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TECTONIC HISTORY AND REGIONAL TECTONIC FRAMEWORK OF THE PALO DURO BASIN, TEXAS PANHANDLE

by

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ABSTRACT

The Palo Duro Basin, a broad structural low in the southern Texas Panhandle, has had a long history of episodic deformation, beginning in the Precambrian. During the middle Proterozoic, the basin was the site of accumulation of more than 30,000 ft (9,100 m) of rhyolite flows and related rocks. The establishment of the northwest-trending structural grain of the area possibly occurred at this time. The presence of pre-upper Cambrian(?) arkosic clastics within the basin suggests active faulting during the late Proterozoic to earliest Cambrian. The southern Panhandle was occupied by a carbonate shelf in the early Ordovician and again in the Mississippian. Sedimentation was probably nearly continuous from the early Ordovician to the early Devonian, however rocks of this age eroded from the central part of the Palo Duro Basin as a result of the uplift of the northwest-trending Texas Arch during the middle Devonian.

The southern midcontinent underwent major deformation during the Pennsylvanian Ancestral Rocky Mountain orogeny, when the southern Panhandle became the site of a distinct depositional basin. Approximately 75 mi (120 km) of left-lateral strike-slip movement occurred along the Amarillo-Wichita Uplift during this time. The axis of subsidence, associated with the formation of the larger Permian Basin, shifted progressively westward during Permian deposition. Renewed subsidence in the late Triassic formed a large lacustrine basin that extended southward from the Palo Duro Basin. During the Cenozoic, basement structures were reactivated, as reflected in the depositional patterns of the upper Miocene to lower Pliocene Ogallala Formation.

The tectonic history of the Palo Duro Basin is closely related to that of the Wichita megashear. This zone of weakness is interpreted to extend northwestward from southern Oklahoma to at least eastern Utah. The megashear formed in the late

Proterozoic and was reactivated during early Cambrian rifting, which produced the Southern Oklahoma Aulacogen. Structures were rejuvenated during the late Cambrian to early Ordovician and again in the middle Devonian. Major deformation occurred during the Pennsylvanian Ancestral Rocky Mountain orogeny. The Laramide (late Cretaceous to early Tertiary) and Basin and Range (late Tertiary) tectonic events reactivated segments of the Wichita megashear in Colorado and Utah, however no evidence of Laramide-age deformation exists along the eastern segment in the Texas Panhandle and Oklahoma. Basement structures were reactivated along parts of the eastern segment coincident with Basin and Range extension to the west. Recent seismicity and evidence of Quaternary faulting indicate that at least parts of the eastern, central, and western segments of the megashear are undergoing deformation.

Tectonic development of the southwestern United States has been influenced by large-scale plate interactions. The Proterozoic basement beneath the Palo Duro Basin probably formed along a convergent plate margin about 1,400 Ma ago. Continental rifting 570 Ma ago produced the Southern Oklahoma Aulacogen and reactivated basement structures within the region. Formation of the Texas Arch occurred during the middle Devonian, possibly in response to continent-continent collisions along the eastern and western margins of North America. The Ancestral Rocky Mountain orogeny was the result of the suturing of Gondwana and Laurussia during the Pennsylvanian. Crustal thinning in the Permian and Triassic, prior to and during the separation of North and South America, may have produced the Permian and Dockum depositional basins. Interaction between the Pacific and North American plates produced crustal extension in the western United States and reactivation of basement structures in the Texas Panhandle during the Miocene. Present seismicity in the region is occurring in response to movement of the North American plate away from the mid-Atlantic ridge.

INTRODUCTION

The saying "what's past is prologue" has become a cliché, but nevertheless it is true in geology. To predict the future tectonic stability of a region, one must understand the history of its tectonic development. This report presents an interpretation of the tectonic history of the Palo Duro Basin and adjoining region so that the long-term (by human standards, that is >10,000 yr) stability of the area can be assessed for the purpose of locating a high-level nuclear waste repository.

Evidence of the tectonic development of the Palo Duro Basin (fig. 1) is recorded in the distribution of Proterozoic and Phanerozoic lithofacies in the southern Texas Panhandle. Thickness and facies changes in these rocks record repeated, generally subtle, deformation in the area beginning in the Proterozoic and continuing through the Phanerozoic. Timing of this tectonic activity coincides with episodes of deformation along a large regional network of faults (figs. 2 and 3), variously termed the Wichita lineament (Sales, 1968), the Wichita megashear (Walper, 1970), the Olympic-Wichita lineament (Baars, 1976), and the Oklahoma-New Mexico-Colorado-Utah tectonic zone (Larson and others, 1985). The name Wichita megashear is used in this paper to emphasize the continuity of the zone and the importance of lateral motion during its history (see discussion under "Tectonic evolution of the Wichita megashear"). Analysis of the tectonic history of the regional system permits a better understanding of the tectonic history of the Palo Duro Basin.

