The Tectonic Framework of Texas

Text to accompany "The Tectonic Map of Texas"

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Second Printing—March 2004
Third Printing—August 2004
Fourth Printing—July 2005

Contents

Figures

Introduction

Creation of a new tectonic map of the state of Texas began at the Bureau of Economic Geology in 1981 under the supervision of Arthur G. Goldstein. Because knowledge of surface and subsurface structural configuration had advanced since earlier mapping, a new compilation was essential. A committee was assembled, including both Bureau researchers and others active in Texas structural geology. In 1982, the author assumed responsibility for compilation of the map and contributions were made by all members of the committee. A review copy of the map was displayed at the 1983 National Convention of the American Association of Petroleum Geologists (Ewing and others, 1983). Subsequently it was taken to local geological societies and geoscience departments at universities across Texas and in adjoining states. Data from regions outside of Texas were reviewed by the geological surveys of adjacent states. Compilation of information for the final map was completed in 1984; new information after that date was not included in the map. However, the present text includes information acquired through spring, 1990. Four-color cross sections corresponding to the map areas will be published separately as part of the Bureau's Cross Section series.

Sources of Data

The first published structural map of Texas (Sellards and Hendricks, 1936) was compiled by E. H. Sellards and published in 1936 by the Bureau of Economic Geology. This map was accompanied by a major text, *The Geology of Texas, Volume 2* (Sellards, 1935), published as University of Texas Bulletin 3401. Subsequent editions of the map were published until 1946; both the map and the text have long been out of print.

The new Tectonic Map of Texas represents a significant increase in the understanding of the tectonic evolution of Texas. Much more detailed data and interpretations derived from surface geology have been included in the present map, based on generations of field work in the exposed, tectonically complex areas of the state, specifically the Llano Uplift, Trans-Pecos Texas, and the Marathon region. Although little deformation is mappable at the surface in most of the state, large-scale deformation is found in the subsurface within the thick sedimentary columns of West Texas, North Texas, and the Gulf Coast. For this reason, mapping deep subsurface horizons is essential to understanding the deformational history of Texas. Since 1946, tens of thousands of wells have been drilled in Texas; many of these penetrated deeper horizons than those upon which Sellards based his work. Consequently, it is now possible to map at deeper structural levels than before, and, by doing so, to delineate the faults and folds that occur in the deeper parts of the West Texas and Gulf Coast Basins.

Several publications have synthesized tectonic information on various parts of Texas since 1932. These include University of Texas Publication 6120, *The Ouachita System*, by Flawn and others (1961); the *Tectonic Map of the Gulf Coast Region, U.S.A.*, by the Gulf Coast Association of Geological Societies (1972); and a 1977 map of the Trans-Pecos region by C. D. Henry and N. T. Bockoven, revised by Henry and others (1985). Hills (1970) and the Panhandle Geological Society (1969) provide notable tectonic syntheses of the West Texas Basin and Panhandle areas, respectively, but do not include detailed maps.

Structural mapping of economically significant subsurface horizons is vital to the oil and gas industry. Many proprietary maps and mapping services exist. Of these, Geomap Company has for many years compiled up-to-date maps of the Gulf Coast and East Texas, which have been adapted (with Geomap's permission) for the present map. Geomap also produces subsurface maps of much of the rest of Texas. Formation elevations are given on publicly available completion cards and on type and sample logs, and articles describing individual oil and gas fields include structural maps of producing structures. Most of these maps are based on borehole data only; seismic reflection data, which are essential for mapping sparsely drilled deep horizons, are not generally available. Several generous donations of formation elevations for more than 20,000 wells were received for this project, most notably from Lennart Teir, Wichita Falls, and the University Lands Office, Midland.

Sources used for the present compilation are listed on the Tectonic Map itself and in the appendix of this text. Information on the onshore areas was compiled at a scale of 1:250,000 by plotting on overlays of topographic sheets at that scale. These sheets are available for inspection at the Bureau of Economic Geology in Austin.

Keywords: tectonic map, tectonics, Texas

Principles of Tectonic Mapping

Coverage

From the beginning, the committee resolved to provide a map that would not terminate at the boundaries of Texas when geologic structures continued across those boundaries. Texas is not a geologic entity; major structural features such as the West Texas Basin and the Amarillo-Wichita axis cannot be fully understood without reference to their continuations into New Mexico and Oklahoma. Therefore, a study area was defined that extended beyond the borders of Texas to reasonable geologic stopping points, tempered by logistical considerations. These boundaries are the southern edge of the Anadarko Basin in Oklahoma; longitude 104.5° West in New Mexico, chosen to include the West Texas Basin; the northeastern edge of the Sabinas Folded Belt in northeastern Mexico; and boundaries east from the mouth of the Rio Grande and south from the Louisiana border that yield a pie slice of the Gulf of Mexico Basin extending to the Sigsbee Abyssal Plain. Only an area of this size could properly display the complex geology of Texas.

Tectonostratigraphic Units

To clarify the complex surface geology and provide a framework for interpreting the tectonic development of Texas, a system of tectonostratigraphic units has been defined. These units are sequences of strata or complexes of igneous and metamorphic rocks that have a similar history of emplacement and deformation. They can be related in time to the tectonic cycle that formed them, as shown graphically in the explanation section of the Tectonic Map. The surface geology is recast in terms of these units in areas where tectonically significant deformation exists in outcrop and in areas (primarily in Trans-Pecos Texas) where well control is entirely lacking.

Contouring

In areas where major structural features can be shown only by subsurface structural contouring, the deepest correlatable horizon for which adequate data could be obtained was used. In general, this represents an easily correlatable lithologic discontinuity, typically an unconformable top of a major tectonostratigraphic unit. In Texas north and west of the Ouachita orogenic belt, the principal mapped horizon is the top of the Lower Ordovician carbonate platform (Ellenburger and Arbuckle Groups). Where this horizon is absent, the top of Precambrian (Cambrian crystalline rock in the Wichita and Devils River Uplifts) is used. In New Mexico, the top of the Siluro-Devonian carbonate is used because the top of the Ellenburger is an indistinct horizon in that area and published data were available for the Devonian. The top of deformed Ouachita-facies Paleozoic rocks forms a narrow strip of contouring along the front of the Ouachita thrust system south from Dallas to San Antonio. The Albian top of the Edwards Group (base of Austin Chalk, Upper Cretaceous, in East Texas) was used in the interior part of the Gulf Coast region, landward of the Stuart City shelf edge. In the exterior part of the Gulf Coast region, several Tertiary horizons were used. In each area these horizons lie at or immediately above the shallowest occurrence of geopressure and near the top of the zone of complex structure. Contouring could not be extended offshore because the data were not available, but general fault trends are shown.

Inset Maps

Along with the main map, inset geophysical maps highlight factors that bear on tectonic reconstructions. These maps include gravity, corrected for the isostatic effects of elevation; magnetic anomalies; seismicity; neotectonics; and topography. In addition, basement lithologic terranes and selected radiometric dates (as of 1984) are included on an inset. Lastly, well density is shown to indicate the overall reliability of the tectonic map.

Scale and Intended Use

The map was designed as a wall-display map. For this purpose, a U.S. Geological Survey base map in four sheets at a scale of 1:750,000 was selected and modified. This is the only available base map that does not detach the Panhandle from the rest of the state and that allows enough room for inset maps and out-of-state coverage. The scale is unusual, as most U.S. state maps are at a scale of 1:500,000 or 1:1,000,000. However, both the requirements of press size and the practical limitation of displaying the map on an average wall prohibited the use of these scales.

General Features of the Tectonic Map

The Tectonic Map includes both surface and subsurface information. The west-central part of the map (darker shades of blue) represents the West Texas Basin (contoured on Ellenburger limestone). This is a composite intracratonic basin that formed primarily during late Paleozoic (Pennsylvanian and Permian) time. To its east is the Bend Arch (light blue), a broad flexure where sediment thickness is less. To the north are uplifts and basins also formed during the late Paleozoic: the Wichita and Amarillo Uplifts (mostly in tan, representing the shallow basement) and the deep Anadarko Basin (much of the Oklahoma portion is not shown). The tips of basement-cored uplifts are exposed in the Wichita and Arbuckle Uplifts of Oklahoma and the Llano Uplift of Central Texas. In the Llano area, complex patterns of blues, reds, and dark pink show the deformed and metamorphosed Precambrian rocks and intrusive granites. The orange to tan area in the northwest represents the region where Ellenburger limestone either was not deposited or was eroded before subsequent deposition.

In a belt bisecting Texas from southwest to northeast are purple to olive colors representing the leading edge of the Ouachita orogenic belt, a long fold and thrust belt of late Paleozoic age extending from Mexico through Texas, Oklahoma, and Arkansas to Mississippi. This belt is buried except in the Marathon Uplift of extreme southwest Texas and in the Ouachita Mountains of Oklahoma. Where it is buried, the internal structure of the belt is poorly known, and contours can only be mapped on the pre-Cretaceous unconformity that forms its upper surface.

Southeast of the Ouachita belt are bands of greens, browns, and oranges representing the Mesozoic and Cenozoic strata that fill in the northwestern Gulf of Mexico Basin. The broad green area represents the part of the northwestern Gulf margin that was only slightly to moderately deformed by early Mesozoic extension; at its seaward edge are Lower Cretaceous reefs that fringed the Gulf of Mexico. Seaward of the reefs, the deep Gulf of Mexico was filled and the continental margin prograded as thick clinoformal wedges of Cenozoic clastic sediment, which are represented by the colored bands paralleling the Gulf shoreline. This series of wedges continues offshore beneath the continental shelf as far as the Quaternary shelf margin.

Along the southwestern border of the map, complex color patterns show the effects of Cretaceous-Tertiary compressional deformation in the Sabinas Folded Belt, the Chihuahua Tectonic Belt, and adjacent areas. Yellow bands in the west end of the map show grabens and intervening horsts that formed during the Basin and Range extensional events of Miocene to Holocene age.

Plate Tectonics and Tectonic Cycles

Major tectonic events in Texas, as well as in North America as a whole, can be arranged into a series of tectonic cycles more or less equivalent to Wilson's (1966) cycles of continental rifting, subduction, collision, and related periods of intracontinental deformation. These cycles can be distinguished by the age and style of deformation. Each cycle produces a series of tectonostratigraphic units that record the generation of rifts and passive continental margins, followed eventually by a change to compressional tectonics, magmatism, metamorphism, uplift, and erosion. In Texas we recognize four main cycles:

(1) The Gulfian cycle, still in progress, began with continental rifting in the Late Triassic at about 220 Ma and proceeded to the generation of oceanic crust in the Late Jurassic at about 160 Ma. Spreading ceased in the Gulf of Mexico ocean basin before 110 Ma, and the basin has remained stable since. However, in the southwestern part of the Gulf of Mexico Basin (including southwest Texas), southwest to northeast compression of Late Cretaceous to Paleogene age (85–50 Ma), related to a convergent or accretionary event at the Pacific plate margin, produced folds and thrust faults assigned to the Laramide orogeny.

(2) The Ouachitan cycle began with continental rifting in the Cambrian at about 550 Ma, creating one or more failed rift basins. Subsidence of the rifted margin led to deposition of a widespread Cambro-Ordovician shelf sediment package from 505 to 480 Ma ago while thinner basinal sediments were deposited to the southeast. An enigmatic Devonian event may mark the changeover to compressional tectonics; thick flysch sediments deposited in the Mississippian are related to convergence. Major thrusting of the Paleozoic basinal and flysch sediments to the north and west over the cratonal platform occurred in the Early Pennsylvanian (320–300 Ma), Late Pennsylvanian (300–286 Ma), and Early Permian (286–270 Ma), causing extensive fault reactivation and intracratonic deformation in Oklahoma and West Texas. Subsidence of an intracratonic basin that centered in West Texas began during the mid-Pennsylvanian and continued to the close of the Permian Period at 245 Ma.

(3) The Llano cycle (Middle Proterozoic) is less well known. Its early phase is recorded in protolith ages of Llano rocks and the Carrizo Mountain Group; a less deformed sedimentary trough may exist in parts of West Texas and New Mexico. Between 1200 Ma and 1080 Ma, metamorphism, igneous activity, and uplift affected a wide area from the Van Horn area of West Texas to the Llano Uplift. This orogenic period corresponds to the Grenville orogeny of Eastern North America. Less widespread felsic and mafic igneous activity of 1160–1100 Ma age may correspond to the Midcontinent Rift episode to the north.

(4) The Sierra Grande–Chaves "cycle" (probably not a true Wilson cycle, and probably composite) formed the oldest known rocks in Texas. It includes very extensive anorogenic granites of 1340–1400 Ma age (Middle Proterozoic); bimodal volcanics of similar age; and probably volcano-sedimentary complexes (volcanic arcs and related basins) of 1700–1800 Ma age (Early Proterozoic) similar to those exposed in central and northern New Mexico and southern Arizona. The tectonic history of this cycle is poorly known because deformed rocks or rocks deformed during this cycle in the map area are nearly completely covered by Phanerozoic sedimentary rocks.

Precambrian Tectonic Cycles

Knowledge of Precambrian rocks and deformation in Texas is incomplete, partly because of the paucity of exposure. The history of the older rocks (Sierra Grande–Chaves "cycle") in the northwestern part of the state can be considered only in reference to exposures in central New Mexico, southern Missouri, and places yet farther afield. Llano-cycle rocks are exposed in scattered ranges in West Texas and in the erosional window of the Llano Uplift in Central Texas. Isolated well samples from elsewhere in the state provide lithologic information and may provide useful radiometric dates, but only rarely do they yield any structural information. Great advances are being made in studying these rocks, however. In particular, the advent of U-Pb zircon dating has allowed precise age determinations of all Precambrian rocks. Scattered dating in Texas has shown so far that many if not most Rb-Sr ages of Precambrian rocks are too young, and they reflect metamorphic peaks and/or chemical exchanges, not the protolith. In addition, detailed structural work has disclosed a far more complex history of deformation than was previously suspected. For this reason, the descriptions of cycles below are provisional; a more satisfactory account will be possible only after much more work.

Sierra Grande–Chaves "Cycle"

The oldest rocks in Texas occur in subcrop beneath the Paleozoic strata northwest of a line from farthest West Texas to southernmost Oklahoma (fig. 1). They are nowhere exposed in Texas; nearest exposures are in the mountain ranges that extend north–south through central New Mexico and in the Arbuckle Mountains of south-central Oklahoma. The terms "Sierra Grande granite terrane," "Chaves granite and gneiss terrane," and "Torrance metamorphic rocks" have been used in the past (Flawn, 1956) to refer to the subsurface, but little or nothing was known of their tectonic history from subsurface data. Recent age determinations, especially using zircons from small quantities of subsurface samples, allow correlation of these rocks with better-known exposures to the west and east.

In the southwestern United States, recent work has detailed a complex accretionary collage of island-arc and interarc sedimentary basins of 1790–1710 Ma age, which were accreted by about 1700 Ma (Condie, 1986; Grambling and others, 1988; Karlstrom and Bowring, 1988). This amalgamated crust was then overlain by felsic or bimodal volcanics and shallow-water sediments and extensively faulted (by thrusting in the Mazatzal orogeny of southern Arizona; also with high-angle faults) and metamorphosed to greenschist or amphibolite grade before emplacement of granites at 1640 Ma. The metasediment-rich packages in southern New Mexico may represent a forearc basin and/or accretionary complex formed above a northwest-dipping slab (Grambling and others, 1988). Rocks similar to the New Mexico and Arizona complexes probably extend eastward into northwest Texas and form the true "basement" in that area. Rocks earlier mapped as "Torrance terrane," most of those mapped as "Chaves terrane," and possibly some mapped as "Sierra Grande terrane" probably are of this affinity; these names are not used in figure 1.

Nelson and DePaolo (1985) determined from Sm-Nd isotope systematics that the crust in central and northern New Mexico has a differentiation age of 1700–1800 Ma, consistent with the geologic history. Similar differentiation ages were found in the United States Midcontinent area.

This earlier history of orogenic accretion and deformation is overprinted by an extensive episode of intracratonic magmatism named the "Western Granite-Rhyolite Province" (Bickford and others, 1986). Zircon dating of subsurface samples indicates that granitic and rhyolitic rocks from northwest Texas and Oklahoma are in the age range of 1340 to 1400 Ma, like the outcropping San Isabel Batholith in Colorado (Thomas and others, 1984). All the exposed rocks in the Arbuckle Mountains of Oklahoma are also part of this province (1375–1400 Ma; Bickford and Lewis, 1979). Slightly older rocks of the same affinity form large anorogenic batholiths in Colorado and northern New Mexico and volcanic complexes in the St. Francois Mountains of southern Missouri.

In Texas, rocks of the Panhandle Rhyolite terrane (Flawn, 1956; PR, fig. 1), sampled in four areas, have yielded zircon dates of 1370–1400 Ma (Thomas and others, 1984), older than previous Rb-Sr dates of about 1200 Ma. These rocks form a 10-km-deep basin that is mappable as a series of subbasins on seismic sections from the Palo Duro Basin area (Budnik, 1984). The Amarillo Granite terrane (AG, fig. 1) is interpreted to represent the subvolcanic equivalent of this very extensive rhyolite (Denison and others, 1984). Many occurrences previously interpreted as "Sierra Grande granite terrane" are probably also part of the Western Granite-Rhyolite Province (Bickford and others, 1986).

Inferred to overlie the Panhandle Rhyolite terrane are diabase and gabbro of the Swisher terrane and sediments of the De Baca sedimentary terrane. These rocks are essentially undated, although a 1220-Ma K-Ar date was obtained on a pyroxene from the Swisher diabase (Muehlberger and others, 1966). These rocks may reflect either a continuation of the Western Interior episode or the early rift stage of the Llano cycle.

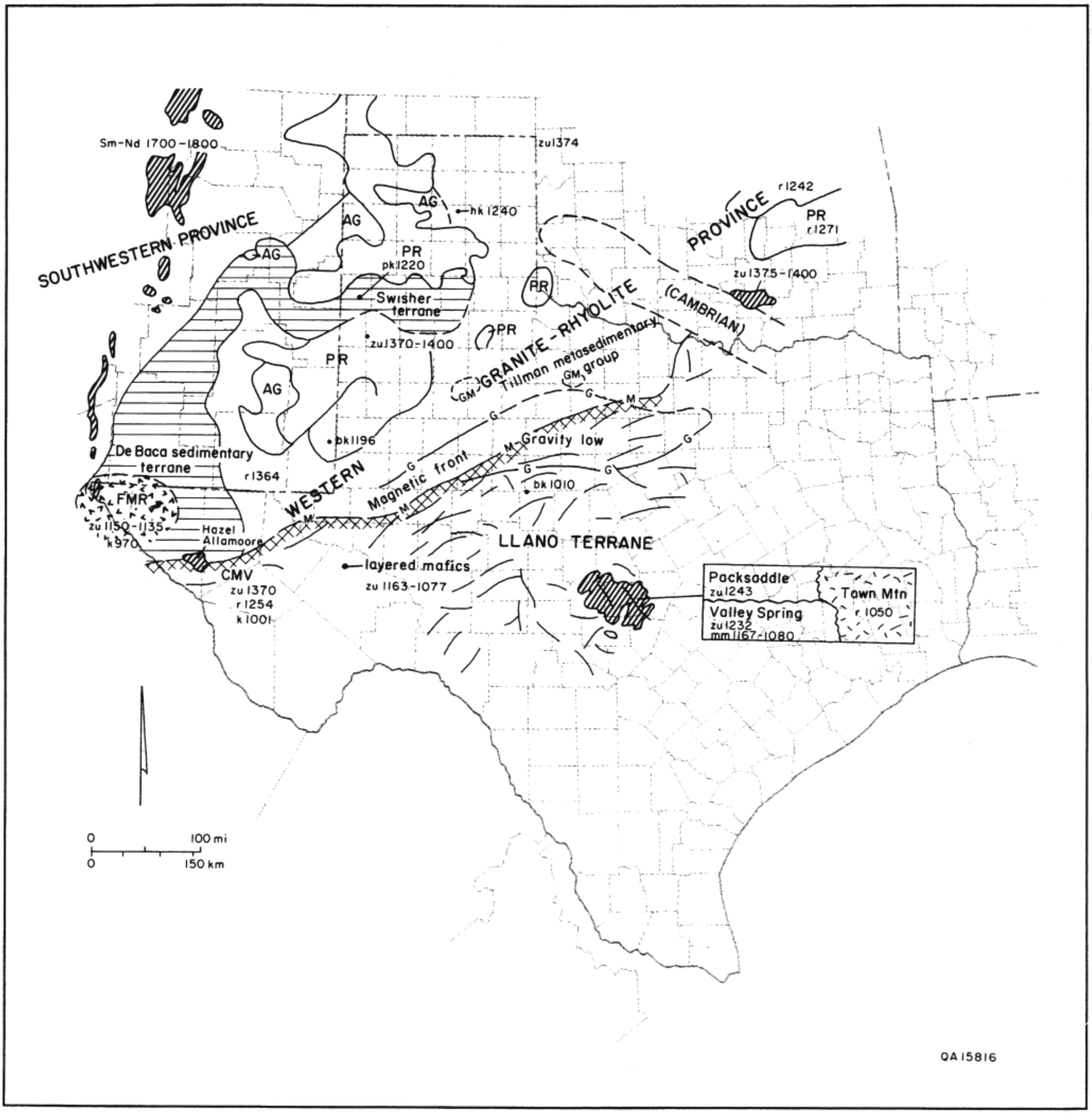


FIGURE 1. Map of Precambrian terranes as they crop out (shaded) or occur as subcrop beneath the Phanerozoic in Texas and adjacent states, with the best available dates. This is a current (to 1990) version of the (1984) inset on the Tectonic Map. Lines of maximum gravity (G) and magnetic (M) gradient are shown through Central Texas, where they help to define the boundary between Llano and older terranes. Abbreviations: PR = Panhandle Rhyolite terrane; AG = Amarillo Granite terrane; FMR = Franklin Mountains Rhyolite terrane; CMV = Carrizo Mountain Volcanics. Radiometric ages are coded as on the Tectonic Map: dates are in million years before the present (Ma B. P.); the letter before the date refers to the dating method (k = K-Ar; r = Rb-Sr; u = U-Pb); the letter before that, to the mineral phase dated (z = zircon; b = biotite; h = hornblende; p = pyroxene). mm = bracketed age of metamorphism and deformation.

In the subsurface of North Texas just south of the Wichita Uplift, rocks of the Tillman Metasedimentary Group have yielded radiometric ages of 1000–1380 Ma (Lidiak, 1990) and represent part of the fill of a deep layered basin (Brewer and others, 1981). They might represent an eastern continuation of the Panhandle layered basins. Alternatively, they could be associated with rifting or foreland-basin processes related to the Llano cycle.

