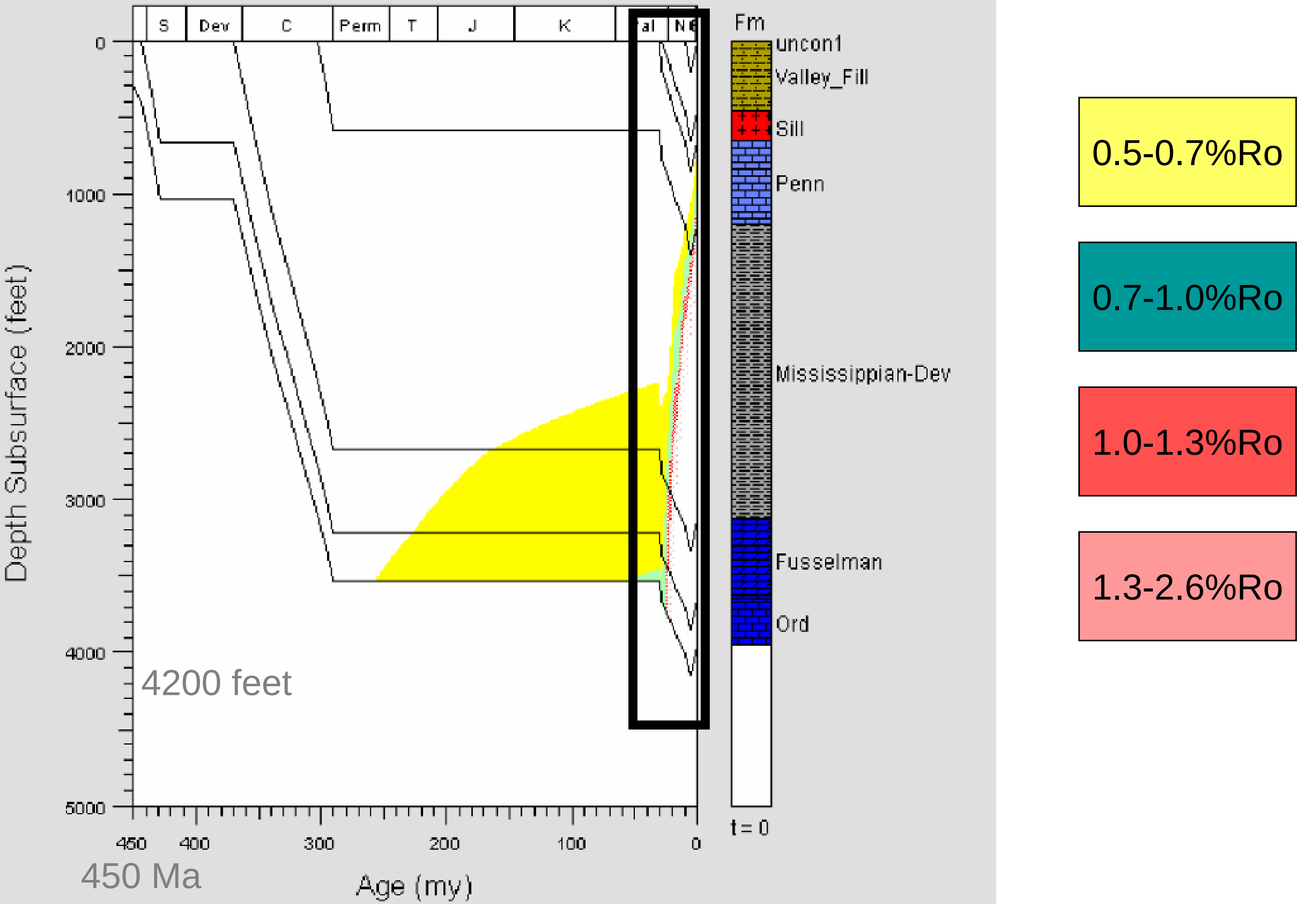
1.0-1.3%Ro

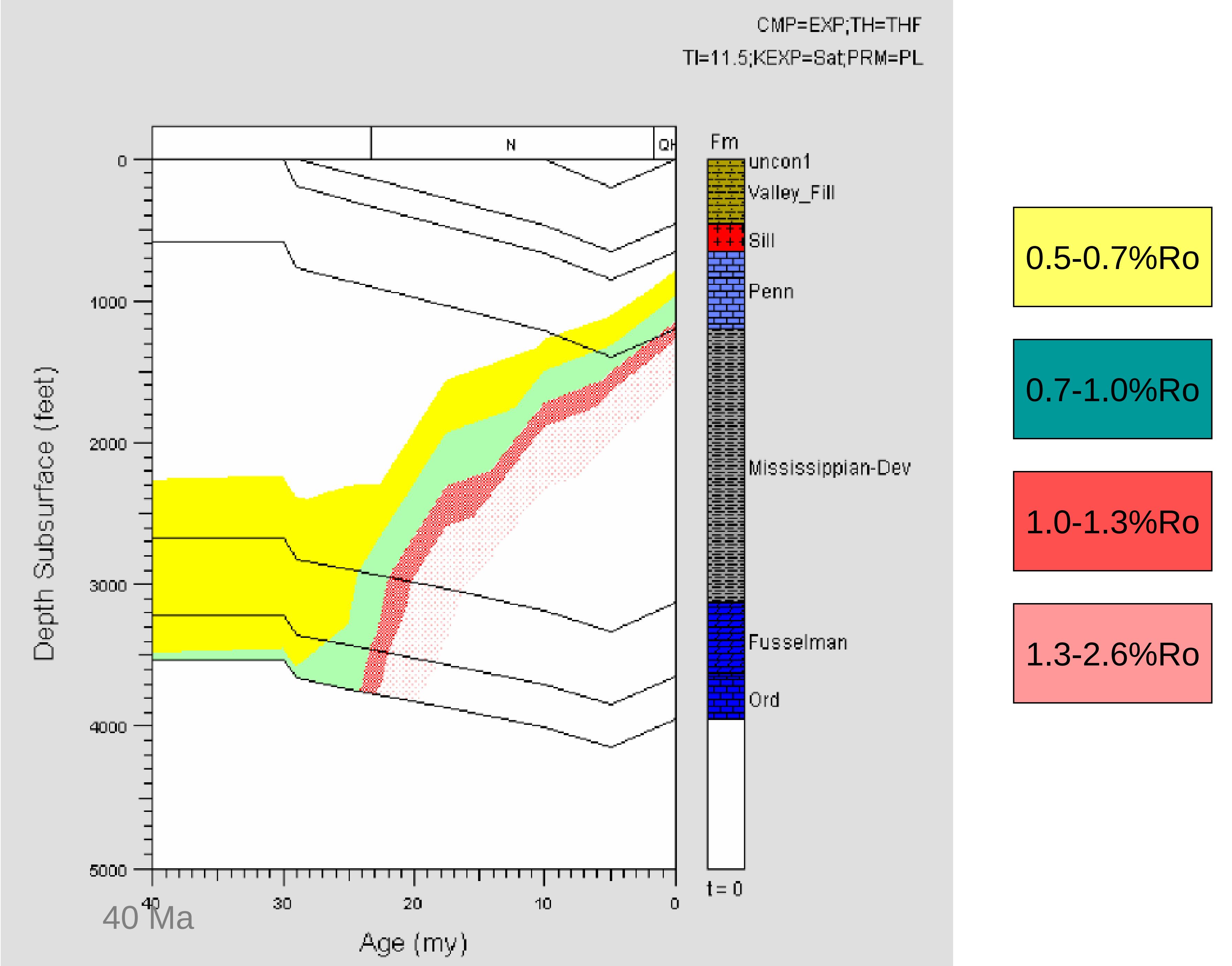
1.3-2.6%Ro




McGregor GDP 51-8
Fairly shallow but high heat flow

# McGregor GDP 51-8





CMP=EXP;TH=THF
TI=11.5;KEXP=Sat;PRM=PL
N
QH
Fm
uncon1
Valley_Fill
Sill
Penn
Mississippian-Dev
Fusselman
Ord
t= 0
Depth Subsurface (feet)
0
1000
2000
3000
4000
5000
40
30
20
10
0
Age (my)
40 Ma
0.5-0.7%Ro
0.7-1.0%Ro
1.0-1.3%Ro
1.3-2.6%Ro