The term "Palo Duro Basin" is used in this paper to refer to a broad structural low in the southern Texas Panhandle that was a distinct depositional basin only during the late Pennsylvanian and early Permian, when well-defined carbonate shelf margins bordered a relatively deep shale basin. This structural basin was occupied by

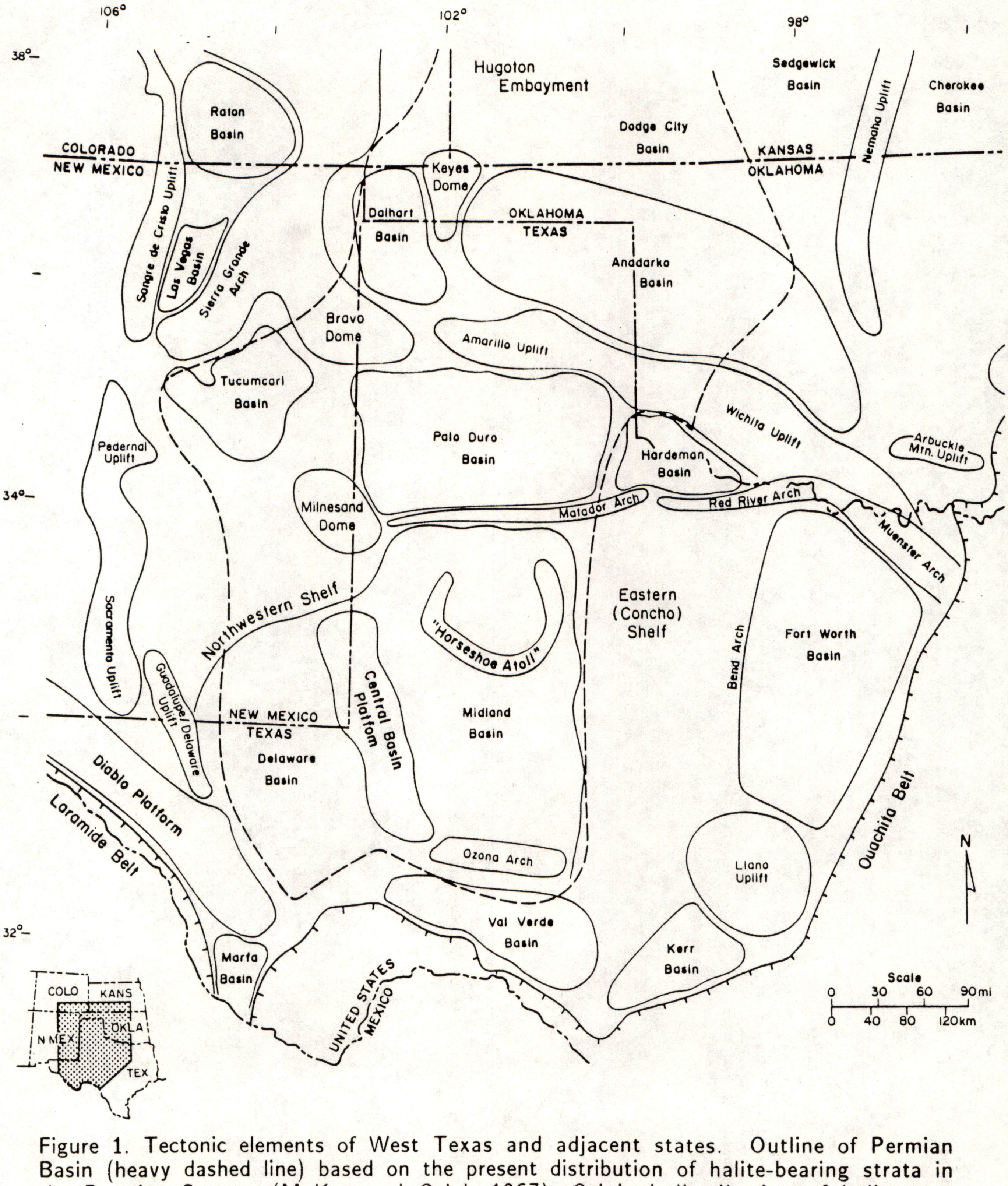

Figure 1. Tectonic elements of West Texas and adjacent states. Outline of Permian Basin (heavy dashed line) based on the present distribution of halite-bearing strata in the Permian System (McKee and Oriel, 1967). Original distribution of halite was probably somewhat greater. The Amarillo-Wichita Uplift, Sierra Grande Uplift, Pedernal Uplift, Diablo Platform, and Central Basin Platform were elements of the Ancestral Rocky Mountains.