Llano Cycle

The Llano (Grenville) tectonic cycle consists of two main parts: a poorly known early rift(?) event and the Grenville orogeny that deformed and metamorphosed most of the continental crust of Central Texas (fig. 1). A fuller summary of the recent work on rocks of this cycle is presented in Mosher (in press).

Rift(?) Stage

The record of possible early Llano-cycle rifting and sedimentation is obscure in Texas. However, many of the protoliths of rocks of the Llano terrane may represent rift-related sediments and certainly yield older, possibly pre-deformation dates.

Thick sequences of unmetamorphosed strata with some basaltic rocks (the Swisher and De Baca terranes of Flawn, 1956) may occupy deep faulted troughs. Exposed sedimentary rocks in the Van Horn area, which probably correlate with the De Baca terrane, are demonstrably older than Llano thrust-faulting and deformation. The allochthonous Carrizo Mountain Group at Van Horn includes metasediments, rhyolite ash-flow tuffs, and gabbros; S.A. Bowring has dated zircons from a rhyolite porphyry at 1370 Ma (Patchett and Ruiz, 1989). The Rb-Sr date is 1254 Ma (Denison and Hetherington, 1969). This date suggests that the Carrizo Mountain protoliths are part of the Western Rhyolite Province, which was deformed by the Grenville orogeny.

In the Llano Uplift, the metamorphosed Valley Spring Gneiss yields U-Pb zircon ages of 1232±7 Ma, and the structurally overlying Packsaddle Schist yields ages of 1243±2 Ma (Walker, 1988; S. Mosher, pers. comm., 1990). The Valley Spring protolith was arkosic, granitic, or rhyolitic (possibly related to rifting or arc volcanism; Garrison, 1985); the Packsaddle Schist protolith was probably an interstratified accumulation of shelf/slope deposits rich in organic material and volcanic and volcaniclastic rocks, which may represent arc-flank deposition (Garrison, 1981; Garrison and Mohr, 1983).

Patchett and Ruiz (1989) determined mantle separation ages from Nd isotopic analyses of the Valley Spring Gneiss and Carrizo Mountain Volcanics formed 1400–1000 Ma ago. They suggested that crustal segregation in the Llano area may temporally overlap the magmatism of the Western Rhyolite Province. From these segregation ages and the old date of the Carrizo Mountain Volcanics, it may be surmised that the Western Rhyolite Province is itself a response to early Llano/Grenville development; either part of an early extensional phase or even related to the beginnings of Grenvillian compression. A much more detailed understanding of both Llano and Western Rhyolite provinces will be necessary to resolve this point.

Llano Orogenic Belt

Rocks that have undergone compressive deformation of the Llano cycle are exposed in the Van Horn Mountains in West Texas and in the Llano Uplift of Central Texas.

In the Llano Uplift three major lithologic units are represented (Barnes, 1988). The structurally lowest is the Valley Spring Gneiss, which is overlain by the Packsaddle Schist (both units described in preceding paragraphs); they are both intruded by a variety of granitic plutons, the most abundant of which are the post-tectonic (1050 Ma or somewhat older) Town Mountain granites. Less abundant are pretectonic to syntectonic granitic plutons; an ultramafic complex (Coal Creek Serpentinite) is also present.

Nelis and others (1989) and Carter (1989), in two recent structural analyses of parts of the Llano outcrop area, identified five phases of deformation: an early generation of folds and foliation, a pervasive isoclinal folding event associated with transposition of bedding and pervasive foliation, and at least three later generations of folds and crenulation cleavages. Metamorphism at medium-pressure amphibolite grade was synchronous with all deformation (Carlson and Nelis, 1986). A second metamorphic event after deformation produced mineral assemblages characteristic of a low-pressure (cordierite-bearing) amphibolite facies. This late metamorphic event may have been caused partly by nearby igneous intrusions (Wilkerson and others, 1988). The extensive Town Mountain granites and broad, gentle folds of the metamorphic units dominate the present-day map pattern.

Gillis and Mosher (1988) reported similarly complex deformation and metamorphism in the Coal Creek Serpentinite, which was emplaced early in the deformational history. Garrison (1981) interpreted this ultramafic body as a partial and dismembered ophiolite. Wilkerson and others (1988) also reported eclogite remnants along the structural contact between the Packsaddle Schist and underlying gneisses, indicating an early high-pressure metamorphism of some rocks that was later largely overprinted by medium- and low-pressure metamorphism.

A pretectonic pluton gave a whole-rock Rb-Sr isochron date of 1167±15 Ma (Garrison and others, 1979); a posttectonic melarhyolite dike cutting deformed Packsaddle strata gave a whole-rock Rb-Sr date of 1080±30 Ma. Town Mountain intrusions have yielded isochron Rb-Sr dates of 1048±34 Ma and 1056±12 Ma (Garrison and others, 1979).

In the Van Horn area, the multiply deformed and metamorphosed Carrizo Mountain Group was thrust northward on the Streeruwitz Thrust over a thick sedimentary succession (King and Flawn, 1953). At least two phases of tight, inclined, northwest-verging folds and one phase of kink folding are identified in the Carrizo Mountain Group (Fayon and Nielsen, 1988). Synorogenic carbonate-clast conglomerate and postorogenic volcanic-and granitic-clast conglomerate are found in the exposed part of the succession, indicating that some of the sedimentary rocks form a foreland basin assemblage in front of the thrust zone. To the south, more ductilely deformed Carrizo Mountain Group rocks record five phases of deformation, the dominant phase being isoclinal folding under amphibolite grade (640°C) with a posttectonic static recrystallization. Their history is quite similar to that of rocks in the Llano Uplift (Bristol and Mosher, 1989).

In the rest of Texas, the Llano-deformed rocks are buried and difficult to study. Analysis of magnetic and gravity maps indicates that the Llano terrane is bounded to the north by a prominent sublinear gravity low and an area of low magnetic relief, which Erdlac (1986) named the Abilene Minimum. To the south of this zone, magnetic signatures similar to those of the exposed Llano Uplift are widespread. The geophysical pattern is suggestive of a sediment-filled foredeep basin, although the few wells in the area have not penetrated sedimentary rocks. The south side of the minimum represents the "Llano Front," the continuation of the Grenville Front in Texas (Muehlberger, 1965). This line passes to the west over the middle of the Central Basin Uplift and to Van Horn; to the east it intersects the Wichita Uplift but is not found northeast of that uplift.

In summary, Llano deformation appears to have been dominated by ductile compressional tectonics at a time older than 1080 Ma but younger than 1230 Ma. Mosher and Reese (1990) suggested that the data currently support northward-directed collision of a continental block with the southern margin of North America at about 1200 Ma.

Silicic lavas, ignimbrites, and associated granites are common in West Texas, forming the Franklin Mountains Igneous Province. Norman and others (1987) infer from geochemical study that the Franklin Mountains rocks represent arc-related or back-arc rocks. Recent U-Pb zircon dating indicates that this activity culminated by 1150–1135 Ma (Copeland and Bowring, 1988), rather than by 1000 Ma as previously estimated. This is slightly older than the basaltic volcanism of the Midcontinent Rift (dated at 1109–1094 Ma; Hoffman, 1989), but both appear to be contemporaneous with Grenville compressional tectonism. A large, possibly layered mafic complex in the Fort Stockton Uplift area in Pecos County yields U-Pb dates of 1163, 1095, and 1077 Ma (Keller and others, 1989). All of these occurrences suggest extensional magmatism, especially during the later part of Grenville deformation, metamorphism, and granitic intrusion.

Ouachitan Cycle (Paleozoic)

In Cambrian time, rifting of the southern margin of North America led to development of a deep-water basin on highly rifted "transitional" or oceanic crust, along with several failed rift basins (fig. 2). This extended terrane began to be compressed in the Mississippian, leading to extensive deformation in the Pennsylvanian and Early Permian (fig. 3): thrusting of a thick basinal sequence over the foreland, and intracratonic foreland deformation both along the old failed rift basins and elsewhere. In addition, major intracratonic subsidence occurred in the West Texas and Anadarko Basins, mainly in Pennsylvanian and Permian time.

Rift Phase

The best-studied rocks representative of this phase come from the Wichita and Arbuckle Uplifts of southern Oklahoma, where rocks of the Southern Oklahoma rift basin have been brought to the surface (figs. 2 and 3). In the Wichita Uplift area (Gilbert, 1982), a series of gabbros and layered mafic complexes is overlain by a thick sequence of rhyolites with sills and stocks of granite. The rhyolite is Early to Middle Cambrian (525–545 Ma; Muehlberger and others, 1967) and is unconformably overlain by Upper Cambrian sandstone of the continent-platform sequence. Bowring and Hoppe (1982) reported a U-Pb zircon age of 550–560 Ma for the gabbro complex. The margins of the Cambrian igneous terrane have been modified by late Paleozoic deformation, but they may originally have been large normal faults.

In the Devils River Uplift area, rhyolitic metavolcanic rocks dated as Cambrian (481–529 Ma; Nicholas, 1983) or Late Proterozoic (ca. 700 Ma; Denison and others, 1977) overlie mafic metaigneous rocks dated at 1120–1250 Ma and affiliated with the Llano cycle. Ewing (1985) discussed the evidence of a failed rift basin in this area.

No thick pre-Upper Cambrian basin-fill sedimentary sequences are known in either the Devils River or the Wichita Uplift areas. Middle Cambrian shelf sandstones and carbonates in the Llano area are coeval with much of the igneous activity in southern Oklahoma.

The position of the continental margin after the Cambrian rifting event is unknown. It is usually assumed to coincide with the very pronounced gravity highs that underlie the Broken Bow and Benton Uplifts of the exposed Ouachita Mountains, and the Waco Uplift of North-Central

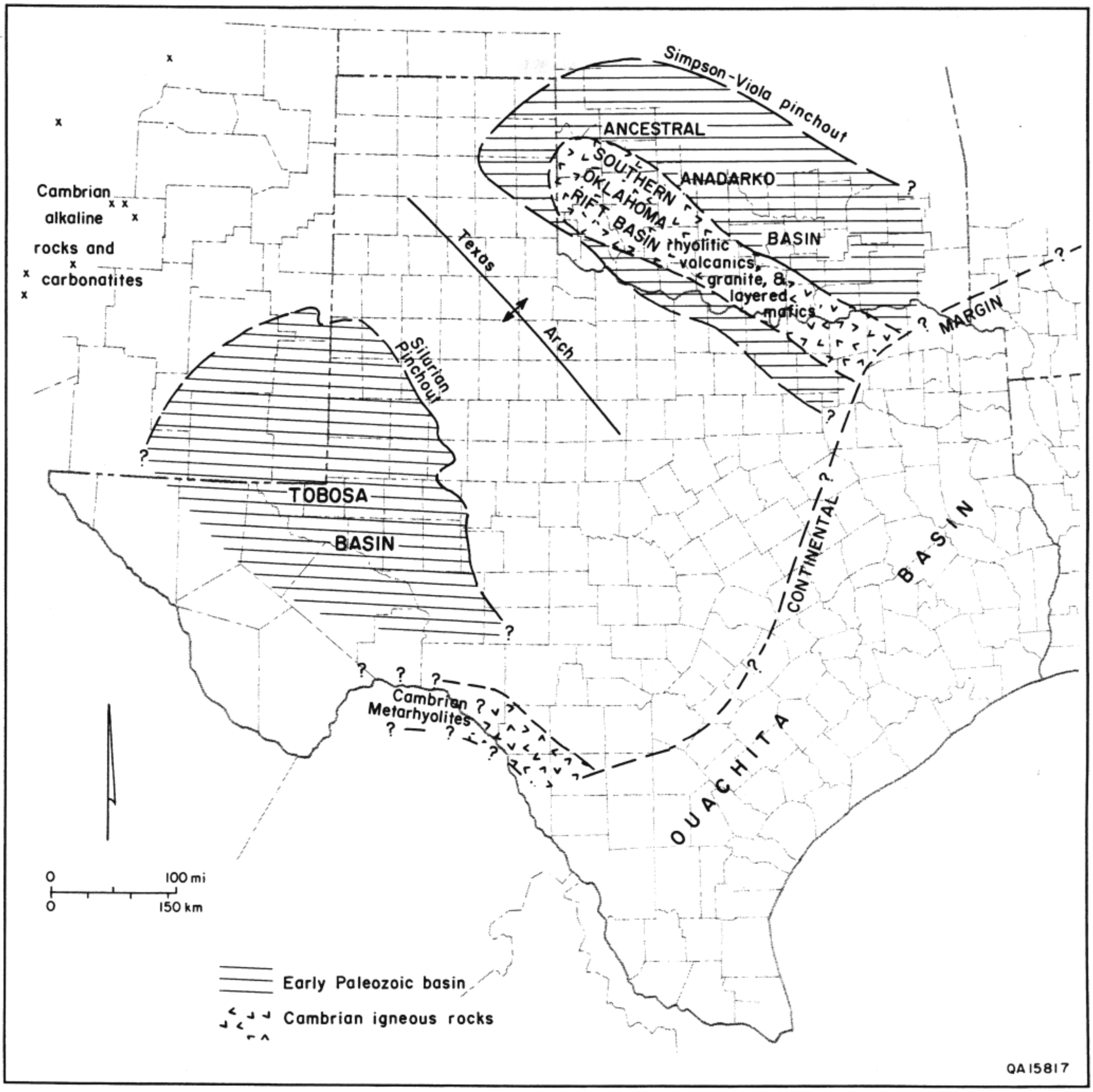


FIGURE 2. Map showing location of Cambrian zones of volcanism, which mark failed rift basins, the possible Cambrian continental margin, and early Paleozoic arches and Tobosa and ancestral Anadarko Basins in West Texas and Oklahoma.

Texas (Arbenz, 1989), but the only evidence for this assumption is inferred from Middle Cambrian facies tracts (Palmer and others, 1984). Seaward of this line, either highly thinned continental crust or oceanic crust existed; it formed the basin floor on which the distinctive "Ouachita facies" (cherts, siliceous shales, and sandstones) were deposited.

After Cambrian activity ceased, a broad Cambro-Ordovician carbonate platform (the Ellenburger Group in Texas; the Arbuckle Group in Oklahoma) was constructed over much of North America. This was followed by carbonate and clastic deposition until the Late Devonian, when the platform was covered by the Woodford Shale. Substantial tectonothermal subsidence centered on the Southern Oklahoma rift basin created the "ancestral Anadarko" depositional basin; all lower Paleozoic strata thicken in this area. A much less pronounced depositional basin, the Tobosa Basin, may have existed in West Texas at this time (Galley, 1958). Very broad arching of large areas generated northwest-trending highs along which

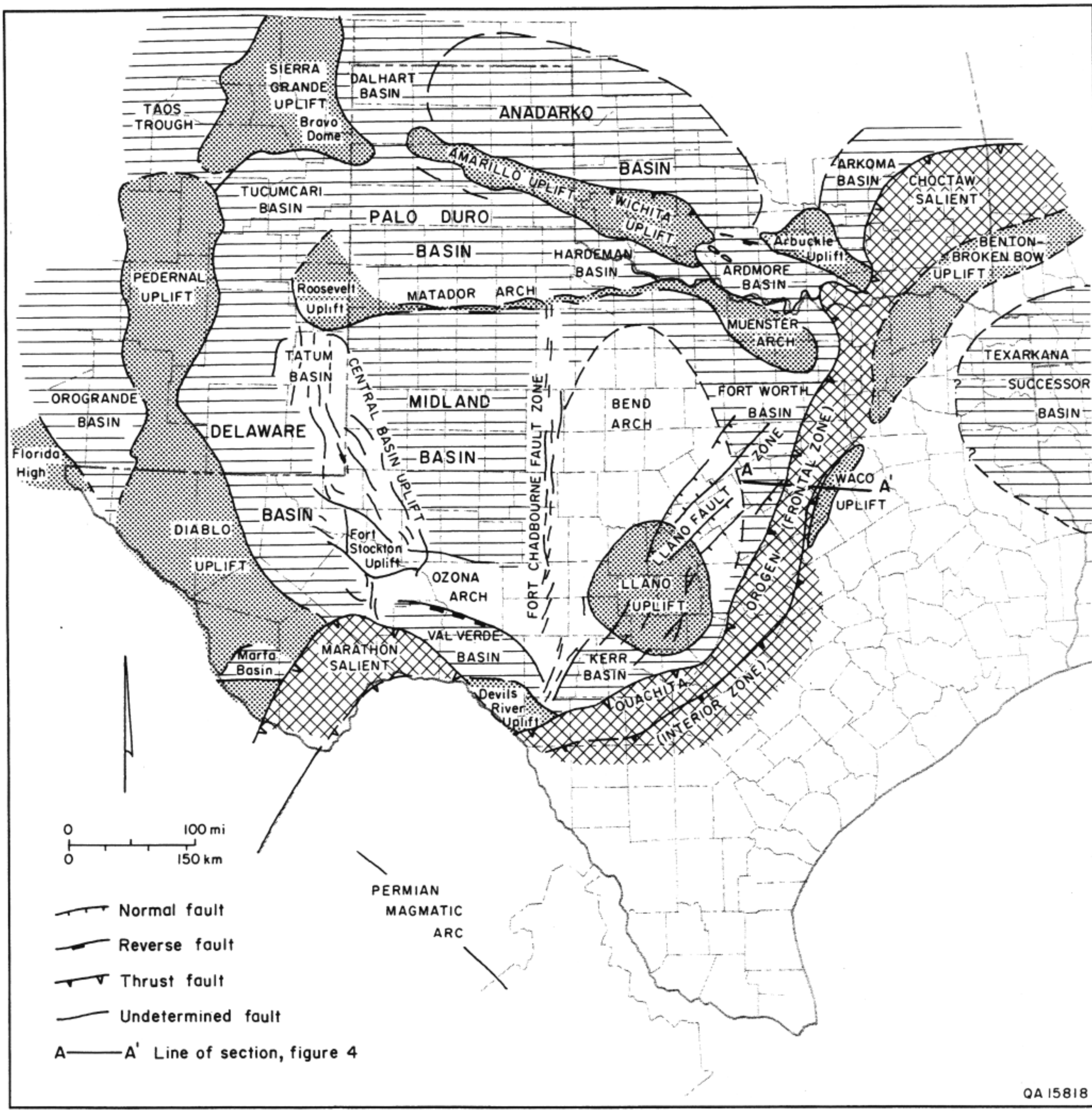


FIGURE 3. Map showing location of major late Paleozoic structural elements of the Ouachita orogen and the foreland deformed belts. The northwest-trending elements from the Ardmore Basin to the Sierra Grande Uplift constitute the Amarillo-Wichita axis; the north-trending elements from the Ozona Arch to the Roosevelt Uplift constitute the Central Basin axis.

some of the lower Paleozoic strata were eroded. An arch of middle Ordovician age in Gaines County north of Midland, over which the Ellenburger carbonates are eroded, is clearly expressed on the tectonic map. The large Texas Arch, probably of Devonian age, extends from Amarillo toward the Llano Uplift and is expressed by the deflection of the zero-thickness line of the Ellenburger in the Texas Panhandle.

In the Ouachita depositional basin lying southeast of the shelf edge, a Cambrian to Devonian "starved basin" sequence was deposited, including shale, sandstone, chert, and novaculite. This sequence has a maximum thickness of less than 4 km and is much thinner than the equivalent platform sequence in southern Oklahoma (Arbenz, 1989). For the most part, sedimentary features indicate deposition in deep water (Arbenz, 1989).

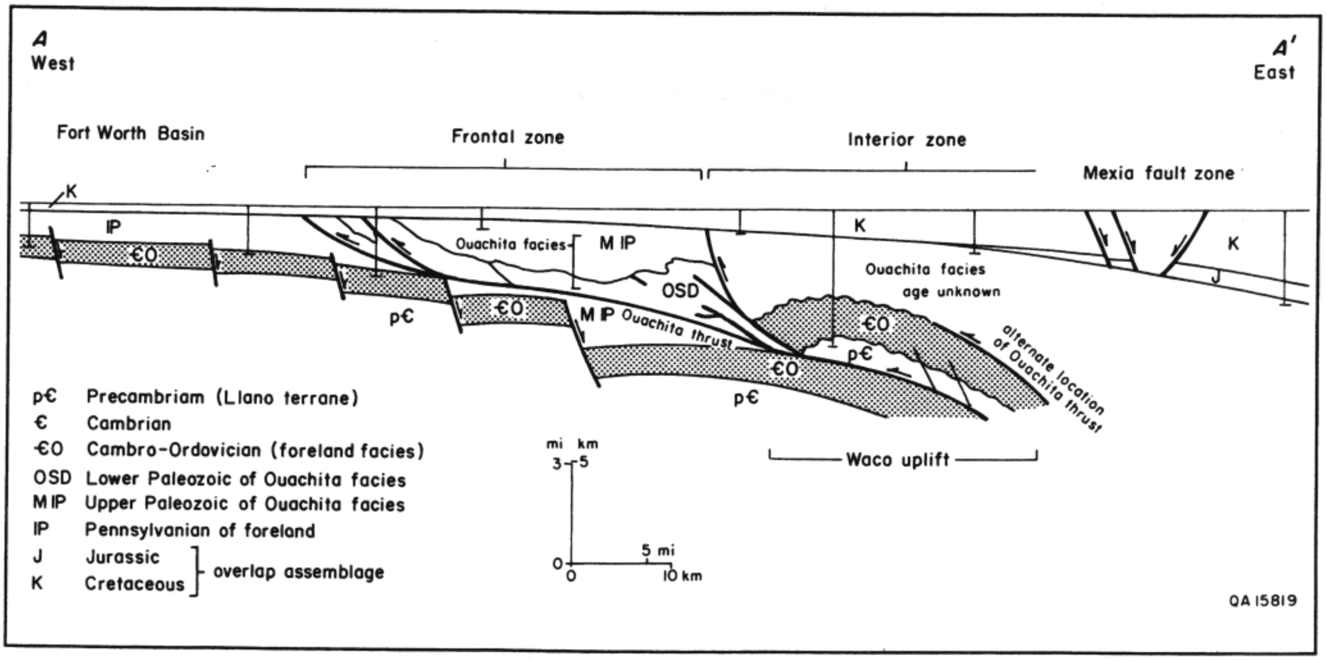


FIGURE 4. Section of the Ouachita orogen over the Waco Uplift, showing the Ouachita thrusts, foreland normal faults, and the interior basement-cored uplift. Modified from Nicholas and Waddell (1990). An alternate interpretation would pass the Ouachita sole thrust above the Precambrian and Cambro-Ordovician of the Waco Uplift. Line of section shown in figure 3.