| | | |
|---|---|---|
| 1. Ridgeway AZ 2-13 State | 43. Humble Oil Co. #1 State “A” | 86. Campbell #1 Hurley |
| 2. Shell 1 Swepi Magnus Mts Federal | 44. Hembrillo Canyon | 87. Campbell #1 Spanel |
| 3. Shell 1 Swepi Etal State | 45. Rich Rim | 88. Campbell #1 McMillan |
| 4. Sun Oil #1 St. Augustine | 46. Lost Man Canyon | 89. Coral #1 Warren |
| 5. Kelly | 47. Dead Man Canyon | 90. Union #1 White |
| 6. Lockhart #1 | 48. Mayberry Canyon | 91. Turner #1 Evans |
| 7. Sun Oil Co. #1 Bingham-State | 49. San Andres Canyon | 92. Flynn, Welch, Yates #1 Donohue |
| 8. Standard Oil Co. Texas #1 Heard | 50. Ash Canyon | 93. Union Oil Co. #1 McMillan |
| 9. San Juan Peak | 51. Salt Canyon | 94. Transocean #1 Ablah |
| 10. Mockingbird Gap | 52. Bear Canyon | 95. Campbell #1 Liberman |
| 11. Can Spring | 53. Organ Mts | 96. Penzoil #1 Southland State 28 |
| 12. Bear Mountain | 54. Indian Wells | 97. Dunigan #1 Alpha Federal |
| 13. Georgetown | 55. Dry Canyon | 98. Hunt #1 McMillan-Turner |
| 14. Santa Rita | 56. Marble Canyon | 99. McGregor GDP 51-8 |
| 15. Hermosa | 57. Tipi Mound | 100. Seaboard #1 Federal |
| 16. North Percha Creek | 58. Deadman Canyon | 101. Peloncillo Mts |
| 17. Hillsboro/Percha Creek | 59. Alamo Canyon | 102. Hatchita Dome #1 Tidball-Berry Fed. |
| 18. Tierra Blanca Canyon | 60. Southern Prod. Co. #1 Cloudcroft | 103. Big Hatchet Mts |
| 19. Brenda Canyon | 61. Mule Canyon | 104. Humble Oil&Refining Co. #1 NM State “BA” |
| 20. Lake Valley | 62. Muleshoe Canyon | 105. Cooks Range |
| 21. Sun Oil Co. #2 Victorio | 63. San Andres Canyon | 106. Gym Peak |
| 22. Sun Oil Co. #1 Victorio | 64. Dog Canyon | 107. Cities Services Corralitos |
| 23. Reservoir | 65. Texaco Federal E | 108. Sinclair Oil&Gas Co. #1 Federal |
| 24. Mud Springs Mt. | 66. Texaco Federal G | 109. Bishops Cap |

| | | |
|---|---|---|
| 25. Burbank Canyon | 67. Texaco Federal F | 110. Grim Mobil-32 #1 |
| 26. Derry Hills | 68. Escondido Canyon | 111. Anthony Pass |
| 27. Gulf Sierra | 69. Moore Ridge | 112. Vinton Canyon |
| 28. Sunray Midcontinent Oil Co. #1-M Federal | 70. Table Top | 113. Maria Canyon |
| 29. Martin Tank | 71. Grapevine Canyon | 114. California Co. #1 Theissen |
| 30. Johnson Park Canyon | 72. Plymouth Oil Co. #1 Federal (Evans) | 115. Magnolia Pet. Co. #1 University 39881 |
| 31. CCC Tank | 73. Sun Oil Co. #1 Pearson | 116. Jones #1 Melbreth-Mowry |
| 32. Capital Peak | 74. Texas Prod. #1 State-Wilson | 117. Hunt C.L. Ranch #1 |
| 33. Lava Gap/Thurgood Canyon | 75. Magnolia Petroleum Co. #1 Black Hills | 118. Border McAdoo #1 |
| 34. Sly Gap | 76. Gulf Oil Co. #1 Chaves “U” | 119. Gulf Oil Corp. #1 Burner-State “B” |
| 35. Salinas Peak | 77. Kewanee 1 FM | 120. Cockrell #1 Pyramid Federal |
| 36. Mackinson Canyon | 78. Sun Oil Co. #2 Pinon | 121. Cockrell #1 Coyote State |
| 37. Rhodes Canyon | 79. Gulf Oil Corp. #1 Munson Federal | 122. Cockrell #1 Playas State |
| 38. Cottonwood Canyon | 80. Zapata Petroleum Corp. #1 Federal 14 | 123. Graham Hatchet Federal |
| 39. Houston State 1453 | 81. Standard of Texas #1 Scarp | 124. Yates #1 One Tree Unit |
| 40. Houston 2 Lewelling | 82. Lefors #1 Federal | 125. Yates #1 Dog Canyon Federal |
| 41. Houston 1 Lewelling | 83. Tri Service #1 Little Dog | 126. Marathon #1 Mesa Verde Ranch |
| 42. Houston State 3724 | 84. Continental #1 Bass | 127. Heyco #1Y Bennet Ranch |