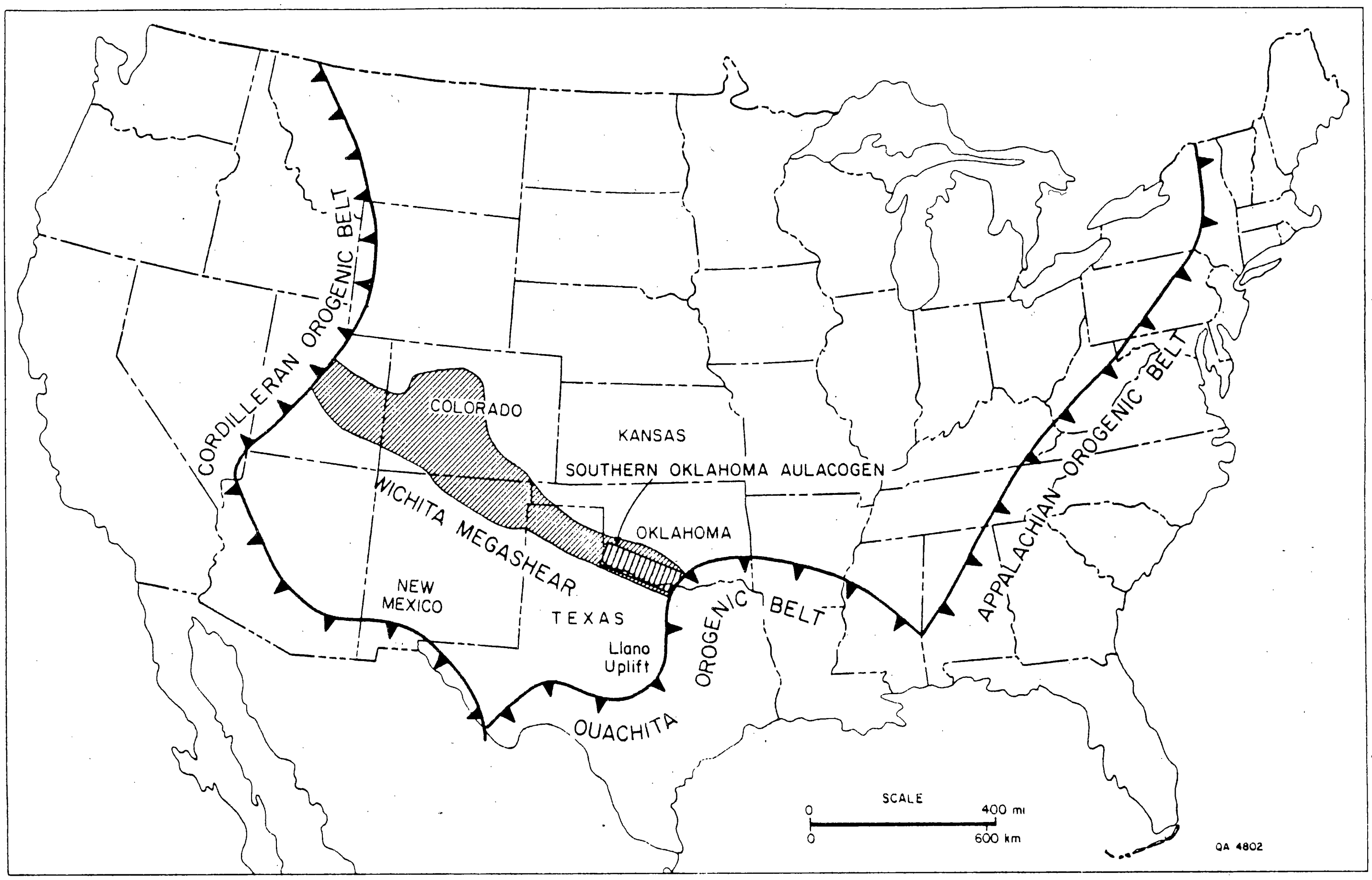

Figure 2. Map of the United States showing major tectonic features.