Convergence Phase

Beginning in the Mississippian Period, the passive-margin history of rifting and subsidence was replaced by foredeep sedimentation and development of convergent and strike-slip structures: the thin-skinned Ouachita thrust belt and its associated structures, which cross Texas from northeast to southwest, and numerous intracratonic structures northwest of the thrust belt (fig. 3). Events in the two areas were synchronous, and some structures are part of both regimes.

Ouachita Orogenic Belt

In the Ouachita depositional basin, a thick (as much as 6 km in Oklahoma, 4 km in the Marathon Uplift in Trans-Pecos Texas) and extensive flysch facies of deep-water shales and sandstones was deposited from Early Mississippian through Early Pennsylvanian time, forming the Stanley, Jackfork, and Lynn Valley (Atoka) units in Oklahoma and the Tesnus, Dimple, and Haymond units in the Marathon area (Flawn and others, 1961; Nicholas and Waddell, 1990). Much of the sandstone was deposited by westward-flowing turbidity currents that may have originated in the area of the southern Appalachian Mountains, where continental convergence was creating large sediment sources (Graham and others, 1975). In zones within the Morrowan Series (earliest Pennsylvanian; Haymond and Johns Valley Formations), boulders of granitic and carbonate rocks are found within a deep-water shale matrix, suggesting reactivated faulting and erosion along the Ouachita basin margin. A thin Mississippian rhyolite tuff exposed in the Broken Bow area of Oklahoma and a rhyolite encountered beneath Middle Pennsylvanian rocks in wells in Sabine County, Texas, indicate at least isolated volcanism in the Ouachita area, possibly on the southern or southeastern side of the Ouachita basin (Nicholas and Waddell, 1990).

Rocks of the Ouachita basin were deformed within a compressional fold-thrust belt and displaced great distances north and west of the continental margin before the Middle Pennsylvanian (fig. 3). In the exposures of the Ouachita Mountains and Marathon Uplift areas, major thrust faults form the northwest limit of exposed Ouachita rocks and carry strongly folded lower Paleozoic basinal strata on the upper plate. In the subsurface, a location of the western extent of Ouachita thrusting (the Ouachita tectonic front) can be defined, and seismic data clearly show the thin-skinned compression within the Frontal zone (fig. 4).

In front of the Ouachita thrust belt north-northeast of the Llano Uplift, subsidence and enhanced sedimentation led to the accumulation of thick foredeep marine shales and turbidite sandstones of the Atoka Formation in the Fort Worth Basin (fig. 3). Similar Pennsylvanian foredeep deposits may occur in the Kerr and Val Verde Basins of southwest Texas, but they are difficult to distinguish from younger Wolfcampian (Lower Permian) deposits. Large-offset normal faults of Atokan age that offset basement are well documented in the Fort Worth Basin and extend (as the Llano Fault Zone) across the Llano Uplift. Similar faults are known from the Arkoma Basin north of the Ouachita Mountains. The Llano Uplift appears to have acted as a buttress to deformation throughout the Ouachitan convergence; deep basins lie to the south, northeast, and southeast.

Chert-bearing gravels were shed westward from the young Ouachita Mountains into North Texas during the Desmoinesian (Middle Pennsylvanian). This occurrence marked the emergence of lower Paleozoic chert-bearing strata in the Ouachita thrust belt. There is little evidence of cherty gravels in southwest Texas, however, suggesting that lower Paleozoic cherts were not exposed in this area.

In the subsurface for 480 km from Waco southward and southwestward beyond San Antonio, Flawn and others (1961) mapped an "Interior zone" that exhibits greater deformation, quartz veining, and low-grade metamorphism. Typical lithologies are schist, phyllite, metaquartzite, and marble; their age and affiliation are unknown. The Interior zone appears to be thrust over the Ouachita facies rocks of the Frontal zone.

South of the Ouachita Mountains, in the Texarkana and Sabine Uplift areas of easternmost Texas, subsurface data show that deformed Carboniferous flysch is overlain by a relatively undeformed Middle Pennsylvanian and younger carbonate-rich sequence, locally overlain by undeformed Permian marine clastics (Woods and Addington, 1973). As much as 2,200 m of these strata may be present (Nicholas and Waddell, 1990). These strata were deposited in a successor basin (a sedimentary basin that formed on top of a deformed belt soon after its deformation) in the Interior zone of the Ouachita orogen. This deposition began while the Frontal zone thrust faults were still active and large uplifts were shedding sediment westward. The overall geometry is reminiscent of the Carpathian Mountains, a still-active thrust belt (deforming a thick flysch sequence) that surrounds the actively extending and subsiding Pannonian Basin in eastern Europe (Burchfiel and Royden, 1982).

In the Marathon Uplift exposures in West Texas, the style of thrusting is complex because of the abundance of thick shale sequences that served as detachment levels. Several levels of folds and thrusts are mappable (Muehlberger and others, 1984; Muehlberger and Tauvers, 1990). Much of the deformation appears to have ended by the mid-Desmoinesian, when Gaptank Formation strata were deposited. The style of thrusting is much influenced by northwest-trending basement discontinuities in the autochthon (Tauvers, 1988).

Later thrusting of Ouachita rocks cratonward is of uncertain magnitude. Gaptank strata in the Marathon Uplift region are somewhat deformed and thrusted and are overlain by Permian rocks with numerous unconformities (Ross, 1986). Ewing (1985) has suggested that this late deformation marks the final emplacement of the frontal part of the Ouachita thrust belt, possibly by sliding into the subsiding Delaware Basin. In the Ouachita Mountains, rocks as young as Desmoinesian are folded by foreland folds related to the thrust faulting, but no younger rocks are present.

Basement Massifs

Beneath the Ouachita thrusts are major elongate massifs of uplifted Precambrian basement and overlying Lower Paleozoic (foreland facies) cover. The best documented is the Waco Uplift (fig. 3), 40 km east of the Ouachita front. About 140 km long and 16 km wide (Nicholas and Rozendal, 1975; Nicholas and Waddell, 1990), this feature was mapped from seismic data as a faulted anticline with a complexly reverse-faulted western margin showing more than 3 km of displacement (fig. 4). A test well penetrated nearly 3 km of Interior zone phyllite and quartzite of the Ouachita orogenic belt, then passed into 1,847 m of deformed carbonate rocks with a thin basal quartzite, below which 162 m of quartz diorite was drilled. All pre-Mesozoic rocks yield Permian to Devonian reset K-Ar ages unrelated to lithology or depth. Nicholas and Rozendal (1975) inferred that the carbonate is equivalent to the Cambro-Ordovician carbonate shelf and that the quartz diorite represents Precambrian basement.

Within the Ouachita Mountains, the Broken Bow and Benton Uplifts are mapped at the surface, exposing deformed and metamorphosed lower Paleozoic rocks within the Ouachita thrust belt. Deep seismic data show that a massif similar to the Waco Uplift lies beneath the surface anticlinoria (Lillie and others, 1983).

The Waco, Broken Bow, and Benton Uplifts lie along the prominent gravity highs that trend east-northeastward and southward from the prominent "triple junction" northeast of Dallas in Collin County (Tectonic Map, inset). Similar but smaller massifs are inferred to be present more or less continuously along the gravity highs east and south of the Llano Uplift. The timing of uplift of these basement massifs is not well constrained. Because they form anticlinoria within the overlying Ouachita thrust belt, it is suggested that they formed after the thrusting, at a late stage in the development of the orogen.

The Devils River Uplift in southwest Texas shares some of the features of the Waco Uplift. It is about 120 km long and 50 km wide, and a complex reverse fault with as much as 6 km of vertical relief separates it from the deep Val Verde Basin to the north. Drilling has encountered a lower Paleozoic foreland sequence overlying Cambrian(?) rhyolite and Precambrian metamorphic rocks. All rocks have been slightly metamorphosed (to lower greenschist grade on the crest and southern flank) and yield K-Ar dates that have been reset to the late Paleozoic. However, there is no overlying cover of Ouachita-facies thrust plates (Nicholas, 1983), and the Cambrian volcanics suggest an analogy to the foreland structures of southern Oklahoma. Nicholas and Waddell (1990) concluded that the Devils River Uplift is best considered a basement massif of the Ouachita belt. However, it may also be considered as one of the foreland basement-cored uplift complexes of West Texas. The higher metamorphic grade beneath the Mesozoic and the absence of Ouachita thrusts indicate a deeper structural level exposed on the subcrop; this may be due to postorogenic, pre-Cretaceous (pre-Mesozoic?) uplift and erosion, increasing to the south, that affected all of southwest Texas.

Foreland Deformation

In the broad area north and west of the Ouachita front, the late Paleozoic was a time of varied tectonic activity. Although there are subtle pre-Woodford (Devonian) structures in several places, the first significant deformation began in the latest Mississippian and continued through the Early Pennsylvanian (Morrowan and Atokan provincial stages), with major uplift, subsidence, and folding in southern Oklahoma; uplift of blocks in West Texas; and faulting in the Llano fault zone and along other fault zones (fig. 3). After a period of quiescence in many areas in the Middle Pennsylvanian (Desmoinesian provincial stage), uplift of blocks and subsidence of basins renewed in the Late Pennsylvanian and Early Permian (Missourian, Virgilian, and Wolfcampian provincial stages) along both the Southern Oklahoma and West Texas axes. Also, major subsidence of the West Texas Basin (or "Permian Basin," including the Delaware and Midland Basins and the Central Basin Uplift) began in the Middle Pennsylvanian and continued through the Permian as a roughly circular basin centered on the Central Basin Uplift (fig. 5). The Anadarko Basin formed part of the fringe of the West Texas Basin but underwent additional subsidence as a result of northward thrusting of the Wichita Uplift, leading to thick Upper Pennsylvanian deposits. Faulting and uplift ceased during the later Wolfcampian, but subsidence continued during the middle and Late Permian (Leonardian, Guadalupian, and Ochoan provincial stages), when more than 2 km of shallow-water carbonates and evaporites was deposited behind prograding carbonate shelf margins with as much as 500 m of relief. In front of these margins, basinal shales accumulated. The residual basin was filled in latest Permian (Ochoan) time by thick evaporites and some clastic strata.

The present-day margins of the West Texas Basin are to some extent an artifact of later tectonics. The southern margin formed by a regional uplift of post-Permian and pre-Cretaceous age, which eroded more than 3 km of Permian sediment from a belt along the Mexican border (Sanders and others, 1983). The western margin resulted from Laramide and Tertiary eastward tilting, which has eroded the Permian strata from large areas.

Amarillo-Wichita Axis

A broad band of late Paleozoic deformation trends southeastward from northeastern New Mexico to south-central Oklahoma. In the eastern part, it coincides with the belt of Cambrian igneous activity inferred to represent a failed rift basin. To the west it affects Middle Proterozoic igneous rocks, although inherited Cambrian weaknesses may have existed there as well.

In the Texas Panhandle, the large Amarillo Uplift is the dominant feature. It consists of a high central block, probably bounded by reverse faults where Precambrian granite lies beneath Lower Permian strata, that is flanked by narrow troughs and uplifts (Budnik, 1989). Coarse granitic detritus ("granite wash") was shed northward and southward throughout the Pennsylvanian, reaching a maximum in Desmoinesian time (Dutton and others, 1982). The block has at least three deep holes that contain several kilometers of coarse clastic rocks. The geometry of these basins and the irregular block boundary suggest that throughgoing strike-slip faults connect the basins with the block margin. On the northern flank are several elongate splaying ridges with as much as 2 km of relief. One of these, which forms the Mills Ranch gas field, has been interpreted as a thin-skinned, out-of-basin thrust and fold with a basal detachment at the base of the Arbuckle Group (Petersen, 1983).

To the east, the Amarillo Uplift passes unbroken into the Wichita Uplift, which underlies much of southwestern Oklahoma. The Wichita Uplift is bounded on the south by a complex reverse-faulted zone, and to the north by folds and moderate-angle thrust faults fringing the deep Anadarko Basin, with structural relief of more than 11 km. The northern flank of the uplift contains outcrops of tightly folded Cambrian volcanic rocks and Cambro-Ordovician carbonate rocks, which have been transported basinward on the Mountain View Fault (Brewer and others, 1983).

At the southeast end of the Wichita Uplift, the structure inverts to a deep and complexly deformed basin, the Ardmore Basin, with internal and external uplifts. This trough is filled by thick Mississippian and Pennsylvanian clastic units, which show some lithologic similarity to coeval Ouachita flysch. The trough was deformed in at least two phases: in the Early Pennsylvanian ("Wichita") and again in the Middle to Late Pennsylvanian ("Arbuckle"). Deep synclines are bounded by major northwest-trending faulted ridges such as the Criner Hills-Overton and Sherman structures, which may represent flower structures formed by strike-slip movement in a transpressional environment (Denison, 1982). The Arbuckle

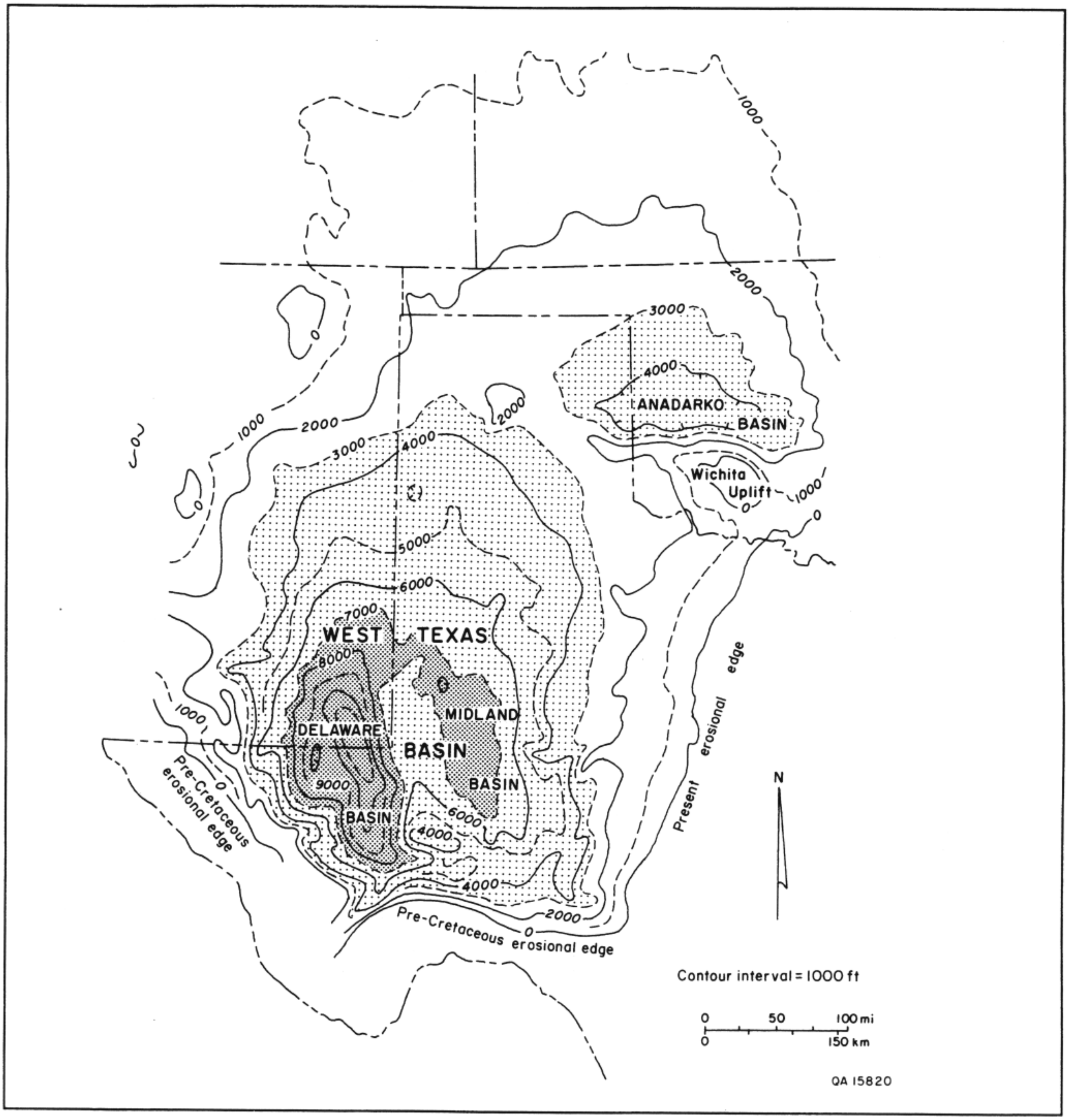


FIGURE 5. Isopach map of post-Wolfcampian Permian strata in the West Texas and Anadarko Basins. Isopachs outline the West Texas Basin, which began to subside during deformation in the Pennsylvanian. The southern and possibly the eastern margins reflect Triassic or Jurassic uplift and erosion; the western margin reflects Cretaceous and Tertiary uplift and erosion.

Uplift on the north flank of the basin is the northernmost boundary of Cambrian volcanic rocks; it appears to be thrusted against the Precambrian of the fringing Tishomingo-Belton Uplift in and near the Washita Valley Fault, although evidence of strike-slip motion is also present. The relative magnitude of compressional versus strike-slip displacement in forming the structures of the basin is a subject of current debate (Nielsen and Brown, 1984; Granath, 1989).

Fringing the Ardmore Basin are two broader positive features cored by Precambrian rocks. To the south are the unexposed Muenster and Waurika Arches, and to the north is the exposed Tishomingo-Belton Uplift. Uplift on the Müenster Arch occurred by Atokan time on a southwest-bounding, possibly reverse fault, but the area continued as a sediment source into the Late Pennsylvanian. The northern boundary of the Tishomingo-Belton Uplift is the strike-slip or oblique-slip Mill Creek Fault; to the north, the Hunton Arch dips off into the Arkoma Basin.

Extending due west from the Muenster Arch is a remarkably linear belt of deformation, called the Red River Uplift in North Texas and the Matador Arch in the Texas Panhandle. The belt passes westward into the Roosevelt Uplift of eastern New Mexico. Along the line are isolated fault-bounded uplifts elongate in the direction of the belt, which are separated by basins as deep as the areas to the north and south. There is some suggestion of a left-stepping, en echelon arrangement of high-angle reverse faults along the belt. Some of the structural activity may have been of Early Pennsylvanian age, but debris from the uplifts is found throughout the Pennsylvanian and Lower Permian strata. The linear belt is inferred to represent a reactivated Precambrian (or possibly Cambrian) strike-slip fault zone.

Between the Amarillo Uplift and the Matador Arch/Red River Uplift lie several shallow basins containing about 1,500 m of strata each: the Tucumcari Basin in eastern New Mexico, the Palo Duro Basin in the Texas Panhandle, and the Hardeman Basin in southwesternmost Oklahoma (fig. 3). These basins contain lower-relief structures of Early and Middle Pennsylvanian age, not all of which are shown on the Tectonic Map because of insufficient well control. By Early Permian time these basins had become part of the north flank of the subsiding West Texas Basin.

Central Basin Uplift

The Central Basin Uplift occupies a north-northwest-trending belt through the center of the West Texas Basin, separating the deep Delaware Basin on the west from the shallower Midland Basin on the east (figs. 3 and 5). The complex uplift, really a chain of uplifts, formed the pedestal on which the Permian carbonate shelf of the Central Basin Platform grew. Structures that form part of the Central Basin axis also lie beneath the Permian deep-water basins on either side of the platform.

On the basis of the mapping compiled for the tectonic map, the disturbed axis can be subdivided into six domains (fig. 6). At the north, the Tatum ridges are a series of north-trending faulted ridges of low to moderate relief extending south from the Roosevelt Uplift. To their south, structural trends (defined by the elongation of faulted ridges) swing toward the southeast, forming the Hobbs transverse zone. The average structural height is markedly higher than that of the Tatum ridges to the north. Structures in the east part of the trend (Hobbs, Fullerton, North Riley; feature names are shown on the Tectonic Map) are asymmetric to the northeast and probably have faulted northeastern margins. To the south, structural trends swing back nearly to the south in the Eunice-Andector ridges domain. This domain includes high-relief linear ridges (including Eunice, Dollarhide, Martin-Embar-Andector, and Bakke); these ridges have one reverse-faulted margin, usually on the east flank, and transverse normal faults (fig. 7). There is no direct evidence of a major north-trending strike-slip fault on the west flank of the axis in this domain or to the south, although many general maps indicate its presence (for example, Hills, 1970).

A domain of complex structures, the Monahans transverse zone, trends northwestward across the Central Basin axis from Upton County to Winkler County. Several faulted domal uplifts (Keystone, Penwell, Block 31) related to fault bends or intersections are separated by deep basins; there are also northwest-trending faulted anticlines and fault-bounded uplifts (Monahans, Apollo). The southern boundary is sharp and probably formed by a major throughgoing strike-slip fault that passes eastward into the east-trending Big Lake fault zone and possibly zones to the south. These fault zones form the northern boundary of the Ozona Arch and the Fort Stockton Uplift and almost certainly have left-lateral strike-slip components of displacement.

South of this discontinuity is the Fort Stockton Uplift, a triangular, relatively unfaulted basement block that stands high above the surrounding basins. The crest of the uplift was eroded to Precambrian rocks in or before Early Permian (Wolfcampian) time. Its northern and southern boundaries are probably major throughgoing strike-slip faults. To the east is the Ozona Arch, a broad area of shallow basement extending eastward toward the Llano Uplift. To the southwest, several wells have penetrated reverse or thrust faults with more than 2,200 m of displacement that placed Precambrian over Paleozoic strata (fig. 8). These thrusts may trend northwestward into the Coyanosa zone, which consists of deeply buried compressional structures of moderate relief (Coyanosa, Worsham-Bayes) that trend northwestward to westward and are for the most part southwest-verging. Large slide blocks of pre-Permian carbonate strata derived from the Fort Stockton Uplift may add to the geologic complexity of this domain (Guinan, 1971; Font and Sayre, 1984). The large thrusts appear to trend southward from the Fort Stockton Uplift into the Puckett fault zone, bounding the high-relief Puckett and Grey Ranch structures on the west before disappearing beneath thrusts of the Ouachita orogenic belt.