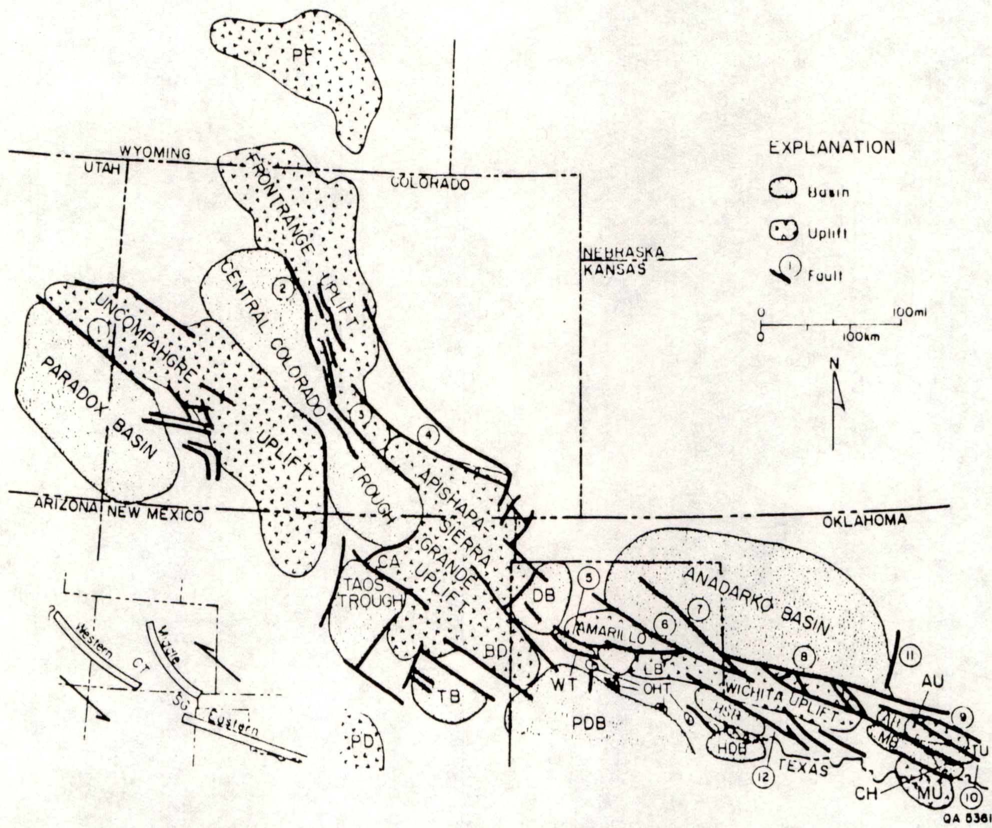

Figure 3. Structural geology of the Wichita megashear. Compiled from Rogatz (1939), Ham and others (1964), Baars and See (1968), MacLachlan and Kleinkopf (1969), Foster and others (1972), Mallory (1972), Evans (1979), Casey (1980), DeVoto (1980), Tweto (1980a, 1983), and Budnik (1984). Inset map shows location of eastern, middle, and western segments of the Wichita megashear.

Major structures are named; minor structures are indicated by initials: AB - Ardmore Basin; AU - Arbuckle Uplift; BD - Bravo Dome; CA - Cimarron Arch; CH - Criner Hills; DB - Dalhart Basin; HDB - Hardeman Basin; HSB - Hollis Basin; LB - LeFors Basin; MB - Marietta Basin; MU - Muenster Uplift; OHT - Oldham-Harmon structural trend; PD - Pedernal Uplift; PDB - Palo Duro Basin; PF - Pathfinder Uplift; TB - Tucumcari Basin; TU - Tishomingo Uplift; WT - Whittenburg Trough. Faults are numbered: 1. Uncompahgre frontal fault; 2. Gore fault; 3. Ilse fault; 4. Apishapa fault; 5. Potter County fault; 6. Wheeler County fault; 7. Lips fault; 8. Mountain View fault; 9. Reagan fault; 10. Washita Valley fault; 11. central Oklahoma fault; 12. Burch fault.

local depocenters within a larger depositional framework during the middle and late Permian, the late Triassic, and the late Tertiary.

The tectonic history of the region was interpreted through the analysis of published and unpublished structure-contour, isopach, and lithofacies maps of the Texas Panhandle and published work of other researchers in adjacent regions. This report is divided into three sections: (1) tectonic history of the Palo Duro Basin, (2) regional tectonic history, and (3) plate tectonic models. The structural geology of the basin has been discussed elsewhere (Budnik, 1984).

STRUCTURAL SETTING OF THE PALO DURO BASIN

The present configuration of the Palo Duro Basin is defined primarily on the basis of structures that formed during the Pennsylvanian Ancestral Rocky Mountain orogeny and that were modified during later subsidence. The basin occupies the northern end of a larger broad basement depression that also includes the Midland Basin (fig. 1). The two basins are somewhat arbitrarily subdivided by the Matador Arch, a discontinuous alignment of small, isolated basement horsts that extends east-west across the southern Texas Panhandle (fig. 4). A complexly deformed zone of horsts and grabens (part of the Wichita megashear), which includes the Oldham-Harmon structural trend (Budnik, 1984) and the Amarillo Uplift, separates the Palo Duro Basin from the Anadarko Basin to the northeast (figs. 3 and 4). A discontinuous structural low consisting of the Whittenburg Trough and the Hollis Basin lies between the Oldham-Harmon trend and the Amarillo Uplift (Soderstrom, 1968).