Timing of deformation on the Central Basin axis is not well constrained at many locations, because of both the complex facies relations of the Pennsylvanian strata and the lack of erosion into the Precambrian in most areas

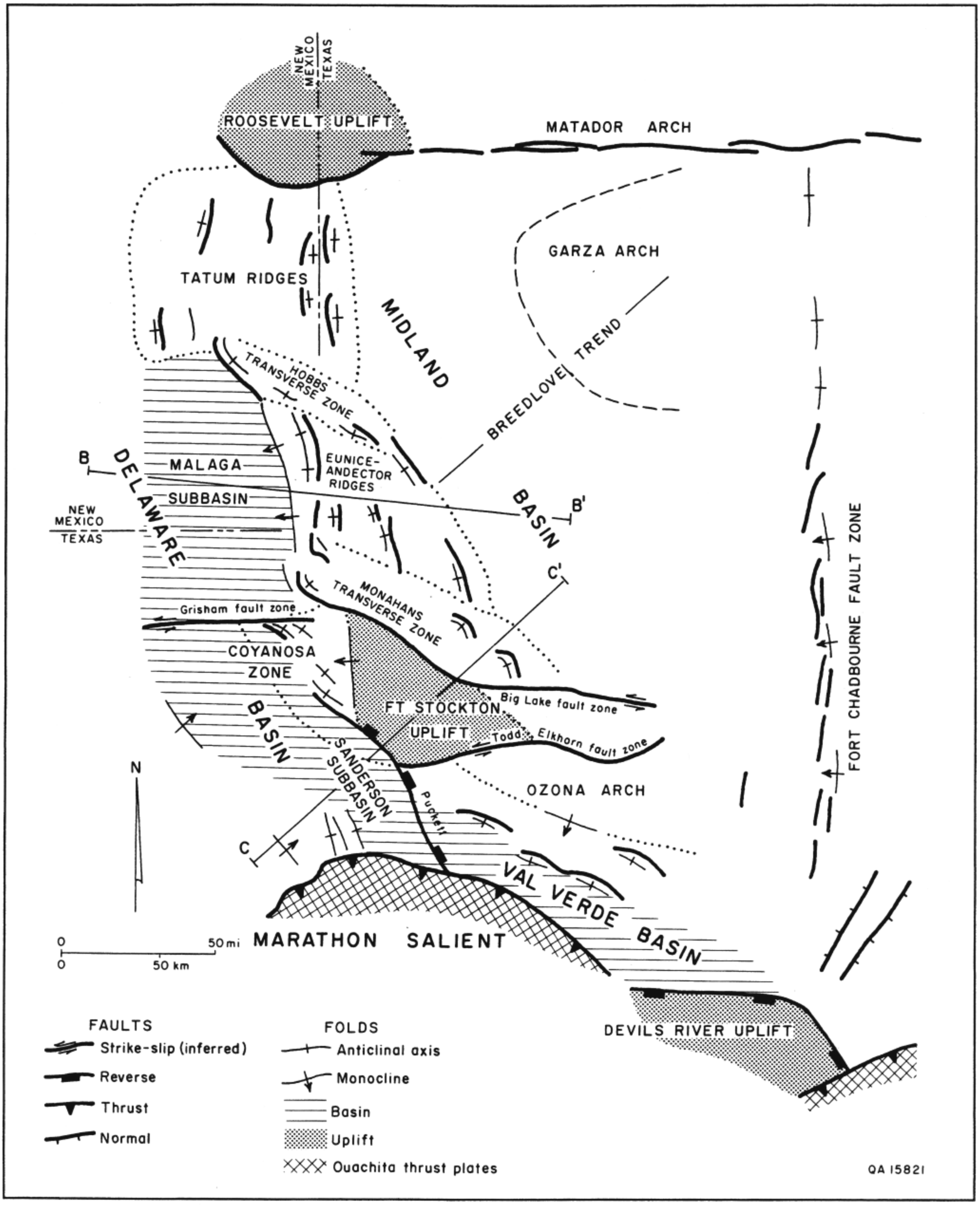


FIGURE 6. Major structural domains of the Central Basin Uplift. Sections B–B′ and C–C′ are shown in figures 7 and 8, respectively.

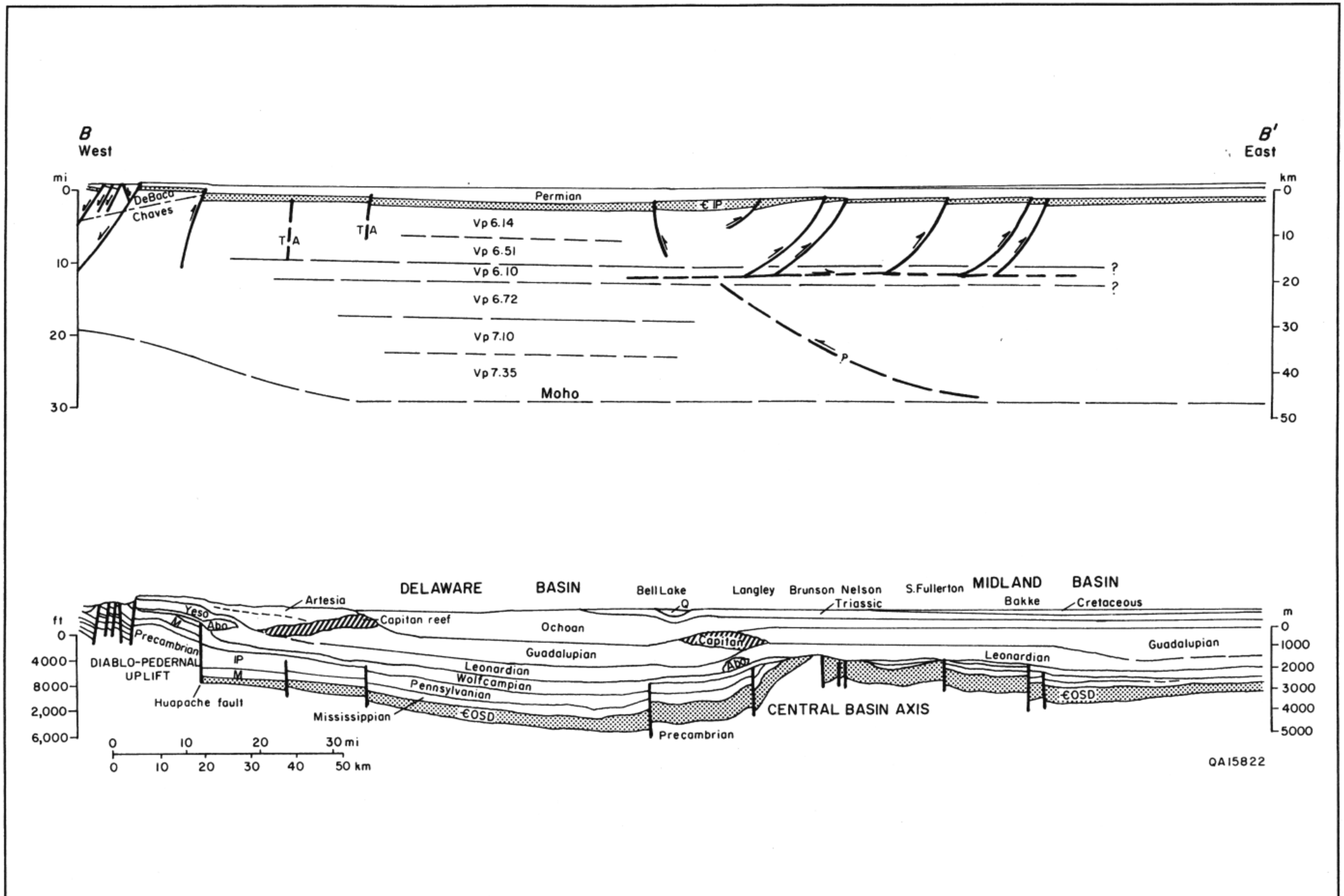


FIGURE 7. East-west cross section of the Central Basin Uplift (Andector Ridges domain); line of section shown in figure 6. The upper section is 1:1 and shows one view of the entire continental crust; the lower is 5:1 and shows the basin architecture as interpreted from wells and seismic sections. Labels above lower cross section identify individual structures or oil fields on the Central Basin Uplift. The compressional ridges may be generated by reverse faults that sole out in a mid-crustal low-velocity zone; the broad basin-uplift form may reflect a deeper reverse motion of the opposite vergence. T/A = strike slip, toward and away sides indicated.

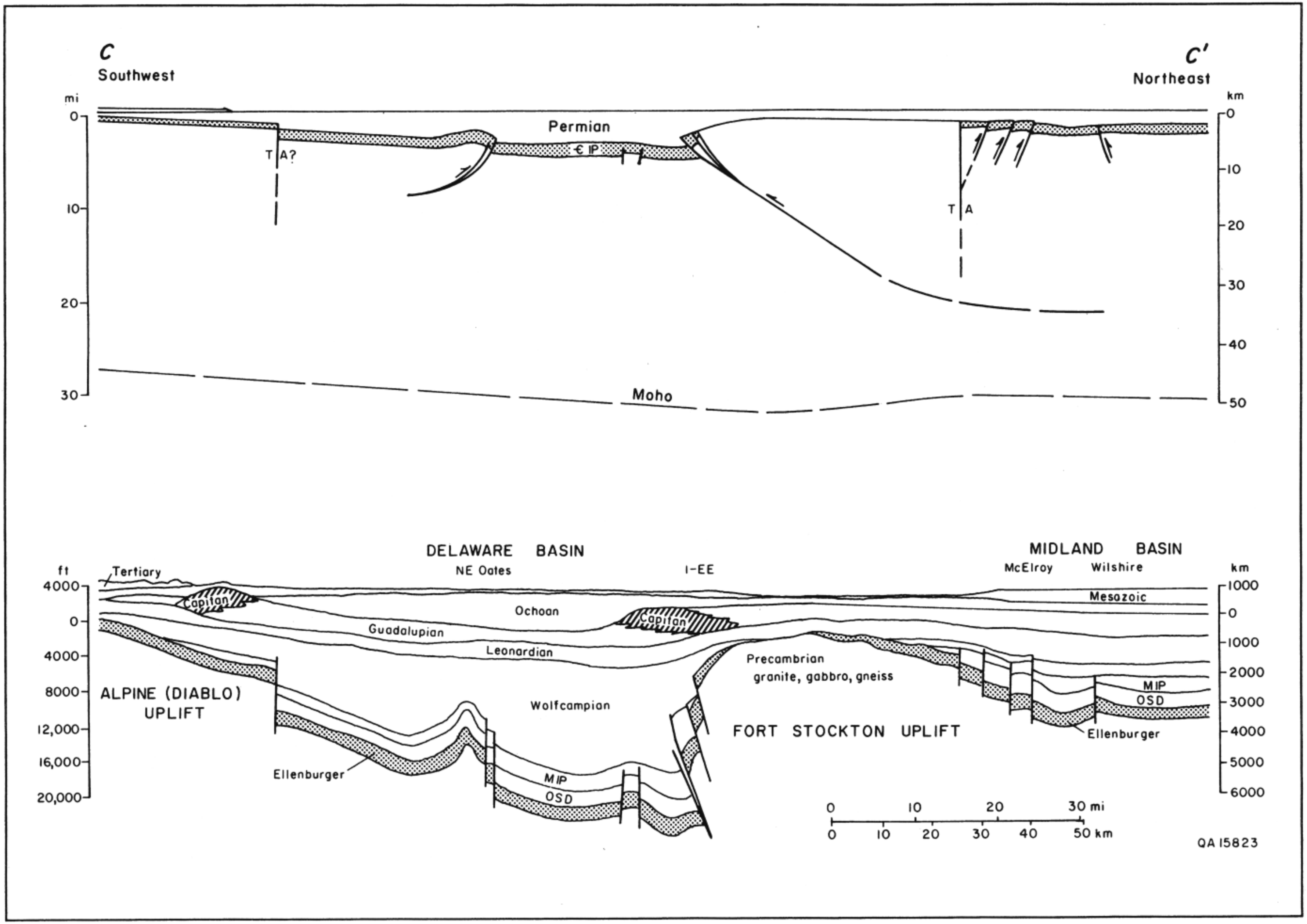


FIGURE 8. Southwest-northeast cross section of the Central Basin Uplift (Fort Stockton High domain); line of section is shown in figure 6; format as in figure 7. The broad Fort Stockton High may reflect involvement of much of the continental crust in a west-verging structure.

that caused a general absence of diagnostic "granite wash" clastic wedges. There appears to have been an early phase of deformation in the Early Pennsylvanian, followed by a later and much stronger phase of deformation of similar trend and style in the latest Pennsylvanian and Early Permian (Virgilian–Wolfcampian). All major deformation appears to have ceased by late Wolfcampian time.

The Delaware Basin to the west of the Central Basin axis is one of the deepest intracratonic basins in North America, having well over 7.5 km of strata in its deepest areas near the Fort Stockton Uplift. Much of the fill, especially in the south, is of Wolfcampian age, possibly derived from erosion of the Marathon-Ouachita thrust sheets. Presence of this unusually thick package of sediment suggests that the southern Delaware Basin may have subsided as a foredeep basin in response to the impinging Central Basin uplifts, the Marathon (Ouachita) thrust belt, and possibly the Diablo Uplift.

Within the deep Delaware Basin are several areas of high-relief deformation, notably the Elsinore ridge. An east-trending disturbed belt transects the basin in Reeves County, with local uplifts such as Grisham, San Martine, and Mi Vida. The disturbed belt is roughly collinear with the Apache Mountains fault and with the faults and flexures mapped in the surface west of the Salt Basin (see the Tectonic Map). The belt divides the Delaware Basin into two subbasins, a northern Malaga subbasin and a southern Sanderson subbasin.

Trans-Pecos Deformation

A complex of Paleozoic highs extends southeastward through Trans-Pecos Texas from the Precambrian outcrops in Hudspeth County to the vicinity of Alpine. The northern part, the Diablo Uplift proper (fig. 3), is best exposed in the Van Horn area, where Permian and Cretaceous rocks overstep older units to lie on the Precambrian. Two stages of uplift can be inferred there: latest Pennsylvanian and post-Permian. This uplift is probably more or less continuous northward with the Pedernal Uplift of New Mexico, as suggested in figure 3. To the southeast, the uplift is concealed by Cretaceous and Tertiary strata but may continue to and beneath the Marathon (Ouachita) thrust belt. The northeast flank of this complex of highs has been accentuated by uplift during the early Mesozoic and again during the Tertiary, which caused the post-Wolfcampian Permian cover to be stripped from large areas.

The Marfa Basin (fig. 3) is a sparsely drilled basin in Presidio County, lying between the Diablo complex uplift to the north and the Tascotal Uplift to the south. It appears to be asymmetric (Mauch, 1982) and more than 4 km in depth. The southern bounding fault, the Chalk Draw Fault, trends eastward and is unusually linear. The basin fill is of Pennsylvanian and Early Permian age and is exposed in the Chinati Mountains. Ewing (1985) noted the geometric similarity of this basin to the Val Verde Basin north of the Devils River Uplift.

Other Features

The Val Verde Basin (figs. 3 and 6) is a deep, highly asymmetric basin trending northwestward through Val Verde and Terrell Counties. Its northern boundary is a homocline off the Ozona Arch; its southern boundary is a high-relief reverse-faulted zone at the flank of the Devils River Uplift. The basin passes eastward into the Kerr Basin and westward into the southern Delaware Basin. Its age and history are poorly known, but most of the basin fill may be Middle to Upper Pennsylvanian (Nicholas, 1983). Vitrinite reflectance data suggest that as much as 3 km of later Permian strata have been removed from the Val Verde Basin and the Devils River Uplift in pre-Cretaceous time (Sanders and others, 1983).

The Bend Arch (fig. 3) is a very broad feature in North Texas, plunging northward from the Llano Uplift. It appears to be a composite feature, formed by Early Pennsylvanian subsidence of the Fort Worth Basin foredeep to the east, followed by westward tilting caused by the subsidence of the West Texas Basin in Permian time. Normal faults of the Llano fault zone trend northeastward across its eastern flank, giving rise to a series of "arches" or horst blocks.

The Fort Chadbourne fault zone (figs. 3 and 6) and related trends form a linear belt of complex low-amplitude deformation extending northward from the Val Verde Basin to the Abilene area, with a broad ridge continuing northward through King and Stonewall Counties to the Matador Arch. Fault-bounded uplifts and grabens with a left-stepping en echelon pattern (Conselman, 1954) are covered by Middle Pennsylvanian deposits. There is also a net down-to-the-west component to the fault zone evident on the tectonic map.

The Garza Arch (fig. 6) is a subtle high of Middle Pennsylvanian or earlier age, visible as a westward deflection of contours on the tectonic map. It served to localize the carbonate platform from which the Upper Pennsylvanian Horseshoe Atoll reef grew. Also in the area is a northeast-trending line of very low relief structures from Andrews County to King County, the Breedlove trend (fig. 6). This trend lies on the gravity and magnetic lineament that is inferred to represent the Grenville Front; the structures may represent a small amount of reactivation of the Precambrian feature.

Tectonic Summary

We are still far from a complete understanding of the history of stresses that produced the varied foreland deformation of West Texas. The foreland deformation is part of the much larger Ancestral Rocky Mountains belt of deformation that extends to Utah and Nebraska (Kluth and Coney, 1981).

In the Amarillo-Wichita axis, there is strong evidence of contractional structures throughout the Pennsylvanian and good evidence of strike-slip faulting. The amount and significance of left-lateral strike-slip is a subject of much debate; strike-slip movement has been estimated to have been minor (Denison, 1982; Nielsen and Brown, 1984) or major (Tanner, 1967; Budnik, 1986). The most recent analysis (Granath, 1989) has suggested that both contractional and strike-slip structures are present in an overall transpressive stress regime. The total amount of strike-slip displacement need not have been more than 20 to 30 km, although early (Wichita) displacement could have been much greater.

Opinions on tectonic development of the Central Basin Uplift have ranged widely. Many if not most workers have believed that strike-slip deformation was a major shaping force in the area, based on the apparent steep dips of many faults and the arrangement of basement highs (Hills, 1970, 1984). The preferred sense of this displacement is commonly considered to be dextral along a north-south axis, but Walper (1977) proposed two orthogonal strike-slip axes. Others have noted the similarity of some areas to the Laramide basement-cored uplifts of the Colorado-Wyoming area (Galley, 1970). Still others have proposed an extensional origin for structures, either by thermal doming (Elam, 1984) or possibly in a strike-slip regime (Dewey and Pitman, 1982). From the present mapping, it appears that an origin by dominantly east-west compression with southeast-oriented strike-slip faults would best explain the structural pattern. The main structural features of the axis, where published information is available, appear to have at least one reverse-fault boundary and show east- or west-vergence. The relief and the inferred contraction increase southward to the Fort Stockton Uplift. No major extensional features have been documented. The small scale of individual structures may be due to delamination along zones within the basement so that the entire crust is not involved; smaller thin-skinned features similar to Mills Ranch ridge in the Anadarko Basin are also possible.

The late Paleozoic contractional deformation occupies a long span of time (ca. 320–270 Ma; Decade of North American Geology time scale). This period is certainly long enough to produce a complicated kinematic history. A summary breakdown of the entire event into phases follows:

I. Early Pennsylvanian (320–304 Ma): Major deformation of the Ouachita orogenic belt; development of foredeeps and Llano fault zone extension; major transpression in the Wichita Uplift ("Wichita"); minor compression with strike-slip faulting in the Central Basin Uplift; minor strike-slip faulting along the Fort Chadbourne zone.

II. Middle Pennsylvanian (304–292 Ma): Major compression, uplift, and subsidence on the Amarillo-Wichita axis; major uplifts in New Mexico and Colorado; later thrust faulting in the Ouachita thrust belt; formation of a successor basin behind the thrust belt; quiescence(?) in the Central Basin axis.

III. Late Pennsylvanian (292–286 Ma): Major compression and strike-slip faulting on the Amarillo-Wichita axis ("Arbuckle"); uplift of basement massifs (Waco, Broken Bow, Benton; Devils River?); beginning of compression and strike-slip faulting in the Central Basin axis; beginning of strong subsidence of the West Texas Basin; continuing subsidence of the successor basin.

IV. Early Permian (286–270? Ma): End of deformation in the Amarillo-Wichita axis; final emplacement of Marathon thrust sheets; major compression and strike-slip faulting in the Central Basin axis; major subsidence of the West Texas Basin. Some subsidence in the successor basin.

This sequence of phases could be related to the closure of the Ouachita basin (possibly a marginal sea basin; Arbenz, 1989) during the Early Pennsylvanian. This was followed by intracontinental convergence during the Late Pennsylvanian (with plate collision south of the Ouachita basin) and concluded with an Early Permian (Wolfcampian) event, possibly due to stress transmitted through the closed Ouachita basin from a younger accretion event (Alleghanian?) to the east.

Gulfian Cycle (Mesozoic and Cenozoic)

Beginning in Triassic time, the southern and eastern margins of North America were subjected to extension and volcanism, leading to Jurassic rifting of the continental margin and formation of oceanic crust in the North Atlantic Ocean and Gulf of Mexico (fig. 9). In the Gulf of Mexico Basin a widespread layer of Callovian (Middle Jurassic) Louann Salt of variable thickness was deposited over moderately to highly attenuated continental crust. On top of the salt, a postrift passive margin sedimentary sequence was deposited. In Texas, this sequence began with early Late Jurassic (Oxfordian–Kimmeridgian) carbonate deposition, continued with thick Late Jurassic and Early Cretaceous (Kimmeridgian to Aptian) clastic sedimentation, and concluded with the creation of late Early Cretaceous (Aptian–Albian) carbonate platforms with a platform margin lying near the boundary between slightly to highly extended crust. Deposition of the postrift sequence mobilized salt into pillows and diapirs in areas of thicker salt such as East Texas. In Mexico, a complex system of mostly northwest-trending basement uplifts and depressions caused by rifting and/or strike-slip faulting was overlain by a thick carbonate-dominated sequence; evaporites filled the deeper depressions. During Late Cretaceous time, the uniform subsidence history of the Gulf of Mexico Basin was interrupted by a series of domal uplifts (including the Sabine Uplift of East Texas) and by the ascent and eruption of alkaline, ultramafic magmas (fig. 10).

Laramide compression and transpression occurred during latest Cretaceous and Paleogene time in the broad area southwest of a line from Corpus Christi to Carlsbad (fig. 10). In northeastern Mexico, folding and thrust faulting deformed the existing evaporite basins, giving rise to the Chihuahua and Sabinas foldbelts. In the Laramide foreland and over old basement highs, broader folds developed. A variety of compressive structures and strike-slip faults formed in West Texas in response to left-lateral transpression. In part these reactivated older Paleozoic features.

During the Tertiary, large river systems with headwaters in the rising Rocky Mountains drained southeastward to the Gulf of Mexico. Major deltas built seaward; they and their flanking barrier-bar or strandplain systems prograded the continental shelf margin for more than 200 km seaward into deep water. These unstable clastic shelf margins underwent large-magnitude syndepositional normal faulting ("growth faulting") and caused salt diapirism in areas of thicker salt (fig. 11). In Neogene time, loading of thick salt southeast of Galveston caused salt to flow laterally for long distances beneath the continental slope.

During Neogene time, all of the Western United States was uplifted, and significant extension by normal faulting created the Basin and Range structural province, which extends into Trans-Pecos Texas (fig. 11). In this area, previously formed Laramide structures were reactivated in a reverse sense, forming complex transtensional structures. Major grabens such as Salt Basin and the Hueco and Presidio Basins were filled with thousands of meters of coarse clastic sediment. Uplift of West Texas continued as far eastward as the Llano area; its eastern contact with the subsiding Gulf Coast Basin was marked by more than 500 m of displacement on normal faults of the Balcones Fault Zone.

Early Mesozoic Rifting

Structures created by the early rifting of the Gulf of Mexico are poorly known in Texas because they are deeply buried and sparsely drilled (fig. 9). Eagle Mills clastic strata are inferred to fill east-trending extensional grabens or half-grabens from northwestern Louisiana to northeast Texas (Woods and Addington, 1973). Rocks inferred to correlate with Eagle Mills have been found in east-central and South Texas (Todd and Mitchum, 1977), although these may in part be Paleozoic (late Ouachitan) in age.

The magnitude of extension that affected pre-Mesozoic continental crust in an area may be gauged by the later subsidence of the area. Sawyer and others (in press) have estimated the total tectonic subsidence from formation thicknesses at various points in the Gulf of Mexico Basin. Their map shows that most of the Gulf Basin west and north of the Lower Cretaceous shelf margins is underlain by slightly to moderately extended crust; extension was greater in the East Texas Basin. Most of the area south and east of the shelf margins is underlain by highly extended continental or "transitional" crust, which may contain abundant basaltic igneous material formed during rifting. These general relationships also can be seen in the distribution and thickness of the Louann Salt, which was deposited over the entire Gulf of Mexico Basin in the latest Middle Jurassic. Salt diapirs are confined to discrete provinces; insofar as vertical salt movement predominated, the location of these provinces may be taken to indicate areas of greater subsidence and thicker original salt. By this criterion, salt was probably thickest originally in the East Texas Basin, in South Texas south of San Antonio, in the Houston diapir province in southeast Texas, and offshore near the present shelf edge and slope. Thin areas are found on the southern edge of the Sabine Uplift (where salt is locally absent; Nicholas and Waddell, 1990) and on the San Marcos Arch. Some diapir-free areas may, however, have been caused by lateral flowage of the

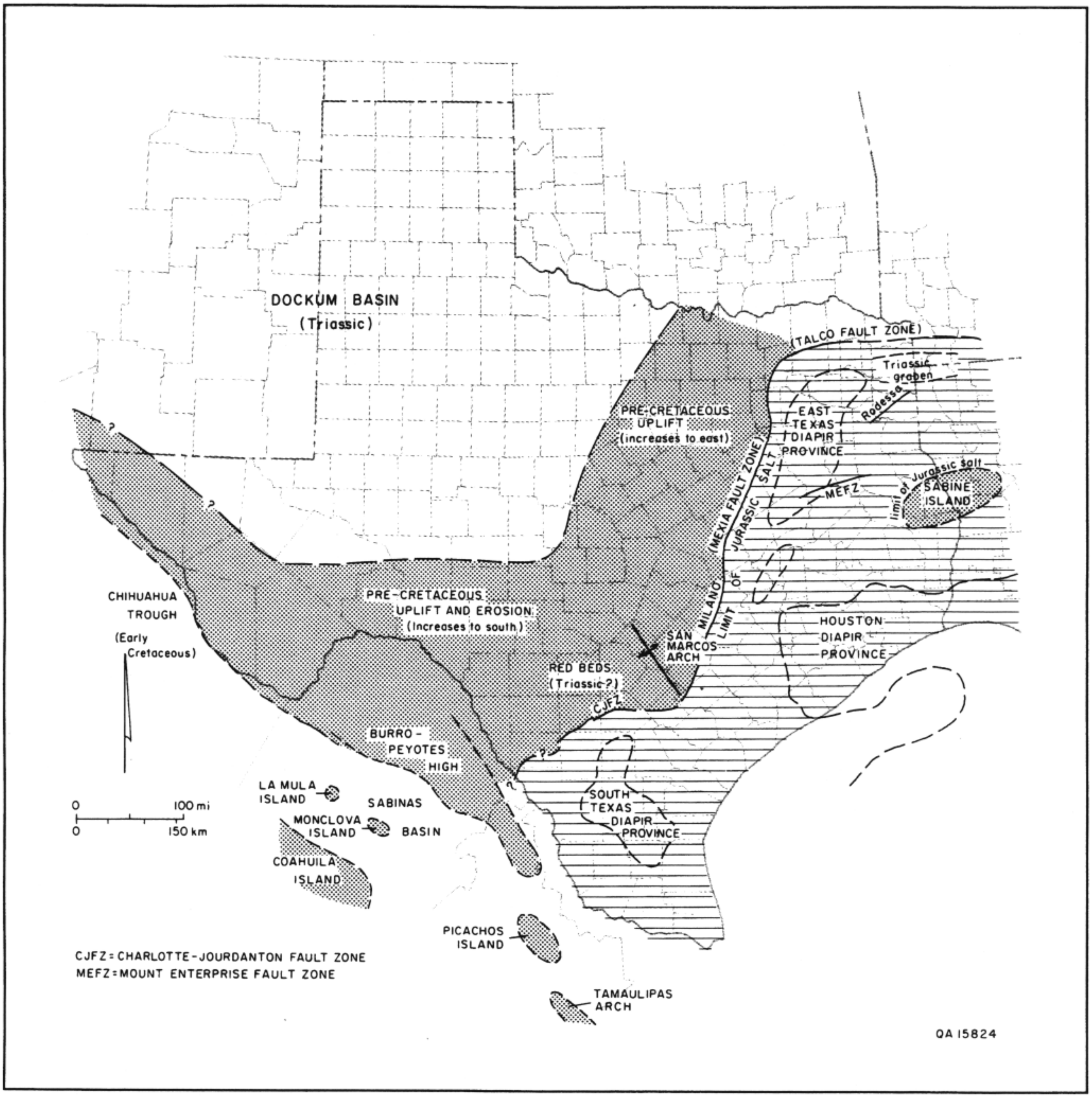


FIGURE 9. Map of early Mesozoic features of Texas; inferred Triassic rift basins, diapir provinces that may reflect originally thick salt deposition and higher extension, and arches, uplifts, and areas of erosion are shown. The features in Mexico are in part of Early Cretaceous age.

original salt layer rather than by thin salt; this has been inferred for the diapir-free area southeast of Galveston (Worrall and Snelson, 1989).

The deep Gulf of Mexico is floored by oceanic crust of Late Jurassic to earliest Cretaceous age overlain by 5 km of sediment. The boundary between oceanic and extended continental crust must lie beneath the present-day continental shelf or slope, but its location is obscure. Buffler and others (1981) and Sawyer and others (in press), from subsidence analyses and plate reconstructions, favor a boundary underneath the present slope, whereas Hall and others (1982) and Ibrahim and Uchupi (1982) favor a boundary along a gravity low and magnetic anomaly extending northeastward along the middle shelf. There may be thicker, less extended blocks of continental crust along the continent-ocean boundary, possibly with Mesozoic carbonate platforms (Ibrahim and Uchupi, 1982).

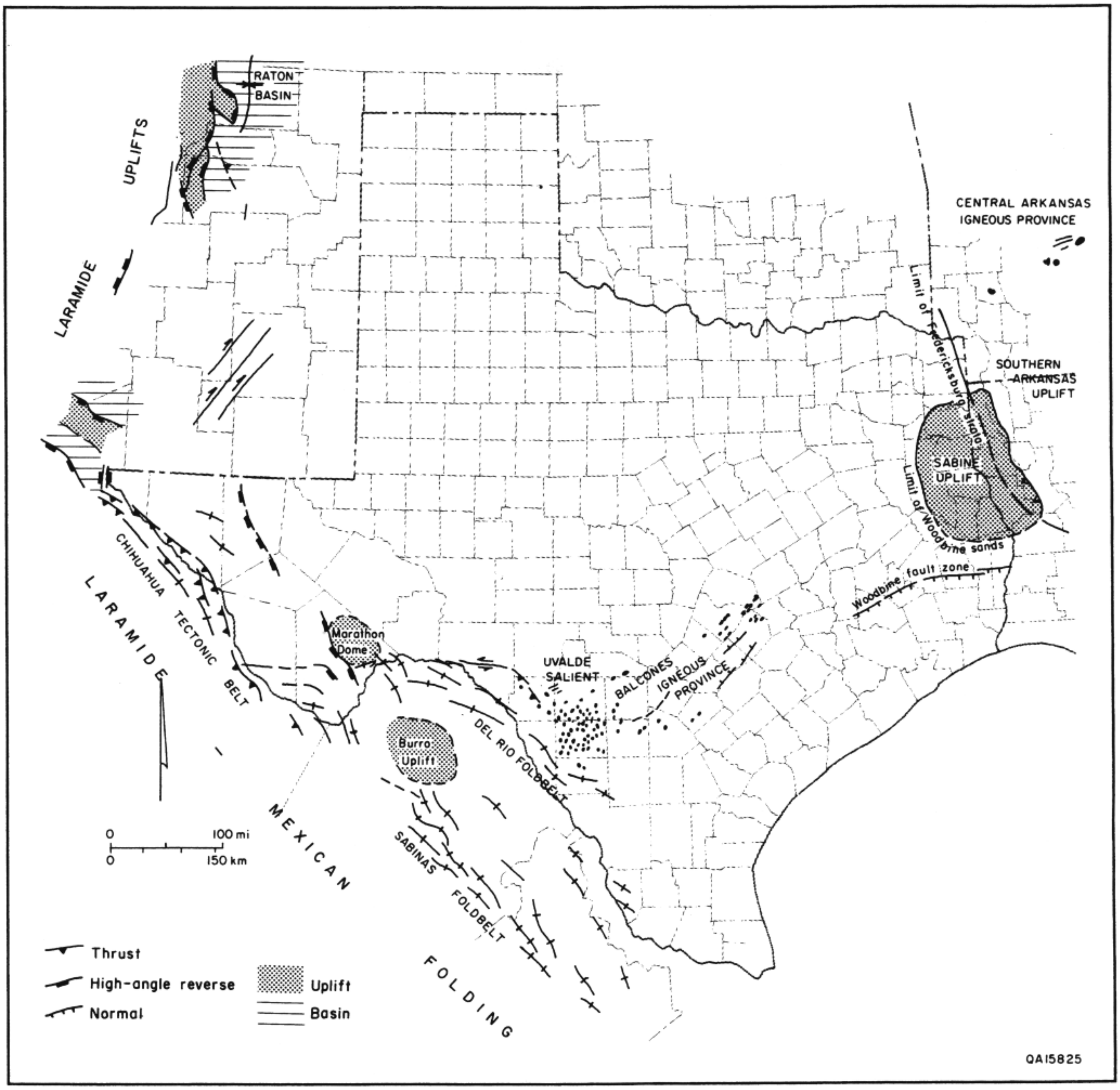


FIGURE 10. Map of mid-Cretaceous to Eocene tectonic elements of Texas: uplifts, volcanic centers, and faults of Late Cretaceous age in the Gulf Coast Basin; folds and faults of Laramide age (latest Cretaceous, Paleocene, and early Eocene) in West Texas and Mexico.

In northeastern Mexico, a complex series of northwest-trending highs and basins formed during Jurassic time. These may have been related to strike-slip faulting or extension associated with the Gulf of Mexico rifting, but the details are obscure. Continued activity on the block-bounding faults into the Cretaceous caused voluminous arkosic sediments to be shed into subsiding basins. This Cretaceous activity extended northwestward into southern Arizona and may be related to extension behind the Cordilleran volcanic arc (Bilodeau, 1982). Evaporites filled the deeper depressions in the Sabinas Basin and in the Chihuahua Trough; however, these may be younger than the Louann evaporites of the main Gulf of Mexico Basin.

Related to the Mexican complex is a broad area of pre-Albian uplift and erosion. In Texas, this band extends from the Llano Uplift to New Mexico and has removed Permian strata of the West Texas Basin. The unconformity is covered by basal clastics and Glen Rose and Edwards strata of Albian age. To the west, a similar uplift is documented in New Mexico and Arizona (Bilodeau, 1986), where it is called the Mogollon Highland. In this area, it is of Early Cretaceous (pre-Cenomanian) age.

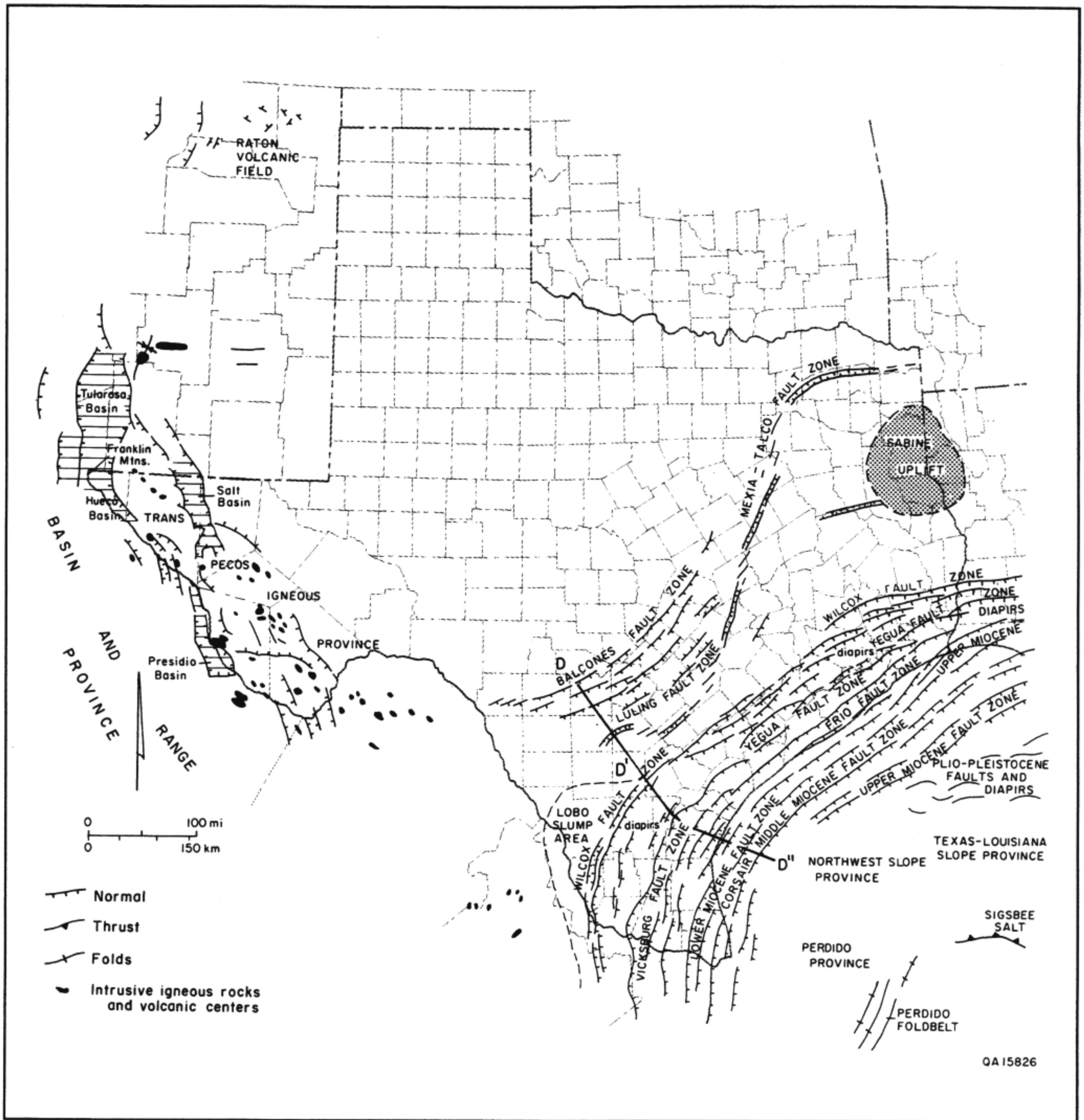


FIGURE 11. Map of Cenozoic tectonic elements of Texas: shelf-margin growth faults in the Gulf Coast; Basin and Range tectonic elements in West Texas; and Balcones faults.

Jurassic–Cretaceous Subsidence

On top of the Louann Salt, a postrift passive-margin sedimentary sequence was deposited. In Texas, this sequence began with lower Upper Jurassic (Oxfordian–Kimmeridgian) carbonates of the Louark Group (Smackover Limestone and related strata) followed by thick Upper Jurassic (Cotton Valley Group) and Lower Cretaceous (Hosston or Travis Peak Formation) clastics and concluding with two significant Lower Cretaceous carbonate platforms: the Sligo Formation (Cupido Limestone in Mexico) of Aptian age and the Edwards Group of Albian age. Modeling of subsidence and sedimentation rates is generally consistent with thermal contraction models of passive margin development (Nunn and others, 1984). The platform margins—the Sligo/Cupido and Stuart City reef trends—lie approximately along the edge of highly extended crust about 100 km inland from the present shoreline. In Mexico, the thick Upper Jurassic and Lower Cretaceous strata are mostly carbonates, except for local clastic wedges that shed off the growing uplifts of the Coahuila, La Mula, and Monclova "islands" and the Burro Uplift (McKee and others, 1990). Enhanced subsidence rates in Mexico and southwesternmost Texas relative to Central and East Texas are shown by the landward migration of successive carbonate shelf margins (Ewing, 1987).

This postrift deposition mobilized the Louann Salt into pillows and diapirs in areas of thicker salt such as East Texas and led to the development of the peripheral graben system—the Talco and Mexia fault zones of the East Texas Basin and their southern extension into the Milano, Karnes/Sample, and Charlotte-Jourdanton fault zones that rim the San Marcos Arch. These grabens formed at or near the pinch-out of salt and formed the headwall of basinward sliding of the entire postsalt sedimentary column. This sliding began in the Late Jurassic and probably continues to the present (Cloos, 1968; Jackson, 1982). Farther basinward, salt "rollers" and high-relief salt pillows developed soon after salt deposition; in the basin centers in East Texas and South Texas, salt diapirs grew out of some pillows during the Early Cretaceous, with associated rim synclines and salt-withdrawal basins (Seni and Jackson, 1982).

Sabine Uplift and Balcones Volcanism

The Sabine Uplift, as defined by present-day contours and by surface outcrop, is a broad pear-shaped arch lying astride the Texas-Louisiana border between the East Texas and North Louisiana diapir provinces. However, the uplift was not expressed in pre-Upper Cretaceous strata, although the entire area was probably slightly less extended than areas to the east and west.

The present form of the Sabine Uplift was created in Mid- to Late Cretaceous time (Granata, 1963) as part of a Gulf-wide series of disturbances and uplifts (fig. 10). The area formed part of the southwest flank of the immense pre-Woodbine uplift centered in northern Louisiana and southern Arkansas, from which up to 2,500 m of Lower Cretaceous strata was eroded at about 100 Ma. This large "Southern Arkansas Uplift" is associated with coeval alkaline igneous rocks in central and southwestern Arkansas. After being covered by Woodbine/Tuscaloosa deltaic strata, several hundred meters of Woodbine and earlier strata were eroded from the present Sabine Uplift at about 90 Ma before deposition of the Austin Chalk; clastics from this uplift were shed southwestward into the Harris delta of Eagle Ford age. A later phase of post-early Eocene uplift created the present outcrop pattern. The southern flank of the uplift was lost to subsidence along the Toledo Bend flexure, probably due to Tertiary continental margin progradation and attendant loading.

Jackson and Laubach (1988) and Laubach and Jackson (1990) argued that the rise of the Sabine Uplift was a distal response to Laramide compressional tectonics; however, given the evidence of the much larger epeirogenic uplift only a few million years earlier in northern Louisiana, an explanation of low-relief epeirogenic doming, possibly caused by relaxation of stresses in the deep lithosphere (Nunn, 1990), seems more plausible.

Late Cretaceous igneous activity of an alkaline character is widespread along the margins of the Gulf of Mexico. In Texas, more than 200 volcanoes of ultramafic alkaline composition erupted, mostly during Santonian and Campanian time (reaching a maximum at about 84 Ma; Ewing and Caran, 1982). In part these volcanoes were aligned on fault trends of the Luling and Balcones systems; there is subsurface evidence of Luling extensional faulting of this age. In southwest Texas, phonolites and basalts of the same period are associated with a poorly known high in the Uvalde area, over which strata of Campanian age (Taylor Group) are missing and near which shoal-water carbonate complexes of the Anacacho Formation were deposited. Similar associations of 80-Ma-old volcanic rocks, uplifts, and carbonate shoals are known from the Monroe and Jackson areas of Louisiana and Mississippi.

Laramide Orogenic Episode

Laramide compression and transpression occurred during latest Cretaceous(?) and Paleogene time in the southwestern and western border regions of Texas (fig. 10), in response to changed conditions of subduction of Pacific plates beneath North America (see Laubach and Jackson, 1990). In northeastern Mexico, large foldbelts with related thrust faults developed atop Upper Jurassic evaporite basins in the Chihuahua Trough (Gries and Haenggi, 1971) and the Sabinas Basin, partly inverting them. In the Laramide foreland and over old basement highs in southwest Texas and Coahuila, broader folds developed (Roebeck and others, 1956; Smith, 1970; Ewing, 1987).

In the Big Bend area, the major episode of Laramide folding occurred in the late Paleocene (Wilson, 1971), but there may have been earlier regional uplift. Henry and Price (1985) proposed two episodes of Laramide compression; an earlier one oriented northeast and a later east-northeast phase. High-angle reverse faults, strike-slip faults, monoclines, and broad anticlines and synclines occur throughout Trans-Pecos Texas (fig. 10). Especially notable are the basement-involved high-angle reverse faults in the Franklin Mountains near El Paso (Lovejoy and Seager, 1978) and the Santiago Mountains (Muehlberger, 1980), which suggest the presence of basement-cored uplifts characteristic of the Laramide episode in New Mexico and Colorado. The pattern of faulting is consistent with left-lateral transpression within a broad zone, the redefined "Texas Lineament" (Muehlberger, 1980). Some of the faults reactivated earlier Paleozoic features, notably the Carta Valley fault zone in Terrell and Val Verde Counties, which overlies the north-bounding fault of the Devils River Uplift (Webster, 1982; Calhoun and Webster, 1983).