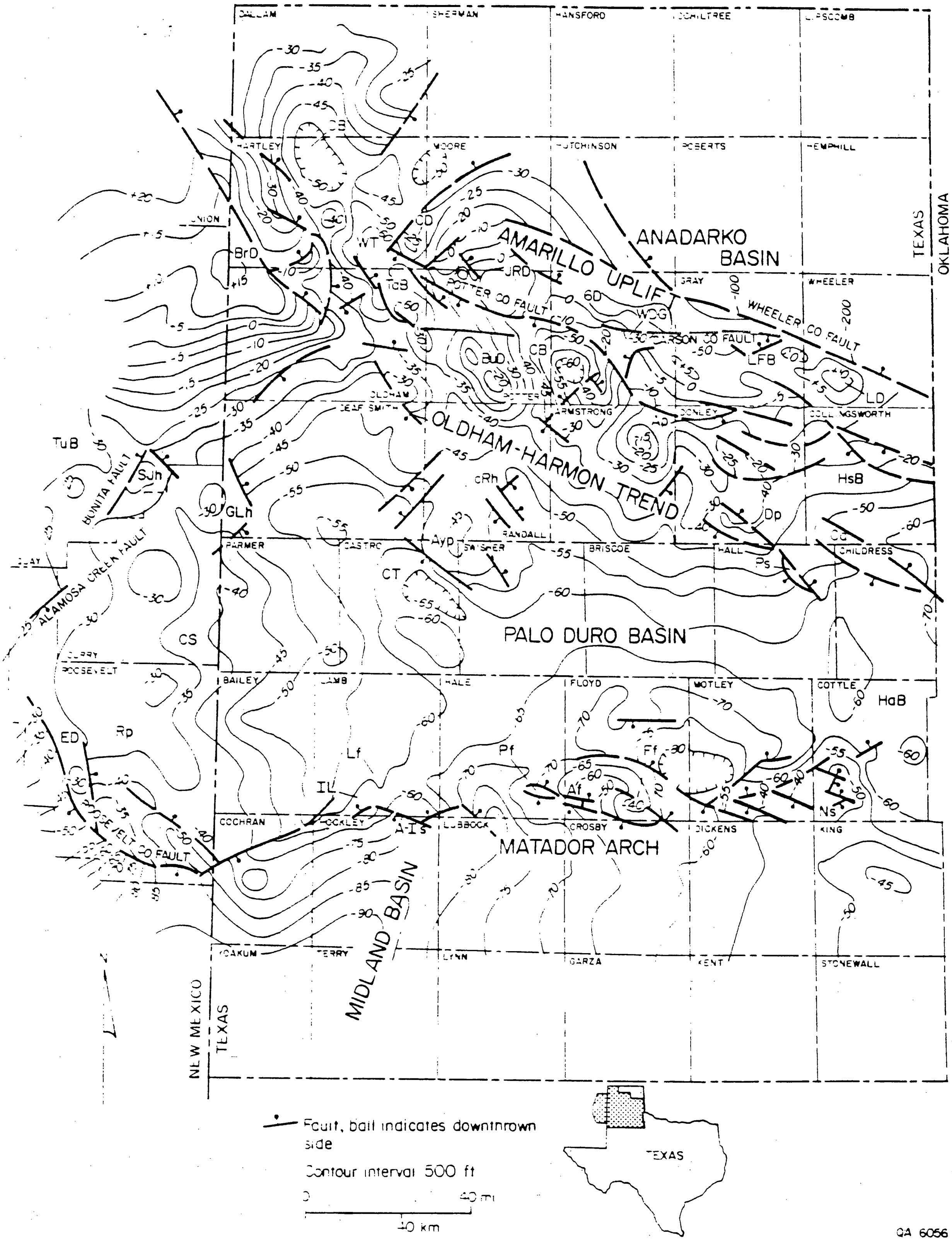

Figure 4. Basement-structure-contour map of the Texas Panhandle. The present structural configuration of the area is the result of episodic deformation throughout the Phanerozoic (Budnik, 1984).

Subtle basement positives separate the Palo Duro Basin from adjacent basins to the east and west. A broad structural divide separates the Palo Duro from the Hardeman Basin (fig. 4), a small fault-bounded graben (Montgomery, 1984) to the east. Although these two structural basins probably formed one continuous depositional basin during the late Pennsylvanian (Dutton, 1980), the pre-Pennsylvanian history of the Hardeman Basin may be more closely related to that of the Anadarko Basin, as will be discussed. The western margin of the Palo Duro Basin is formed by a series of poorly defined basement positives in east-central New Mexico, including the Roosevelt positive in Roosevelt County (Krisle, 1959), the San Jon high in Quay County (Krisle, 1959), and the Garcia Lake high in Curry County and Deaf Smith County, Texas (fig. 4; Budnik, 1984).

Structures within the Palo Duro Basin are generally subtle and not well defined, in part because of sparse subsurface control. Better delineated structures include the Castro Trough and adjacent Arney positive (fig. 4; Budnik, 1983, 1984), which form northwest-trending structural elements within the northwestern part of the basin. The central Randall positive (Budnik, 1984) is a small basement uplift northeast of the Arney positive.

TECTONIC HISTORY OF THE PALO DURO BASIN

The southern Texas Panhandle has undergone episodic deformation from the middle Proterozoic to the present. Timing of this deformation is indicated by the distribution, thickness, and lithofacies of Proterozoic and Phanerozoic strata and by the pattern of recent seismicity. Basement structures in the southern Panhandle appear to have formed in the middle Proterozoic and were reactivated in the early to middle Paleozoic and in the Pennsylvanian, Permian, Triassic, Cretaceous, and Cenozoic.

Proterozoic Igneous Activity and Deformation

Crystalline basement of the southern Texas Panhandle consists largely of undeformed rhyolite of the Panhandle volcanic sequence that is surrounded and presumably underlain by coeval granitic rocks (figs. 5 and 6; Flawn; 1956; Muehlberger and others, 1967). The volcanic sequence consists predominantly of rhyolite tuffs and flows and only minor amounts of intermediate and mafic volcanics. Muehlberger and others (1967) described the widespread occurrence of ignimbrites having well-preserved eutaxitic structure.

Total thickness of the Panhandle volcanic sequence is unknown, but geological and geophysical evidence indicates that it must be very thick. Several petroleum exploration wells were drilled a few hundred feet into the rhyolite without penetrating the base of the unit. One well, the Catherine H. Whittenburg, Whittenburg-Masterson No. 1 in Potter County (fig. 7), was drilled 3,821 ft (1,165 m) into basement, encountering, with the exception of a 270-ft (82-m) thick gabbroic body, only rhyolite.

Seismic reflection lines in the southern Texas Panhandle exhibit strong primary reflectors (fig. 8) to a depth of at least 30,000 ft (9,100 m; based on an average interval velocity of 18,000 ft/s, or 5,500 m/s) below the surface of the basement. These reflections are probably caused by an impedance contrast between the rhyolite and intercalated diabasic sills or flows, similar to that encountered in the Whittenburg well (fig. 7). A gravity low, centered in the area of the Panhandle volcanics (Goldstein, 1982), also suggests a great thickness of rhyolite or rhyolite and sedimentary rock (Flawn, 1956).

Early age determinations using K-Ar dating techniques suggested that the rhyolites are approximately 1,100 to 1,200 Ma old (Muehlberger and others, 1966). However, recent U-Pb dating of zircons from the terrane indicates that the rhyolites