Tertiary Shelf-Margin Progradation and Salt Tectonism

During the Tertiary, large river systems with headwaters in the rising Rocky Mountains drained southeastward toward the Gulf of Mexico. Major deltas built seaward across the Lower Cretaceous shelf margin; they and their flanking barrier-bar or strandplain systems prograded the continental margin for more than 200 km seaward into deep water (200–4,000 m water depth). Rapid deposition of deltaic sands over slope and basinal muds resulted in overpressuring of the deep, mud-rich units and a mechanically unstable section, leading to syndepositional normal faulting (referred to as "growth faulting" in the Gulf Coast Basin). This process formed linear zones of faults of various ages from northeastern Mexico into Louisiana (figs. 11 and 12). Each zone takes its name from the major shelf-margin progradational stratigraphic unit, during the deposition of which most faulting in the zone took place. In the Houston and South Texas areas of salt tectonism, growth fault structures were originally present but have been extensively modified by dome growth (Ewing, 1983). In Louisiana and in Pleistocene depocenter offshore Texas, in contrast, growth fault systems were entirely disrupted by salt flowage into complexes of faults, depocenters, and salt uplifts (Worrall and Snelson, 1989; Ewing, in press).

Growth faults occur in a spectrum of structural styles, as measured by relative amounts of vertical and lateral movement. In general they may be classified as

- glide systems, which involve a basal décollement into which upper-plate strata have been rotated and in which lateral translation of hangingwall rocks is greater than vertical motion; and
- deep listric fault systems ("differential compaction faults" of Bruce, 1973), in which faults flatten into a deep, diffuse detachment level in ductile shale and in which vertical subsidence of hangingwall rocks is greater than horizontal displacement.

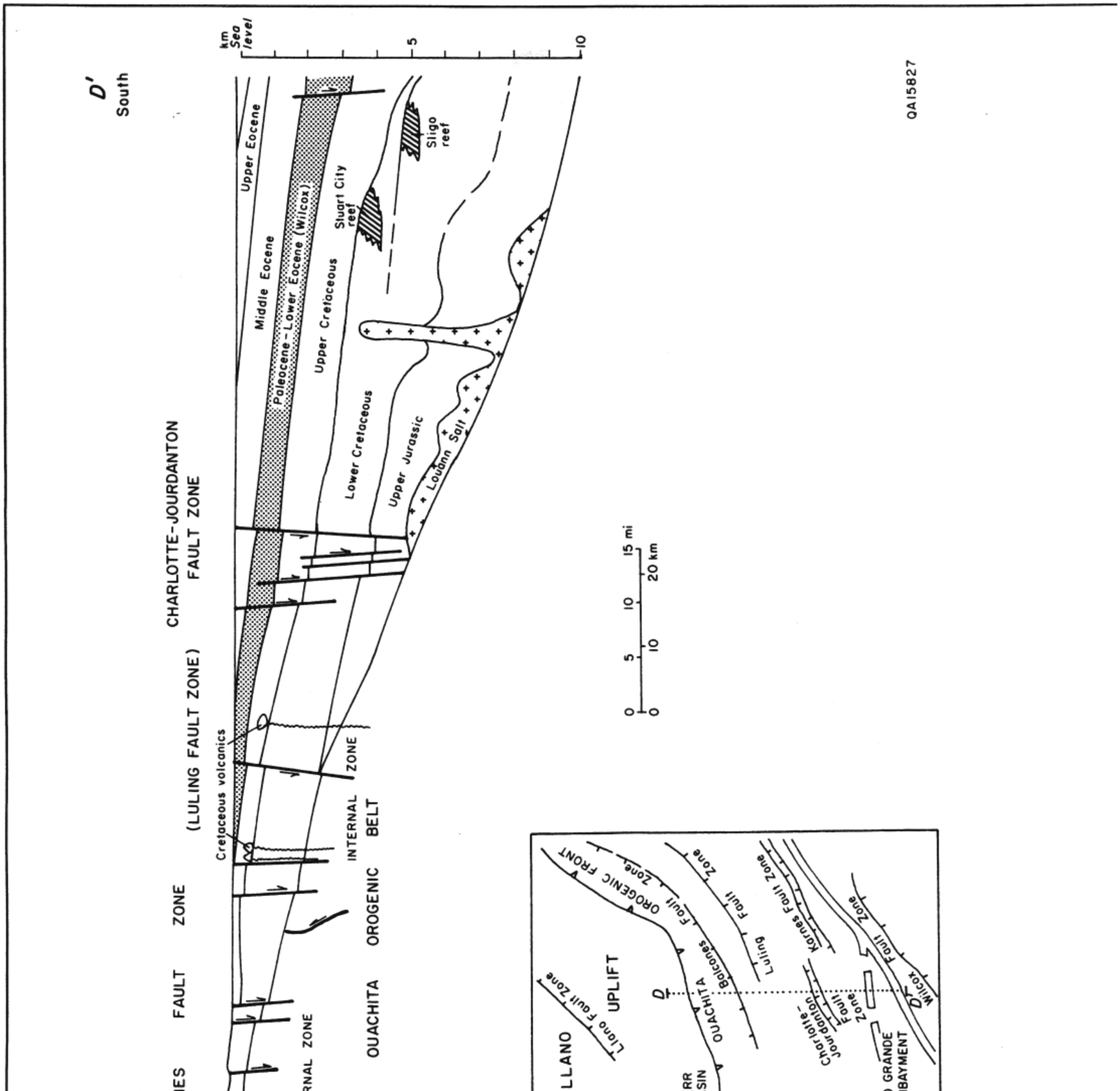
Glide systems include intraformational slumps, "domino-style" detachments displacing great thicknesses of sediments laid down before faulting began, and "escalator-style" detachments displacing highly expanded sediments, which form large pods in the upper plate (Ewing, 1988). Late motion on both glide and deep listric systems is typical; this phase of faulting with reverse drag is responsible for the large "rollover anticlines" that form major shallow oil and gas fields. Many of these late faults continue to the surface.

In Texas, the first major shelf-margin progradation occurred in the Paleocene and early Eocene when large deltas of the Wilcox Group built out in Central and southeast Texas (lower Wilcox) and southeast and South Texas (upper Wilcox). The Wilcox fault zone, developed where these deltas prograded basinward of the Lower Cretaceous shelf margin, consists of several closely spaced, deep listric faults that expand the deltaic section up to five times. In some areas, glide-fault systems with visible detachment surfaces have been observed in the basinward parts of the zone. In South Texas, a greater thickness of mobile, overpressured Upper Cretaceous shale resulted in a complex structural style with shale ridges and large antithetic faults (Ewing, 1986). Behind the main fault trend in South Texas is the widespread Lobo intraformational slump that affects lowermost Wilcox and Midway strata.

Episodic progradation and faulting occurred in middle to late Eocene time, creating the Yegua fault zone (Ewing, 1989). This zone is best defined southwest of the Houston Embayment, where it consists of a domino-style glide-fault system downdip of a series of deep listric or transitional faults, some of which may be inherited from Wilcox structures. Yegua-age faulting is also widespread in the Houston Embayment and eastward into Louisiana, with both glide-fault and deep listric geometries.

Major deltaic progradation in South Texas and adjacent Mexico in early Oligocene time created the Vicksburg fault zone (Stanley, 1970), which consists of a complex escalator-style glide-fault system with secondary headwalls and complex subsidiary faults and shale anticlines (Ashford, 1972; Erxleben and Carnahan, 1983). This distinctive fault system can be traced northward to Refugio County, where it becomes more diffuse. Vicksburg-age faults occur in southeast Texas but may in part be reactivated Yegua faults.

Late Oligocene Frio deltaic and strandplain sedimentation prograded the shelf margin approximately to the present shoreline. The Frio fault zone is a broad deep listric system consisting of several major sinuous normal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OUACHITA OROGENIC BELT
Cretaceous volcanics
Upper Eocene
Middle Eocene
Paleocene-Lower Eocene (Wilcox)
Upper Cretaceous
Lower Cretaceous
Upper Jurassic
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Sligo reef
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Llano Fault Zone
KERR BASIN
OUACHITA OROGENIC FRONT
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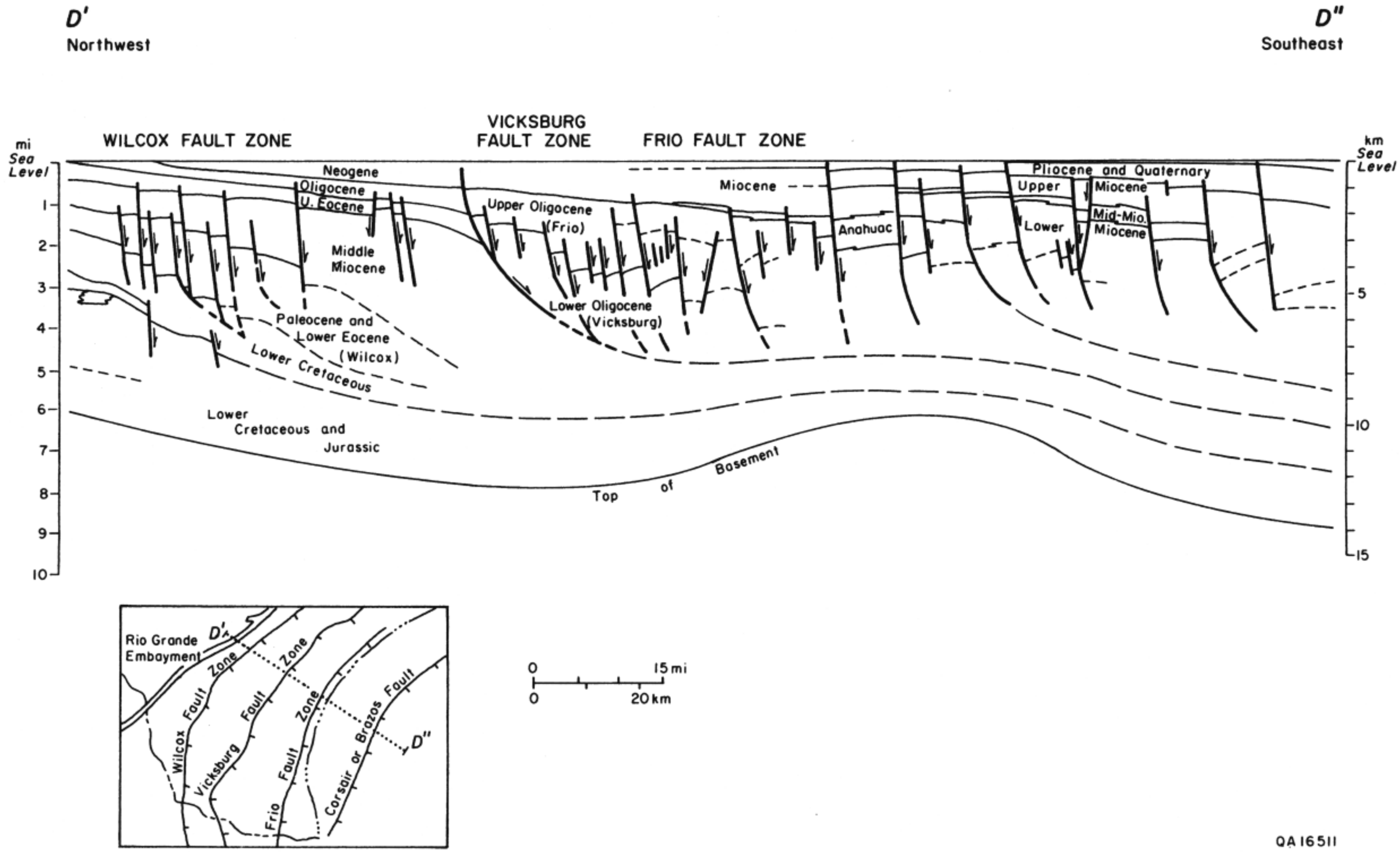

FIGURE 12. Cross section of the Texas Gulf Coast Basin, showing basin-margin faults, diapirs, and Cenozoic growth faults. From Ewing (in press).

faults spaced 5 to 10 km apart, with intervening equant rollover anticlines and some up-to-the-basin faults (Ewing, 1986). Shale diapirs are abundant in the central Texas Gulf Coast (Bishop, 1977). Strong progradation in South Texas created sequentially younger faults from west to east, but to the northeast the same faults were active throughout Frio deposition (Winker and others, 1983; Ewing, 1986).

Three pulses of Miocene progradation along the entire Texas coast created lower, middle and upper Miocene fault systems. The lower Miocene fault zone ("Lunker and Clemente-Tomas fault zones" of Worrall and Snelson, 1989) lies near and just seaward of the present shoreline but comes onshore in the Rio Grande delta; it is generally of a deep listric character. The middle Miocene or Corsair fault zone is an escalator-style glide fault system extending for 300 km in the middle shelf from about Corpus Christi to Galveston (Vogler and Robison, 1987). Closer to the present shelf edge is the upper Miocene fault system ("Wanda fault zone" of Worrall and Snelson, 1989), of deep listric character. Worrall and Snelson (1989) proposed that the extension on all of these systems is compensated for by deep lateral flow of salt.

In the eastern part of the Texas Outer Continental Shelf, Plio-Pleistocene sedimentation induced growth-fault and salt mobilization near the present shelf edge; the major depocenter is located to the east in Louisiana. Faults here are complex and intimately associated with salt diapirism and lateral flowage (Geitgey, 1988).

On the present continental slope, salt features predominate. Structures in the area south of the Plio-Pleistocene progradation are similar to those of offshore Louisiana. At the base of the lower slope is the Sigsbee salt tongue, which overrides Miocene and younger sediments of the continental rise (Humphris, 1978). The middle and lower slope contains very broad, steep-sided diapiric massifs separated by narrow, deep intraslope basins (including Gyre and Orca Basins). These massifs are inferred to have developed by disruption of horizontal salt tongues; base of salt is commonly visible on seismic sections, especially on the lower slope (Lee and others, 1989). The upper slope contains relatively small, cylindrical salt stocks and ridges with lateral flowage into salt tongues and sheets.

To the west, the salt style changes in the Northwest Slope province. Along the upper slope, salt stocks similar to those to the east are known; but most of the slope is underlain by a shallow reflector inferred to be salt, which is gently deformed, uplifted, and faulted with only a few diapirs (Martin, 1980). This may represent a salt-intrusion complex of tongues coalescing into canopies (Hardin, 1989). The area appears to be less disrupted by sediment loading than is the area to the east.

South of the Northwest Slope province is the Perdido diapir province, characterized by salt diapirs and narrow anticlines on the upper slope, large irregular massifs on the middle and lower slope, and northeast-trending, salt-cored compressional anticlines of the Perdido Foldbelt deforming abyssal-plain strata (Martin, 1984; Blickwede and Queffelec, 1988).

Basin and Range Deformation

In Trans-Pecos Texas, volcanism occurred from the Eocene to the Miocene, mostly between 38 and 28 Ma. Approximately 14 calderas and subcircular bounding faults, which produced ash-flow tuffs and associated volcanic rocks, have been identified. Price and Henry (1984) showed that until about 30 Ma ago, volcanism, including development of most of the calderas, occurred while the area was under east-northeast compression, possibly reflecting waning Laramide deformation. A transition to a tensional environment occurred at about 30 Ma, followed by normal faulting a few million years later (at least by 23 Ma; Henry and others, 1983).

Early extension in the area was oriented east-northeastward, similar to that of the rest of the Basin and Range province (Zoback and others, 1981; Henry and others, 1983). A change to northwest-oriented extension occurred later, probably at about 10 Ma. Basin and Range extension occurred in part along older (Laramide) structures, with a reversal of the sense of displacement and shear, leading to right-lateral displacements along northwest- and west-northwest-striking faults (Moustafa, 1988) and normal-fault collapse along older reverse faults, as at the Santiago Mountains (Cobb and Poth, 1980).

Basin and Range extension has formed a series of north- and northwest-trending basins and ranges (fig. 11). Large basins, such as the Hueco at El Paso, the Salt, and the Presidio, contain as much as several kilometers of graben-filling clastic rocks of Miocene and younger ages. Most faults are high angle, but low-angle normal faults possibly related to detachments have been identified in the Franklin Mountains near El Paso (Harbour, 1972). In the Franklin Mountains the uplifted strata dip 40 degrees west, much steeper than in most ranges in Texas; these high dips suggest a greater magnitude of extension and a buried low-angle décollement surface. Recent faults are observed along the margins of the larger grabens. The Valentine earthquake, the largest known earthquake in historical times in Texas, is related to right-lateral transtensional faulting in the Lobo Valley area (Dumas and others, 1980).

Regional uplift of the Western United States, centered on the Basin and Range province and the Colorado Plateau, occurred in Miocene and later time, leading to the present high elevations of the region. This uplift continued east to the area of the Llano Uplift and Kerr Basin, which was stripped of its post-lower Cretaceous cover in the Miocene (Weeks, 1945). At the boundary between the uplifting plateau and the subsiding Gulf Coast Basin is the Balcones Fault Zone, a series of mostly down-to-the-southeast normal faults with locally more than 500 m of cumulative displacement. A parallel set of down-to-the-northwest normal faults, the Luling fault zone, occurs 30 to 60 km southeast of the Balcones trend. Most of the faulting appears to be Miocene in age (Weeks, 1945), although Late Cretaceous movement on some of these trends is likely. These faults extend downward into Ouachita rocks. They may die out at greater depth and may be the result of extensional failure of the upper crust as it underwent flexuring; or they may pass downward into extensionally reactivated Ouachita or pre-Ouachita faults. No Recent tectonic activity on Balcones faults has been documented.

Acknowledgments

Special thanks are due to all of the members of the Tectonic Map Committee who contributed text, discussions, and mapping for the project, especially C. D. Henry, M. P. A. Jackson, R. L. Nicholas, and W. R. Muehlberger.

The sections on Laramide and Tertiary evolution of Trans-Pecos Texas were taken with some alteration from Henry and Price (1985). The section on Gulf Coast growth faults was modified slightly from Ewing (in press).

The manuscript benefited from review by several geologists, notably Sharon Mosher, W. R. Muehlberger, and Stephen E. Laubach. Special thanks go to Tucker F. Hentz, who suggested distilling the present manuscript from a more ambitious project and subjected it to a critical reading. The manuscript was edited by Amanda R. Masterson, reformatted by Melissa Snell, and typeset by Susan Lloyd. The figures were drafted by Richard L. Dillon. Publication design was by Margaret L. Evans.

We thank W. R. Muehlberger for inspiring the Tectonic Map Project and A. G. Goldstein for carrying the ball in the early days. We especially thank all of the concerned geologists in Texas, New Mexico, and Oklahoma to whom we showed the map and who made valuable suggestions, contributions, and comments.

References

INTRODUCTION

Ewing, T. E., Henry, C. D., Jackson, M. P. A., Woodruff, C. M., Jr., Goldstein, A. G., and Garrison, J. R., Jr., 1983, Tectonic map of Texas—a progress report: American Association of Petroleum Geologists Bulletin, v. 67, no. 3, p. 458.

Flawn, P. T., Goldstein, August, Jr., King, P. B., and Weaver, C. E., 1961, The Ouachita System: Austin, University of Texas Publication 6120, 401 p.

Gulf Coast Association of Geological Societies, 1972, Tectonic map of the Gulf Coast region, U.S.A., scale 1:1,000,000.

Henry, C. D., Gluck, J. K., and Bockoven, N. T., 1985, Tectonic map of the Basin and Range Province of Texas and adjacent Mexico: The University of Texas at Austin, Bureau of Economic Geology Miscellaneous Map 36, scale 1:500,000.

Henry, C. D., and Price, J. G., 1985, Summary of the tectonic development of Trans-Pecos Texas: The University of Texas at Austin, Bureau of Economic Geology, Text to accompany Miscellaneous Map 36, 8 p.

Hills, J. M., 1970, Late Paleozoic structural directions in southern Permian Basin, West Texas and southeastern New Mexico: American Association of Petroleum Geologists Bulletin, v. 68, p. 250–267.

Panhandle Geological Society, 1969, Pre-Pennsylvanian geology of the Western Anadarko Basin, 33 p.

Sellards, E. H., 1935, The geology of Texas, volume 2, Structural and economic geology: Austin, University of Texas Bulletin 3401, 884 p.

Sellards, E. H., and Hendricks, Leo, 1936, Structural map of Texas: Austin, University of Texas, Bureau of Economic Geology Miscellaneous Map 30, scale 1:500,000.

Wilson, J. T., 1966, Did the Atlantic close and then reopen?: Nature, v. 211, p. 676–681.

PRECAMBRIAN CYCLES

Barnes, V. E., 1988, The Precambrian of Central Texas, *in* Hayward, O. T. (ed.), Geological Society of America Centennial Field Guide—v. 4, South Central Section, p. 361–368.

Bickford, M. E., and Lewis, R. D., 1979, U-Pb geochronology of exposed basement rocks in Oklahoma: Geological Society of America Bulletin, v. 90, p. 540–544.

Bickford, M. E., Van Schmus, W. R., and Zietz, Isidore, 1986, Proterozoic history of the midcontinent region of North America: Geology, v. 14, p. 492–496.

Brewer, J. A., Brown, L. D., Steiner, D., Oliver, J. E., Kaufman, S., and Denison, R. E., 1981, A Proterozoic basin in the southern midcontinent of the United States revealed by COCORP deep seismic reflection profiling: Geology, v. 9, p. 569–575.

Bristol, D. A., and Mosher, Sharon, 1989, Grenville-age, polyphase deformation of mid-Proterozoic basement, northwest Van Horn Mountains, Trans-Pecos Texas: Journal of Geology, v. 97, p. 25–43.

Budnik, R. T., 1984, Seismic reflection evidence of a late Proterozoic basin in the Texas Panhandle (abs.): Geological Society of America Abstracts with Programs, v. 16, no. 2, p. 79.

Carlson, W. D., and Nelis, M. K., 1986, An occurrence of staurolite in the Llano Uplift, Texas: American Mineralogist, v. 71, p. 682–685.

Carter, K. E., 1989, Grenville orogenic affinities in the Red Mountain area, Llano Uplift, Texas: Canadian Journal of Earth Sciences, v. 26, p. 1124–1135.

Condie, K. C., 1986, Geochemistry and tectonic setting of Early Proterozoic supracrustal rocks in the southwestern United States: Journal of Geology, v. 94, p. 845–864.

Copeland, P., and Bowring, S. A., 1988, U-Pb zircon and Ar-40/Ar-39 ages from Proterozoic rocks, West Texas (abs.): Geological Society of America Abstracts with Programs, v. 20, p. 95–96.

Denison, R. E., and Hetherington, E. A., Jr., 1969, Basement rocks in far West Texas and south-central New Mexico: New Mexico Bureau of Mines and Mineral Resources Circular 104, p. 1–16.

Denison, R. E., Lidiak, E. G., Bickford, M. E., and Kisvarsanyi, E. B., 1984, Geology and geochronology of Precambrian rocks in the Central Interior region of the United States: U.S. Geological Survey Professional Paper 1241-C, p. C1–C20.

Erdlac, R. J., Jr., 1986, The Abilene Minimum—a Precambrian boundary with Paleozoic reactivation (abs.): Geological Society of America Abstracts with Programs, v. 18, no. 3, p. 219.

Fayon, A. K., and Nielsen, K. C., 1988, Large scale structures within the Grenville age basement of West Texas (abs.): Geological Society of America Abstracts with Programs, v. 20, p. 98.

Flawn, P. T., 1956, Basement rocks of Texas and southeast New Mexico: Austin, University of Texas Publication 5605, 261 p.

Garrison, J. R., Jr., 1981, Coal Creek serpentinite, Llano Uplift, Texas: a fragment of an incomplete Precambrian ophiolite: Geology, v. 9, p. 225–230.

———— 1985, Petrology, geochemistry, and origin of the Big Branch and Red Mountain Gneisses, southeastern Llano Uplift, Texas: American Mineralogist, v. 70, p. 1151–1163.

Garrison, J. R., Jr., Long, L. E., and Richman, D. L., 1979, Rb-Sr and K-Ar geochronologic and isotopic studies, Llano Uplift, central Texas: Contributions to Mineralogy and Petrology, v. 69, p. 361–374.

Garrison, J. R., Jr., and Mohr, D., 1983, Geology of the Precambrian rocks of the Llano Uplift, Central Texas, field trip notes: Geological Society of America, South-Central Section 1983 field trip: Texas A&M University, Field trip guidebook, 58 p.

Gillis, G. M., and Mosher, Sharon, 1988, Polyphase deformation of the middle Proterozoic Coal Creek Serpentinite, Llano Uplift, Texas (abs.): Geological Society of America Abstracts with Programs, v. 20, p. 99.

Grambling, J. A., Williams, M. L., and Mawer, C. K., 1988, Proterozoic tectonic assembly of New Mexico: Geology, v. 16, p. 724–727.

Hoffman, P. F., 1989, Precambrian geology and tectonic history of North America, *in* Bally, A. W., and Palmer, A. R. (eds.), The geology of North America—an overview: Geological Society of America, The Geology of North America, v. A, p. 447–512.

Karlstrom, K. E., and Bowring, S. A., 1988, Early Proterozoic assembly of tectonostratigraphic terranes in southwestern North America: Journal of Geology, v. 96, p. 561–576.

Keller, G. R., Hills, J. M., Baker, M. R., and Wallin, E. T., 1989, Geophysical and geochronological constraints on the extent and age of mafic intrusions in the basement of West Texas and eastern New Mexico: Geology, v. 17, p. 1049–1052.

King, P. B., and Flawn, P. T., 1953, Geology and mineral deposits of Precambrian rocks of the Van Horn area, Texas: Austin, University of Texas Publication 5301, 218 p.

Lidiak, E. G., 1990, Basement rocks along the southern midcontinent-Texas craton transect (abs.): Geological Society of America Abstracts with Programs, v. 22, no. 1, p. 13.

Mosher, Sharon, in press, Western extensions of Grenville age rocks: Texas, *in* Reed, J. C., Jr., and others (eds.), The Precambrian: Geological Society of America, The Geology of North America, v. S.

Mosher, Sharon, and Reese, J. F., 1990, The southern collisional margin of the Precambrian North American craton: the Texas Grenville orogenic belt (abs.): Geological Society of America Abstracts with Programs, v. 22, no. 1, p. 29.

Muehlberger, W. R., 1965, Late Paleozoic movement along the Texas Lineament: New York Academy of Sciences Transactions, series 11, v. 27, p. 385–392.

Muehlberger, W. R., Hedge, C. E., Denison, R. E., and Marvin, R. F., 1966, Geochronology of the Midcontinent region, United States, Part 3. Southern area: Journal of Geophysical Research, v. 71, p. 5409–5426.

Nelis, M. K., Mosher, Sharon, and Carlson, W. D., 1989, Grenville-age orogeny in the Llano Uplift of central Texas: deformation and metamorphism of the Rough Ridge Formation: Geological Society of America Bulletin, v. 101, p. 876–883.

Nelson, B. K., and DePaolo, D. J., 1985, Rapid production of continental crust 1.7–1.9 b.y. ago: Nd isotopic evidence from the basement of the North American midcontinent: Geological Society of America Bulletin, v. 96, p. 746–754.

Norman, D. I., Condie, K. C., Smith, R. W., and Thomann, W. F., 1987, Geochemistry and Sr and Nd isotope constraints on the origin of late Proterozoic volcanics and associated tin-bearing granites from the Franklin Mountains, West Texas: Canadian Journal of Earth Sciences, v. 24, p. 830–839.

Patchett, P. J., and Ruiz, J., 1989, Nd isotopes and the origin of Grenville-age rocks in Texas: implications for Proterozoic evolution of the United States Mid-continent region: Journal of Geology, v. 97, p. 685–695.

Thomas, J. J., Shuster, R. D., and Bickford, M. E., 1984, A terrane of 1,350- to 1,400-m.y.-old silicic volcanic and plutonic rocks in the buried Proterozoic of the mid-continent and in the Wet Mountains, Colorado: Geological Society of America Bulletin, v. 95, p. 1150–1157.

Walker, N. W., 1988, U-Pb zircon evidence for 1305-1231 Ma crust in the Llano Uplift, Central Texas (abs.): Geological Society of America Abstracts with Programs, v. 20, no. 7, p. A205.

Wilkerson, Amy, Carlson, W. D., and Smith, D., 1988, High-pressure metamorphism during the Llano Orogeny inferred from Proterozoic eclogite remnants: Geology, v. 16, p. 391–394.

OUACHITAN CYCLE

Arbenz, J. K., 1989, The Ouachita system, *in* Bally, A. W., and Palmer, A. R. (eds.), The geology of North America—an overview: Geological Society of America, The Geology of North America, v. A, p. 371–396.

Bowring, S. A., and Hoppe, W. J., 1982, U/Pb zircon ages from Mount Sheridan gabbro, Wichita Mountains, *in* Gilbert, M. C., and Donovan, R. N. (eds.), Geology of the eastern Wichita

Mountains, southwestern Oklahoma: Oklahoma Geological Survey Guidebook 21, p. 54–59.

Brewer, J. A., Good, R., Oliver, J. E., Brown, L. D., and Kaufman, S., 1983, COCORP profiling across the Southern Oklahoma Aulacogen: overthrusting of the Wichita Mountains and compression within the Anadarko Basin: Geology, v. 11, no. 2, p. 109–114.

Budnik, R. T., 1986, Left-lateral intraplate deformation along the Ancestral Rocky Mountains: implications for late Paleozoic plate motions: Tectonophysics, v. 132, p. 195–214.

__________ 1989, Tectonic structures of the Palo Duro Basin, Texas Panhandle: The University of Texas at Austin, Bureau of Economic Geology Report of Investigations No. 187, 43 p.

Burchfiel, B. C., and Royden, L., 1982, Carpathian foreland fold and thrust belt and its relation to Pannonian and other basins: American Association of Petroleum Geologists Bulletin, v. 66, p. 1179–1195.

Conselman, F. B., 1954, Preliminary report on the Cambrian trend of west-central Texas: Abilene Geological Society Geological Contributions, p. 10–24.

Denison, R. E., 1982, Geologic cross-section from the Arbuckle Mountains to the Muenster Arch, southern Oklahoma and Texas: Geological Society of America Map and Chart Series 28-R, 8 p.

Denison, R. E., Burke, W. H., Otto, J. B., and Hetherington, E. A., 1977, Age of igneous and metamorphic activity affecting the Ouachita foldbelt, *in* Symposium on the geology of the Ouachita Mountains, Vol. 1: Little Rock, Arkansas Geological Commission, p. 25–40.

Dewey, J. F., and Pitman, W. C., III, 1982, Late Palaeozoic basins of the southern U.S. continental interior (abs.), *in* The evolution of sedimentary basins: Philosophical Transactions, Royal Society of London, series A, v. 305, p. 145–148.

Dutton, S. P., Goldstein, A. G., and Ruppel, S. C., 1982, Petroleum potential of the Palo Duro Basin, Texas Panhandle: The University of Texas at Austin, Bureau of Economic Geology Report of Investigations No. 123, 87 p.

Elam, J. G., 1984, Structural systems in the Permian Basin: West Texas Geological Society Bulletin, v. 24, no. 1, p. 7–10.

Ewing, T. E., 1985, Westward extension of the Devils River Uplift—implications for the Paleozoic evolution of the southern margin of North America: Geology, v. 13, p. 433–436.

Flawn, P. T., Goldstein, August, Jr., King, P. B., and Weaver, C. E., 1961, The Ouachita system: Austin, University of Texas Publication 6120, 401 p.

Font, R. G., and Sayre, L. M., 1984, Mechanical implications of the slide block theory, eastern Delaware Basin, Texas: West Texas Geological Society Bulletin, v. 23, no. 8, p. 6–9. Discussions in no. 9, p. 21–23; v. 24, no. 1, p. 21–22.

Galley, J. E., 1958, Oil and geology in the Permian Basin of Texas and New Mexico, *in* Weeks, L. G. (ed.), Habitat of oil: American Association of Petroleum Geologists, p. 395–446.

__________ 1970, Some principles of tectonics in the Permian Basin, *in* Stewart, W. J. (ed.), Basins of the Southwest, v. 1: West Texas Geological Society Publication 70-68, p. 5–20.

Gilbert, M. C., 1982, Geologic setting of the eastern Wichita Mountains, with a brief discussion of unresolved problems, *in* Gilbert, M. C., and Donovan, R. N. (eds.), Geology of the eastern Wichita Mountains, southwestern Oklahoma: Oklahoma Geological Survey Guidebook 21, p. 1–30.

Graham, S. A., Dickinson, W. R., and Ingersoll, R. V., 1975, Himalayan-Bengal model for flysch dispersal in the Appalachian-Ouachita system: Geological Society of America Bulletin, v. 86, p. 273–286.

Granath, J. W., 1989, Structural evolution of the Ardmore Basin, Oklahoma: progressive deformation in the foreland of the Ouachita collision: Tectonics, v. 8, no. 5, p. 1015–1036.

Guinan, M. A., 1971, More evidence of the slide-block event will follow Delaware Basin drilling: Oil and Gas Journal, v. 69, no. 27, p. 120–127.

Hills, J. M., 1970, Late Paleozoic structural directions in the southern Permian Basin, West Texas and southeastern New Mexico: American Association of Petroleum Geologists Bulletin, v. 54, no. 10, p. 1809–1827.

__________ 1984, Sedimentation, tectonism and hydrocarbon generation in Delaware Basin, West Texas and New Mexico: American Association of Petroleum Geologists Bulletin, v. 68, no. 3, p. 250–267.

Kluth, C. F., and Coney, P. J., 1981, Plate tectonics of the Ancestral Rocky Mountains: Geology, v. 9, p. 10–15.

Lillie, R. J., Nelson, D. K., DeVoogd, B., Brewer, J. A., Oliver, J. E., Brown, L. D., Kaufman, S., and Viele, G. W., 1983, Crustal structure of Ouachita Mountains, Arkansas: a model based on integration of COCORP reflection profiles and regional geophysical data: American Association of Petroleum Geologists Bulletin, v. 67, no. 6, p. 907–931.

Mauch, J. J., 1982, The late Paleozoic tectono-sedimentary history of the Marfa Basin, West Texas: Texas Christian University, Master's thesis, 95 p.

Muehlberger, W. R., DeMis, W. D., and Leason, J. O., 1984, Geologic cross-sections, Marathon region, Trans-Pecos Texas: Geological Society of America Map and Chart Series MC-28T.

Muehlberger, W. R., Denison, R. E., and Lidiak, E. G., 1967, Basement rocks in continental interior of United States: American Association of Petroleum Geologists Bulletin, v. 51, p. 2351–2380.

Muehlberger, W. R., and Tauvers, P. R., 1990, Marathon fold-thrust belt, West Texas, *in* Hatcher, R. D., Jr., Thomas, W. A., and Viele, G. W. (eds.), The Appalachian–Ouachita orogen in the United States: Geological Society of America, The Geology of North America, v. F-2, p. 673–680.

Nicholas, R. L., 1983, Structure and stratigraphy of the Val Verde Basin–Devils River Uplift, West Texas: West Texas Geological Society Publication 83-77, p. 125–137.

Nicholas, R. L., and Rozendal, R. A., 1975, Subsurface positive elements within Ouachita foldbelt in Texas and their relation to Paleozoic cratonic margin: American Association of Petroleum Geologists Bulletin, v. 59, no. 2, p. 193–216.

Nicholas, R. L., and Waddell, D. E., 1990, The Ouachita system in the subsurface of Texas, Arkansas and Louisiana, *in* Hatcher, R. D., Jr., Thomas, W. A., and Viele, G. W. (eds.), The Appalachian–Ouachita Orogen in the United States: Geological Society of America Geology of North America, v. F-2, p. 661–672.

Nielsen, K. C., and Brown, W. G., 1984, Comparative structural evolution of the Arbuckle and Ouachita Mountains: South-Central Section, Geological Society of America Field Trip Guidebook 4, 100 p.

Palmer, A. R., DeMis, W. D., Muehlberger, W. R., and Robison, R. A., 1984, Geological implications of Middle Cambrian boulders from the Haymond Formation (Pennsylvanian) in the Marathon Basin, West Texas: Geology, v. 12, p. 91–94.

Petersen, F. A., 1983, Foreland detachment structures, *in* Lowell, J. D. (ed.), Rocky Mountain foreland basins and uplifts: Rocky Mountain Association of Geologists, p. 75.

Ross, C. A., 1986, Paleozoic evolution of the southern margin of the Permian Basin: Geological Society of America Bulletin, v. 97, p. 536–554.

Sanders, D. E., Boyce, R. G., and Peterson, N., 1983, The structural evolution of the Val Verde Basin, West Texas (abs.), *in* Kettenbrink, E. C. Jr., (ed.), Structure and stratigraphy of the Val Verde Basin–Devils River Uplift, Texas: West Texas Geological Society Publication 83-77, p. 123.

Tanner, J. H., 1967, Wrench fault movements along Washita Valley fault, Arbuckle Mountain area, Oklahoma: American Association of Petroleum Geologists Bulletin, v. 51, p. 126–134.

Tauvers, P. R., 1988, Basement-influenced deformation in the Marathon fold-thrust belt, West Texas: Journal of Geology, v. 96, p. 577–590.

Walper, J. L., 1977, Paleozoic tectonics of the southern margin of North America: Gulf Coast Association of Geological Societies Transactions, v. 27, p. 230–241.

Woods, R. D., and Addington, J. W., 1973, Pre-Jurassic geologic framework, northern Gulf Basin: Gulf Coast Association of Geological Societies Transactions, v. 23, p. 92–108.

GULFIAN CYCLE

Ashford, T., 1972, Geoseismic history and development of Rincon field, Texas: Geophysics, v. 37, p. 797–812.

Bilodeau, W. L., 1982, Tectonic models for early Cretaceous rifting in southeastern Arizona: Geology, v. 10, p. 466–470.

__________ 1986, The Mesozoic Mogollon Highlands, Arizona: an early Cretaceous rift shoulder: Journal of Geology, v. 94, p. 724–735.

Bishop, R. S., 1977, Shale diapir emplacement in South Texas: Laward and Sherriff examples: Gulf Coast Association of Geological Societies Transactions, v. 27, p. 20–31.

Blickwede, J. F., and Queffelec, T. A., 1988, Perdido Fold Belt: a new deep-water frontier in the western Gulf of Mexico (abs.): American Association of Petroleum Geologists Bulletin, v. 72, p. 163.

Bruce, C. H., 1973, Pressured shale and related sediment deformation: a mechanism for development of regional contemporaneous faults: American Association of Petroleum Geologists Bulletin, v. 57, p. 878–886.

Buffler, R. T., Shaub, F. J., Huerta, R., Ibrahim, A-B. K., and Watkins, J. S., 1981, A model for the early evolution of the Gulf of Mexico Basin: Oceanological Acta, no. SP, p. 129–136.

Calhoun, G. G., and Webster, R. E., 1983, Surface and subsurface expression of the Devils River Uplift, Kinney and Val Verde Counties, Texas, *in* Kettenbrink, E. C., Jr. (ed.), Stratigraphy and structure of the Val Verde Basin–Devils River Uplift, Texas: West Texas Geological Society Publication 83-77, p. 101–118.

Cloos, H., 1968, Experimental analysis of Gulf Coast fracture patterns: American Association of Petroleum Geologists Bulletin, v. 52, p. 420–444.

Cobb, R. C., and Poth, S., 1980, Superposed deformation in the Santiago and northern Del Carmen Mountains, Trans-Pecos Texas, *in* Dickerson, P. W., and Hoffer, J. M. (eds.), Trans-Pecos Region: New Mexico Geological Society Guidebook, 31st Field Conference, p. 71–75.

Erxleben, A. W., and Carnahan, G., 1983, Slick Ranch area, Starr County, Texas, *in* Bally, A. W. (ed.), Seismic expression of structural styles, a picture and work atlas: American Association of Petroleum Geologists Studies in Geology 15, v. 2, p. 2.3.1–22 to 26.

Ewing, T. E., 1983, Growth faults and salt tectonics in the Houston diapir province—relative timing and exploration significance: Gulf Coast Association of Geological Societies Transactions, v. 33, p. 83–90.

__________ 1986, Structural styles and structural evolution of the Wilcox and Frio growth-fault trends in Texas: constraints on geopressured reservoirs: The University of Texas at Austin, Bureau of Economic Geology Report of Investigations No. 154, 86 p.

__________ 1987, The Frio River Line in South Texas—transition from Cordilleran to northern Gulf tectonic regimes: Gulf Coast Association of Geological Societies Transactions, v. 37, p. 87–94.

__________ 1988, Variation of "growth fault" structural styles in the Texas Gulf Coast Basin (abs.): Gulf Coast Association of Geological Societies Transactions, v. 38, p. 579.

__________ 1989, The downdip Yegua trend—an overview: Gulf Coast Association of Geological Societies Transactions, v. 39, p. 75–83.

__________ in press, Structural framework, *in* Salvador, A. (ed.), The Gulf of Mexico Basin: Geological Society of America, The Geology of North America, v. J, chapter 3.

Ewing, T. E., and Caran, S. C., 1982, Late Cretaceous volcanism in South and Central Texas—stratigraphic, structural and seismic models: Gulf Coast Association of Geological Societies Transactions, v. 32, p. 137–145.

Geitgey, J. E., 1988, Plio-Pleistocene evolution of central offshore Louisiana: Gulf Coast Association of Geological Societies Transactions, v. 38, p. 151–156.

Granata, W. H., 1963, Cretaceous stratigraphy and structural development of the Sabine Uplift area, Texas and Louisiana, *in* Report on selected North Louisiana and South Arkansas oil and gas fields and regional geology: Shreveport Geological Society, Reference Volume V, p. 50–95.

Gries, J. G., and Haenggi, W. T., 1971, Structural evolution of the eastern Chihuahua Tectonic Belt, *in* The geologic framework of the Chihuahua Tectonic Belt: West Texas Geological Society, p. 119–138.

Hall, D. J., Cavanaugh, T. D., Watkins, J. S., and McMillen, K. J., 1982, The rotational origin of the Gulf of Mexico based on regional gravity data, *in* Watkins, J. S., and Drake, C. L. (eds.), Studies in continental margin geology: American Association of Petroleum Geologists Memoir 34, p. 115–128.

Harbour, R. L., 1972, Geology of the northern Franklin Mountains, Texas and New Mexico: U.S. Geological Survey Bulletin 1298, 129 p.

Hardin, N. S., 1989, Salt distribution and emplacement processes, Northwest Gulf lower slope: a suture between two provinces, *in* Gulf of Mexico salt tectonics, associated processes and exploration potential: Gulf Coast Section Society of Economic Paleontologists and Mineralogists, 10th Annual Research Conference, Program and Extended Abstracts, p. 54–59.

Henry, C. D., Price, J. G., and McDowell, R. W., 1983, Presence of the Rio Grande rift in West Texas and Chihuahua: El Paso Geological Society Guidebook 15, p. 108–118.

Henry, C. D., and Price, J. G., 1985, Summary of the tectonic development of Trans-Pecos Texas: The University of Texas at Austin, Bureau of Economic Geology Miscellaneous Map 36, 8 p.

Humphris, C. C., Jr., 1978, Salt movement on continental slope, northern Gulf of Mexico, *in* Bouma, A. H., Moore, G. T., and Coleman, J. M. (eds.), Framework, facies, and oil-trapping characteristics of the upper continental margin: American Association of Petroleum Geologists Studies in Geology 7, p. 69–85.

Ibrahim, A-B. K., and Uchupi, E., 1982, Continental oceanic crustal transition in the Gulf Coast Geosyncline, *in* Watkins, J. S., and Drake, C. L. (eds.), Studies in continental margin geology: American Association of Petroleum Geologists Memoir 34, p. 115–128.

Jackson, M. L. W., and Laubach, S. E., 1988, Cretaceous and Tertiary compressional tectonics as the cause of the Sabine Arch, East Texas and Northwest Louisiana: Gulf Coast Association of Geological Societies Transactions, v. 38, p. 245–256.

Jackson, M. P. A., 1982, Fault tectonics of the East Texas Basin: The University of Texas at Austin, Bureau of Economic Geology Geological Circular 82-4, 31 p.

Laubach, S. E., and Jackson, M. L. W., 1990, Origin of arches in the northwestern Gulf of Mexico Basin: Geology, v. 18, p. 595–599.

Lee, G. H., Bryant, W. R., and Watkins, J. S., 1989, Salt structures and sedimentary basins in the Keathley Canyon area, northwestern Gulf of Mexico: their development and tectonic implications, *in* Gulf of Mexico salt tectonics, associated processes and exploration potential: Gulf Coast Section Society of Economic Paleontologists and Mineralogists 10th Annual Research Conference, Program and Extended Abstracts, p. 90–93.

Lovejoy, E. M. P., and Seager, W. R., 1978, Discussion of structural geology of Franklin Mountains, *in* Hawley, J. T. (compiler), Guidebook to Rio Grande rift in New Mexico and Colorado: New Mexico Bureau of Mines and Mineral Resources Circular 163, p. 68–69.

Martin, R. G., 1980, Distribution of salt structures in the Gulf of Mexico: U.S. Geological Survey Miscellaneous Field Studies Map MF-1213, 2 sheets.

———— 1984, Diapiric trends in the deep-water Gulf basin: Gulf Coast Section Society of Economic Paleontologists and Mineralogists Fifth Research Conference, Program and Abstracts, p. 60–62.