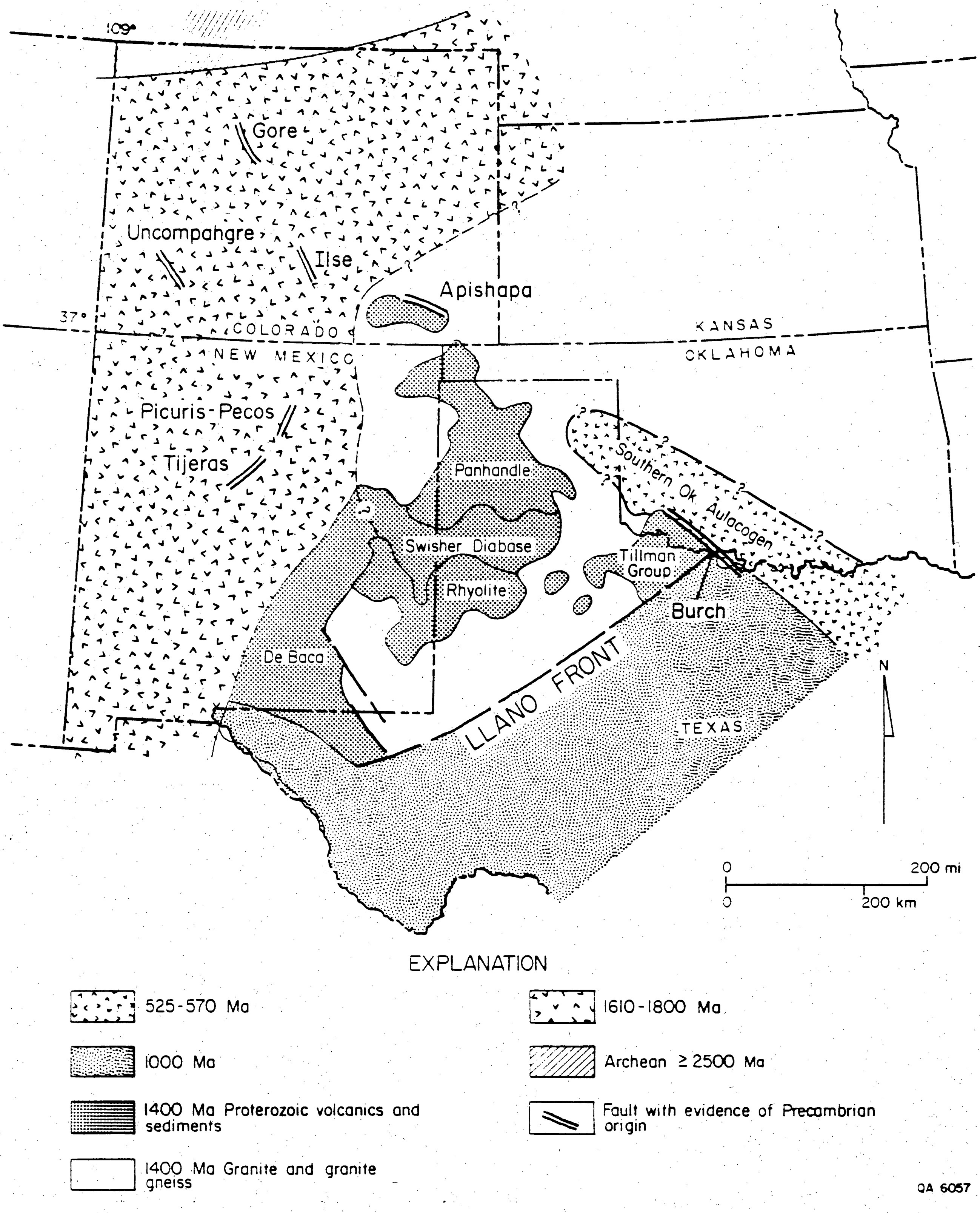

Figure 5. Distribution of basement terranes in the southwestern United States (Flawn, 1956; Foster and Stipp, 1961; Miller and others, 1963; Muehlberger and Denison, 1964; Muehlberger and others, 1966, 1967; Denison and Hetherington, 1969; Baars, 1976; Lisenbee and others, 1979; Tweto, 1980b, 1983; Condie, 1981). The named faults are reported to have been active during the Proterozoic. Igneous activity associated with the opening of the Southern Oklahoma Aulacogen occurred 525 to 570 Ma ago.

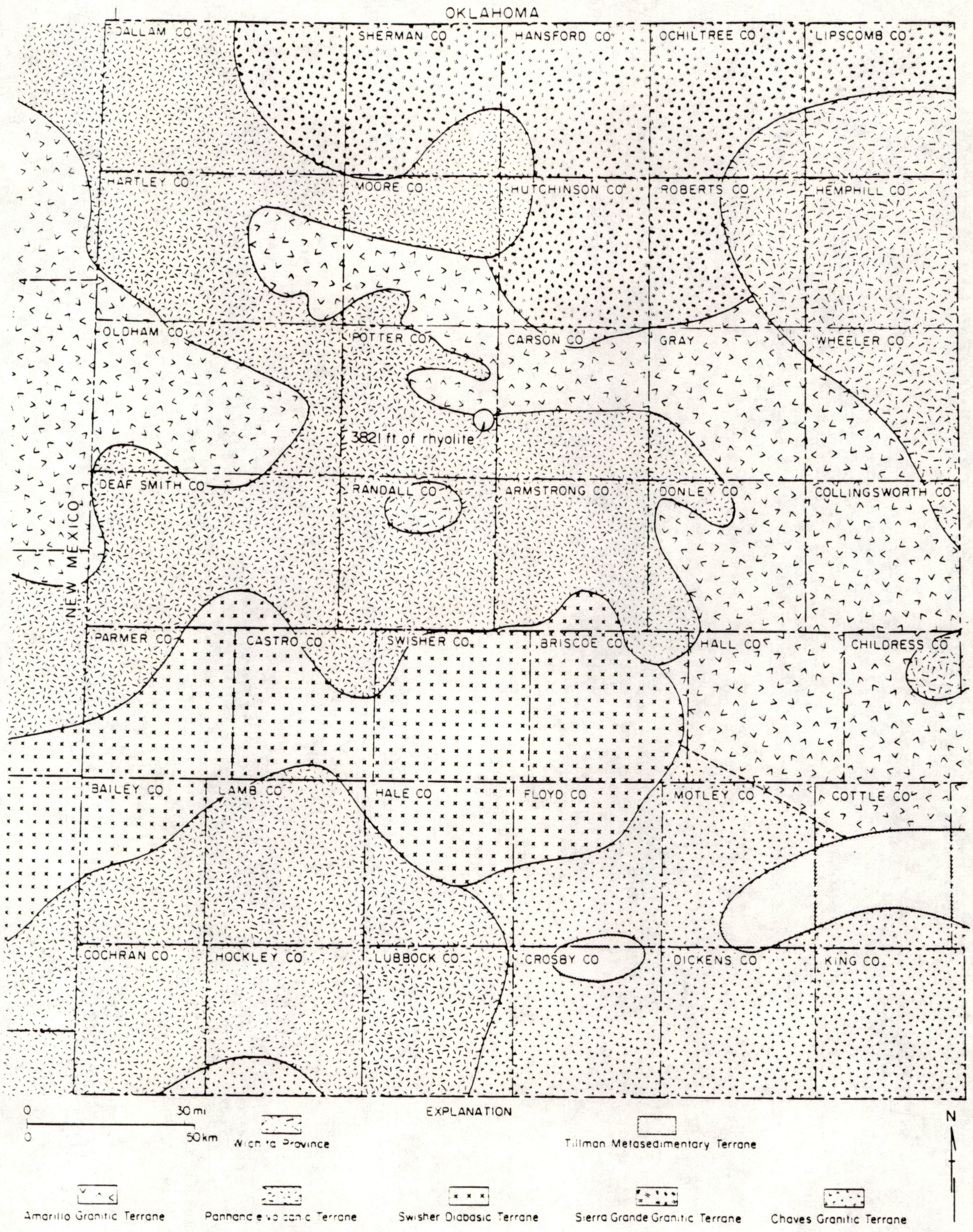

Figure 6. Basement lithologic provinces in the Palo Duro Basin (modified from Muehlberger and others, 1967). Outline of the Palo Duro Basin is indicated by dashed line.