McKee, J. W., Jones, N. W., and Long, L. E., 1990, Stratigraphy and provenance of strata along the San Marcos fault, central Coahuila, Mexico: Geological Society of America Bulletin, v. 102, p. 593–614.

Moustafa, A. R., 1988, Structural geology of Sierra del Carmen, Trans-Pecos Texas: The University of Texas at Austin, Bureau of Economic Geology Geologic Quadrangle Map 54, 28 p.

Muehlberger, W. R., 1980, Texas Lineament revisited, *in* Dickerson, P. W., and Hoffer, J. M. (eds.), Trans-Pecos region, southwestern New Mexico and West Texas: New Mexico Geological Society Guidebook, 31st Field Conference, p. 113–122.

Nicholas, R. L., and Waddell, D. E., 1990, The Ouachita system in the subsurface of Texas, Arkansas and Louisiana, *in* Hatcher, R. D., Jr., Thomas W. A., and Viele, G. W. (eds.), Appalachian–Ouachita Orogen in the United States: Geological Society of America, The Geology of North America, v. F-2, p. 661–672.

Nunn, J. A., 1990, Relaxation of continental lithosphere: an explanation for Late Cretaceous reactivation of the Sabine Uplift of Louisiana–Texas: Tectonics, v. 9, p. 341–359.

Nunn, J. A., Scardina, A. D., and Pilger, R. H., Jr., 1984, The thermal evolution of the north-central Gulf Coast: Tectonics, v. 3, p. 723–740.

Price, J. G., and Henry, C. D., 1984, Stress orientations during Oligocene volcanism in Trans-Pecos Texas: timing the transition from Laramide compression to Basin and Range tension: Geology, v. 12, p. 238–241.

Roebeck, R. C., Pesquera V., R., and Ulloa A., S., 1956, Geologia y depositos de carbon de la region de Sabinas, Estado de Coahuila: Mexico D. F., 20th Congreso Geologico Internacional, 109 p.

Sawyer, D. S., Buffler, R. T., and Pilger, R. H., Jr., in press, The crust under the Gulf of Mexico Basin, *in* Salvador, A. (ed.), The Gulf of Mexico Basin: Geological Society of America, The Geology of North America, v. J, chapter 4.

Seni, S. J., and Jackson, M. P. A., 1982, Evolution of salt structures, East Texas diapir province, Part 1: Sedimentary record of halokinesis: American Association of Petroleum Geologists Bulletin, v. 67, no. 8, p. 1219–1244. Part 2: Patterns and rates of halokinesis: American Association of Petroleum Geologists Bulletin, v. 67, no. 8, p. 1245–1274.

Smith, C. I., 1970, Lower Cretaceous stratigraphy, northern Coahuila, Mexico: The University of Texas at Austin, Bureau of Economic Geology Report of Investigations No. 65, 101 p.

Stanley, T. B., Jr., 1970, Vicksburg fault zone, Texas, *in* Geology of giant petroleum fields: American Association of Petroleum Geologists Memoir 14, p. 301–308.

Todd, R. G., and Mitchum, R. M., Jr., 1977, Seismic stratigraphy and global changes of sea level, Part 8: Identification of upper Triassic, Jurassic and lower Cretaceous seismic sequences in the Gulf of Mexico and offshore West Africa, *in* Payton, C. E. (ed.), Seismic stratigraphy—applications to hydrocarbon exploration: American Association of Petroleum Geologists Memoir 26, p. 145–163.

Vogler, H. A., and Robison, B. A., 1987, Exploration for deep geopressured gas: Corsair Trend, offshore Texas: American Association of Petroleum Geologists Bulletin, v. 71, no. 7, p. 777–787.

Webster, R. E., 1982, Geology of the Carta Valley fault zone area, Edwards, Kinney, and Val Verde Counties, Texas: The University of Texas at Austin, Bureau of Economic Geology, Geologic Quadrangle Map 53, scale 1:96,000.

Weeks, A. W., 1945, Balcones, Luling and Mexia fault zones in Texas: American Association of Petroleum Geologists Bulletin, v. 29, p. 1733–1737.

Wilson, J. A., 1971, Vertebrate biostratigraphy of Trans-Pecos Texas and northern Mexico, *in* The geologic framework of the Chihuahua Tectonic Belt: West Texas Geological Society, p. 157–166.

Winker, C. D., Morton, R. A., Ewing, T. E., and Garcia, D. D., 1983, Depositional setting, structural style, and sandstone distribution in three geopressured geothermal areas, Texas Gulf Coast: The University of Texas at Austin, Bureau of Economic Geology Report of Investigations No. 134, 60 p.

Woods, R. D., and Addington, J. W., 1973, Pre-Jurassic geologic framework, northern Gulf Basin: Gulf Coast Association of Geological Societies Transactions, v. 23, p. 92–108.

Worrall, D. M., and Snelson, S., 1989, Evolution of the northern Gulf of Mexico, with emphasis on Cenozoic growth faulting and the role of salt, *in* Bally, A. W., and Palmer, A. R. (eds.), The geology of North America—an overview: Geological Society of America, The Geology of North America, v. A, p. 97–138.

Zoback, M. L., Anderson, R. E., and Thompson, G. A., 1981, Cainozoic evolution of stress and style of tectonism of the Basin and Range Province of the western United States: Philosophical Transactions of the Royal Society of London, Series A-300, p. 407–434.

Appendix

Sources of Data Used to Compile the Tectonic Map of Texas

A. TRANS-PECOS TEXAS

Ammon, W. L., 1977, Geology and plate tectonic history of the Marfa Basin, Presidio County, Texas: Texas Christian University, Master's thesis, 44 p.

Bureau of Economic Geology, The University of Texas at Austin, data base on open file.

Dumas, D. B., Dorman, H. J., and Latham, G. V., 1980, A reevaluation of the August 16, 1931, Texas earthquake: Bulletin of the Seismological Society of America, v. 70, p. 1171–1180.

Harbour, R. L., 1972, Geology of the northern Franklin Mountains, Texas and New Mexico: U.S. Geological Survey Bulletin 1298, 129 p.

Henry, C. D., Gluck, J. K., and Bockoven, N. T., 1985, Tectonic map of the Basin and Range province of Texas and adjacent Mexico: The University of Texas at Austin, Bureau of Economic Geology Miscellaneous Map 36, scale 1:500,000.

Mauch, J. J., 1982, The late Paleozoic tectono-sedimentary history of the Marfa Basin, West Texas: Texas Christian University, Master's thesis, 95 p.

B. WEST TEXAS

Herald, F. A., ed., 1957, Occurrence of oil and gas in West Texas: Austin, University of Texas Publication 5716, 442 p.

Hiss, W. L., 1976, Structure of the Permian Guadalupian Capitan aquifer, southeast New Mexico and west Texas: New Mexico Bureau of Mines and Mineral Resources Resource Map 6, scale 1:250,000.

Petroleum Information data base, edited by G. R. Keller, The University of Texas at El Paso.

University of Texas System Lands Office, Midland, Texas, data base.

West Texas Geological Society, 1966, Oil and gas fields in West Texas symposium: West Texas Geological Society Publication 66-52, 396 p.

———— 1969, Vol. II, Oil and gas fields in West Texas symposium: West Texas Geological Society Publication 69-57, 134 p.

———— 1977, Vol. III, Gas fields in West Texas symposium: West Texas Geological Society Publication 77-67, 117 p.

C. SOUTHEASTERN NEW MEXICO

Calzia, J. P., and Hiss, W. L., 1978, Igneous rocks in northern Delaware Basin, New Mexico and Texas: New Mexico Bureau of Mines and Mineral Resources Circular 159, p. 39–45.

Haigler, L. B., and Cunningham, R. R., 1972, Structure contour map on top of the undifferentiated Silurian and Devonian rocks in southeastern New Mexico: U.S. Geological Survey Map OM-218, scale 1:250,000.

Roswell Geological Society, 1956, The oil and gas fields of southeastern New Mexico, *in* Stipp, T. F., Helwig, P. D., Alcorn, R., and Murphy, R. E. (eds.), 375 p.; 1960, The oil and gas fields of southeastern New Mexico, 1960 supplement, *in* Sweeney, H. N., Dietrich, E. S., Dunn, D. A., Fay, R. L., Holt, R. D., McCampbell, W. G., and Stipp, T. F. (eds.), 229 p.; 1967, The oil and gas fields of southeastern New Mexico, 1966 supplement, *in* Kinney, E. E., and Schatz, F. L. (eds.), 185 p.

D. NORTH TEXAS

Bureau of Economic Geology, The University of Texas at Austin well file.

Flawn, P. T., ed., 1967, Wells penetrating basement in North America: Tulsa, American Association of Petroleum Geologists, p. 577–628.

Phongprayoon, Pongsak, 1972, Subsurface geology of Wilbarger and Baylor Counties, Texas: The University of Texas at Austin, Master's thesis, 79 p.

Unpublished information, Lennart Teir, Wichita Falls.

E. PANHANDLE

Budnik, R. T., 1989, Tectonic structures of the Palo Duro Basin, Texas Panhandle: The University of Texas at Austin, Bureau of Economic Geology Report of Investigations No. 187, 43 p.

Bureau of Economic Geology, The University of Texas at Austin well file.

Dutton, S. P., Goldstein, A. G., and Ruppel, S. C., 1982, Petroleum potential of the Palo Duro Basin, Texas Panhandle: The University of Texas at Austin, Bureau of Economic Geology Report of Investigations No. 123, 87 p.

Jemison, R. M., Jr., 1968, Development of the Mills Ranch complex, Wheeler County, Texas: Transactions, Southwest Section American Association of Petroleum Geologists Publication 78-69, p. 48–60.

Panhandle Geological Society, 1977, Selected gas fields of the Texas Panhandle, 83 p.

Petroleum Information, 1982, The deep Anadarko Basin.

F. NORTHEASTERN NEW MEXICO

Bureau of Economic Geology, The University of Texas at Austin data base.

Dane, C. H., and Bachman, G. O., 1965, Geologic map of New Mexico: U.S. Geological Survey, scale 1:500,000.

Flawn, P. T., ed., 1967, Wells penetrating basement in North America: Tulsa, American Association of Petroleum Geologists, p. 478–505.

Foster, R. W., Frentress, R. M., and Niese, W. C., 1972, Subsurface geology of east-central New Mexico: New Mexico Geological Society Special Publication 4, 22 p.

Foster, R. W., and Stipp, T. F., 1961, Preliminary geologic and relief map of the Precambrian rocks of New Mexico: New Mexico Bureau of Mines and Mineral Resources Circular 57, 37 p.

Osburn, J. C., 1980, Geologic and structure map of the Precambrian rocks in New Mexico: New Mexico Bureau of Mines and Mineral Resources unpublished map, scale 1:500,000.

Petroleum Information data base.

Pitt, W. D., 1973, Hydrocarbon potential of pre-Pennsylvanian rocks in Roosevelt County, New Mexico: New Mexico Bureau of Mines and Mineral Resources Circular 130, 7 p.

Woodward, L. A., and Snyder, D. O., 1976, Structural framework of the southern Raton Basin: New Mexico Geological Society Guidebook 27, p. 125–128 and map.

G. OKLAHOMA

Carr, J. E., and Bergman, D. L., 1976, Reconnaissance of the water resources of the Clinton quadrangle, west-central Oklahoma: Oklahoma Geological Survey Hydrologic Atlas 5, scale 1:250,000.

Ham, W. E., Denison, R. E., and Merritt, C. A., 1964, Basement rocks and structural evolution of southern Oklahoma: Oklahoma Geological Survey Bulletin 95, 302 p.

Hart, D. L., Jr., 1974, Reconnaissance of the water resources of the Ardmore and Sherman quadrangles, southern Oklahoma: Oklahoma Geological Survey Hydrologic Atlas 4, scale 1:250,000.

Havens, J. S., 1977, Reconnaissance of the water resources of the Lawton quadrangle, southwestern Oklahoma: Oklahom Geological Survey Hydrologic Atlas 6, scale 1:250,000.

Hicks, I. C., 1971, Southern Oklahoma folded belt, *in* Future petroleum provinces of the United States (v. 2): American Association of Petroleum Geologists Memoir 15, p. 1070–1077.

Laing, W. E., 1963, Geoseismic problems and production profiles, eastern Palo Duro Basin, southwestern Oklahoma, *in* Eighth symposium on subsurface geology: University of Oklahoma, p. 17–69.

McBee, W., Jr., and Vaughan, L. G., 1956, Oil fields of the Central Muenster-Waurika Arch, Jefferson County, Oklahoma and Montague County, Texas, *in* Petroleum geology of southern Oklahoma—a symposium (v. 1): Tulsa, American Association of Petroleum Geologists, p. 355–372.

Petroleum Information, 1982, The deep Anadarko Basin.

Tarr, R. S., Jordon, L., and Rowland, T. L., 1965, Geologic map and section of pre-Woodford rocks in Oklahoma: Oklahoma Geological Survey Geological Map GM-9, scale 1:750,000.

Unpublished data bases, Lennart Teir and University of Oklahoma.

H. FORT WORTH BASIN AND MUENSTER ARCH

Bradfield, H. H., 1956, Generalized subsurface map of Cooke and Grayson Counties, Texas and parts of Love and Marshall Counties, Oklahoma, *in* The geology and geophysics of Cooke and Grayson Counties, Texas: Dallas Geological Society, 211 p.

Flawn, P. T., ed., 1967, Wells penetrating basement in North America: Tulsa, American Association of Petroleum Geologists, p. 527–628.

Fort Worth Geological Society,' Fort Worth Basin map as modified by Browning, D. W., 1982, Geology of the North Caddo area, Stephens County, Texas, *in* Petroleum geology of the Fort Worth Basin and Bend Arch area: Dallas Geological Society, p. 315–329.

Thompson, D. M., 1982, Atoka Group (Lower to Middle Pennsylvanian), northern Fort Worth Basin, Texas: The University of Texas at Austin, Bureau of Economic Geology Report of Investigations No. 125, 62 p.

I. WEST-CENTRAL TEXAS

Berumen, Manuel, 1979, Fort Chadbourne fault system, eastern Coke County, Texas: The University of Texas at Austin, Master's thesis, 65 p.

Bureau of Economic Geology, The University of Texas at Austin data base.

Conselman, F. B., 1954, Preliminary report on the Cambrian trend of west central Texas: Abilene Geological Society, Geological Contributions, p. 10–24.

Core Laboratories, 1972, A survey of the subsurface saline water of Texas: volume 6, geologic well data, Central Texas: Texas Department of Water Resources Report 157, 438 p.

Rall, R. W., and Rall, E. P., 1958, Pennsylvanian subsurface geology of Sutton and Schleicher Counties, Texas: American Association of Petroleum Geologists Bulletin, v. 42, p. 839–870.

University of Texas System Lands Office, Midland, Texas data base.

Walker, G. P., III, 1967, Subsurface geologic reconnaissance of Kerr Basin and adjacent areas, south central Texas: University of Texas, Austin, Master's thesis, 217 p.

J. DEVILS RIVER UPLIFT–VAL VERDE BASIN

Calhoun, G. G., and Webster, R. G., 1983, Surface and subsurface expression of the Devils River Uplift, Kinney and Val Verde Counties, Texas, *in* West Texas Geological Society Guidebook 83-77, p. 101–120.

Nicholas, R. L., 1983, Devils River Uplift, *in* West Texas Geological Society Guidebook 83-77, p. 125–138.

K. OUACHITA SYSTEM

Flawn, P. T., Goldstein, August, Jr., King, P. B., and Weaver, C. E., 1961, The Ouachita System: Austin, University of Texas Publication 6120, 401 p.

L. BALCONES FAULT ZONE

Bureau of Economic Geology, The University of Texas at Austin, well file data base.

Klemt, W. B., Knowles, T. R., Elder, G. R., and Sieh, T. W., 1979, Ground-water resources and model applications for the Edwards (Balcones Fault Zone) aquifer in the San Antonio region, Texas: Texas Department of Water Resources Report 239, 88 p.

M. GULF COAST AND EAST TEXAS

Mapping generalized from commercial mapping (1982) of Geomap Company (used by permission).

N. EAST TEXAS

Seni, S. J., and Jackson, M. P. A., 1983, Evolution of salt structures, East Texas diapir province, part I: sedimentary record of halokinesis: American Association of Petroleum Geologists Bulletin, v. 67, no. 8, p. 1219–1244.

O. NORTH COAHUILA

Smith, C. I., 1970, Lower Cretaceous stratigraphy, northern Coahuila, Mexico: The University of Texas at Austin, Bureau of Economic Geology Report of Investigations No. 65, 101 p.

P. CENTRAL COAHUILA

Roebeck, R. C., Pesquera V., R., and Ulloa A., S., 1956, Geologia y depositas de carbon de la region de Sabinas, Estado de Coahuila: Mexico, 20th Congreso Geologico Internacional, 109 p.

Q. MEXICO

Lopez Ramos, E., 1967, Carta geologica del Estado de Coahuila: Instituto de Geologia de la Universidad Autonoma de Mexico, scale 1:500,000.

———— 1972, Carta geologica del Estado de Nuevo Leon: Instituto de Geologia de la Universidad Autonoma de Mexico, scale 1:500,000.

———— 1972, Carta geologica del Estado de Tamaulipas: Instituto de Geologia de la Universidad Autonoma de Mexico, scale 1:500,000.

Modified from Landsat imagery, topographic maps, and unpublished data.

R. CUENCA DE BURGOS

Busch, D. A., 1973, Oligocene studies, northeast Mexico: Gulf Coast Association of Geological Societies Transactions, v. 23, p. 136–145.

Rodriguez Santana, E., 1969, Sedimentos del Oligoceno de la Cuenca de Burgos—aspecto regional, *in* Seminaria sobre exploración petrolera, Mesa Redonda No. 1, Problemas de exploración de la Cuenca de Burgos: Instituto Mexicano del Petroleo, n. p.

S. GULF COAST AREAS

Ewing, T. E., 1986, Structural styles and structural evolution of the Tertiary growth-fault trends of the Texas Gulf Coast: constraints on geopressured reservoirs: The University of Texas at Austin, Bureau of Economic Geology Report of Investigations No. 154, 86 p.

Winker, C. D., Morton, R. A., Ewing, T. E., and Garcia, D. D., 1983, Depositional setting, structural style, and sandstone distribution in three geopressured geothermal areas, Texas Gulf Coast: The University of Texas at Austin, Bureau of Economic Geology Report of Investigations No. 134, 60 p.

T. OFFSHORE

Berryhill, H. L., Jr., and Trippett, A. R., 1981, Map showing structure of the continental terrace in the Port Isabel 1 × 2 quadrangle, Texas: U.S. Geological Survey Map I-1254-F, scale 1:250,000.

Bouma, A. H., 1982, Intraslope basins in the northwest Gulf of Mexico: a key to ancient submarine canyons and fans: American Association of Petroleum Geologists Memoir 34, p. 567–581.

Martin, R. G., 1980, Distribution of salt structures in the Gulf of Mexico: map and descriptive text: U.S. Geological Survey Map MF-1213, 8 p.

Martin, R. G., and Foote, R. Q., 1981, Geology and geophysics of the Maritime Boundary assessment area: U.S. Geological Survey Open-File Report 81-265, p. 30–67.

Morton, R. A., Miocene fault trends data.

Trippett, A. R., 1981, Location of diapirs, fold axes and faults: Minerals Management Service Open File Report 82-02, scale 1:250,000.

Trippett, A. R., and Berryhill, H. L., Jr., 1981a, Map showing structure of the continental terrace in the Beeville 1×2 quadrangle, Texas: U.S. Geological Survey Map I-1288-F, scale 1:250,000.

———— 1981b, Map showing structure of the continental terrace in the Corpus Christi 1×2 quadrangle, Texas: U.S. Geological Survey Map I-1287-F, scale 1:250,000.

U.S. Geological Survey, 1983, Topographic map of Texas, scale 1:500,000, with bathymetry from National Ocean Survey.

U. EXPOSED BASEMENT

Barnes, V. E., project director, Geologic Atlas of Texas: The University of Texas at Austin, Bureau of Economic Geology, scale 1:250,000. All sheets, especially Austin (1974), Emory Peak–Presidio (1979), Fort Stockton (1982), Llano (1981), Marfa (1979), San Antonio, (1974), Seguin (1974), and Van Horn–El Paso (1968).

Garrison, J. R., Jr., unpublished compilation, 1985.

Muehlberger, W. R., unpublished compilation, 1985.

BASEMENT INSET—

Bowring, S. A., and Hoppe, W. J., 1982, U/Pb zircon ages from Mount Sheridan gabbro, Wichita Mountains: Oklahoma Geological Society Guidebook 21, p. 54–59.

Condie, K. C., 1981, Precambrian rocks of the southwestern United States and adjacent areas of Mexico: New Mexico Bureau of Mines and Mineral Resources Resource Map 13, scale 1:250,000.

Denison, R. E., 1982, Basement rocks in northeastern Oklahoma: Oklahoma Geological Survey Circular 84, 84 p.

Flawn, P. T., 1956, Basement rocks of Texas and southeastern New Mexico: Austin, University of Texas Publication 5605, 73 p.

Garrison, J. R., Jr., unpublished compilation, 1985.

Hall, D. J., Cavanaugh, T. D., Watkins, J. S., and McMillen, K. J., 1982, The rotational origin of the Gulf of Mexico based on regional gravity data, *in* Watkins, J. S., and Drake, C. L. (eds.), Studies in continental margin geology: American Association of Petroleum Geologists Memoir 34, p. 115–126.

Muehlberger, W. R., Denison, R. E., and Lidiak, E. G., 1967, Basement rocks in continental interior of United States: American Association of Petroleum Geologists Bulletin, v. 51, p. 2351–2380.

Nicholas, R. L., 1983, Devils River Uplift, *in* West Texas Geological Society Guidebook 83-77, p. 125–138.

NEOTECTONICS INSET—

Davis, S. D., 1985, Investigations of natural and induced seismicity in the Texas Panhandle: The University of Texas at Austin, Master's thesis, 230 p.

Dumas, D. B., 1981, Seismicity of West Texas: The University of Texas at Dallas, Ph.D. dissertation, 105 p.

Gough, D. I., and Bell, J. S., 1981, Stress orientations from oil-well fractures in Alberta and Texas: Canadian Journal of Earth Sciences, v. 18, p. 638–645.

———— 1982, Stress orientations from borehole wall fractures with examples from Colorado, East Texas, and northern Canada: Canadian Journal of Earth Sciences, v. 19, p. 1358–1370.

Pennington, W. R., seismicity compilation, 1985.

Zoback, M. L., and Zoback, M., 1980, State of stress in the conterminous United States: Journal of Geophysical Research, v. 85, p. 6113–6156.