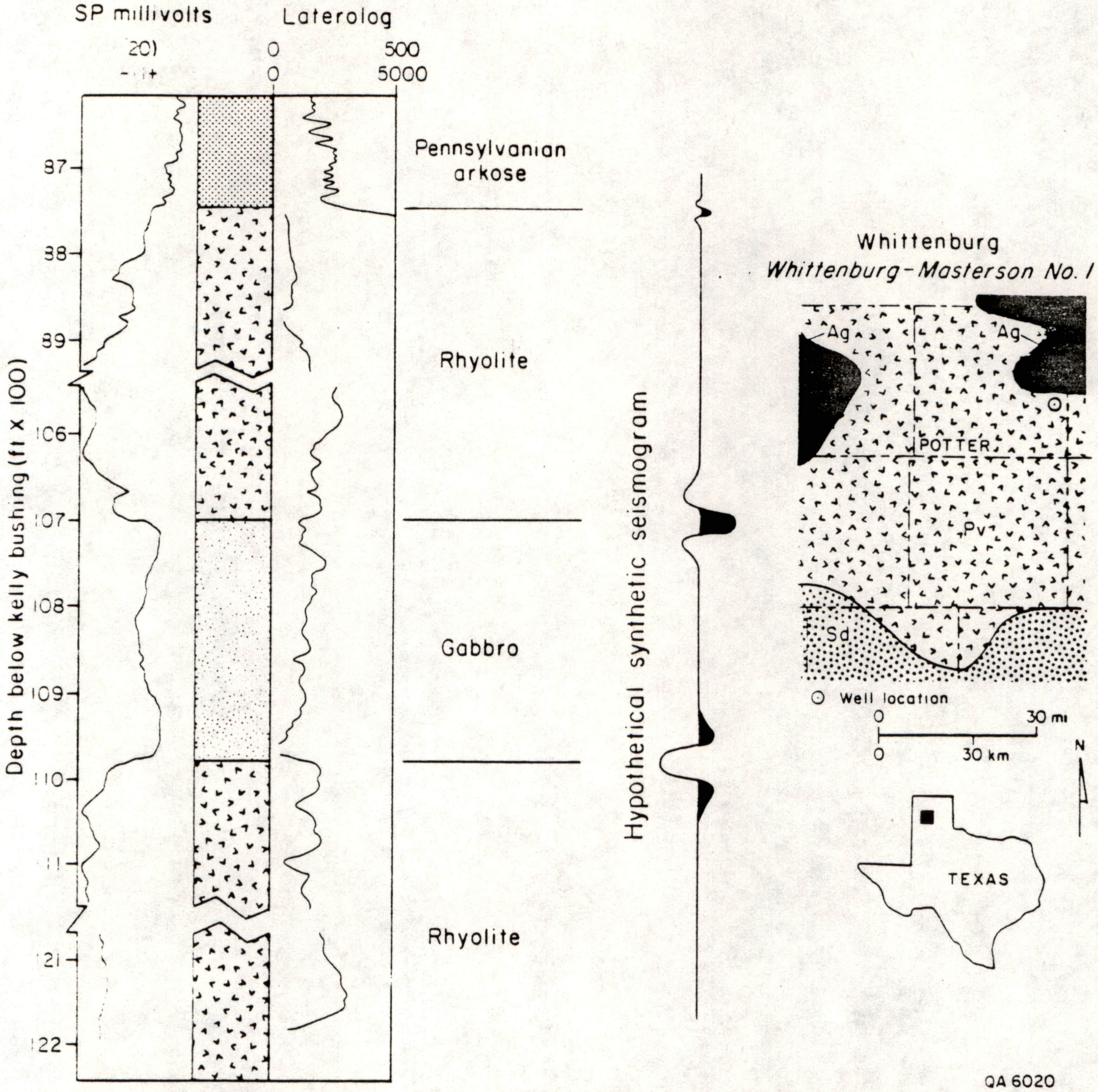

Figure 7. Basement lithologies in the Catherine H. Whittenburg, Whittenburg-Masterson No. 1 well, Potter County. The well was drilled 3,821 ft (1,165 m) into rhyolite of the Panhandle terrane. One gabbro body, 270 ft (82 m) thick, was encountered. The hypothetical synthetic seismogram indicates the expected seismic response from the sequence. Ag - Amarillo Granite terrane; Pv - Panhandle Rhyolite Terrane; Sd - Swisher Diabase Terrane.

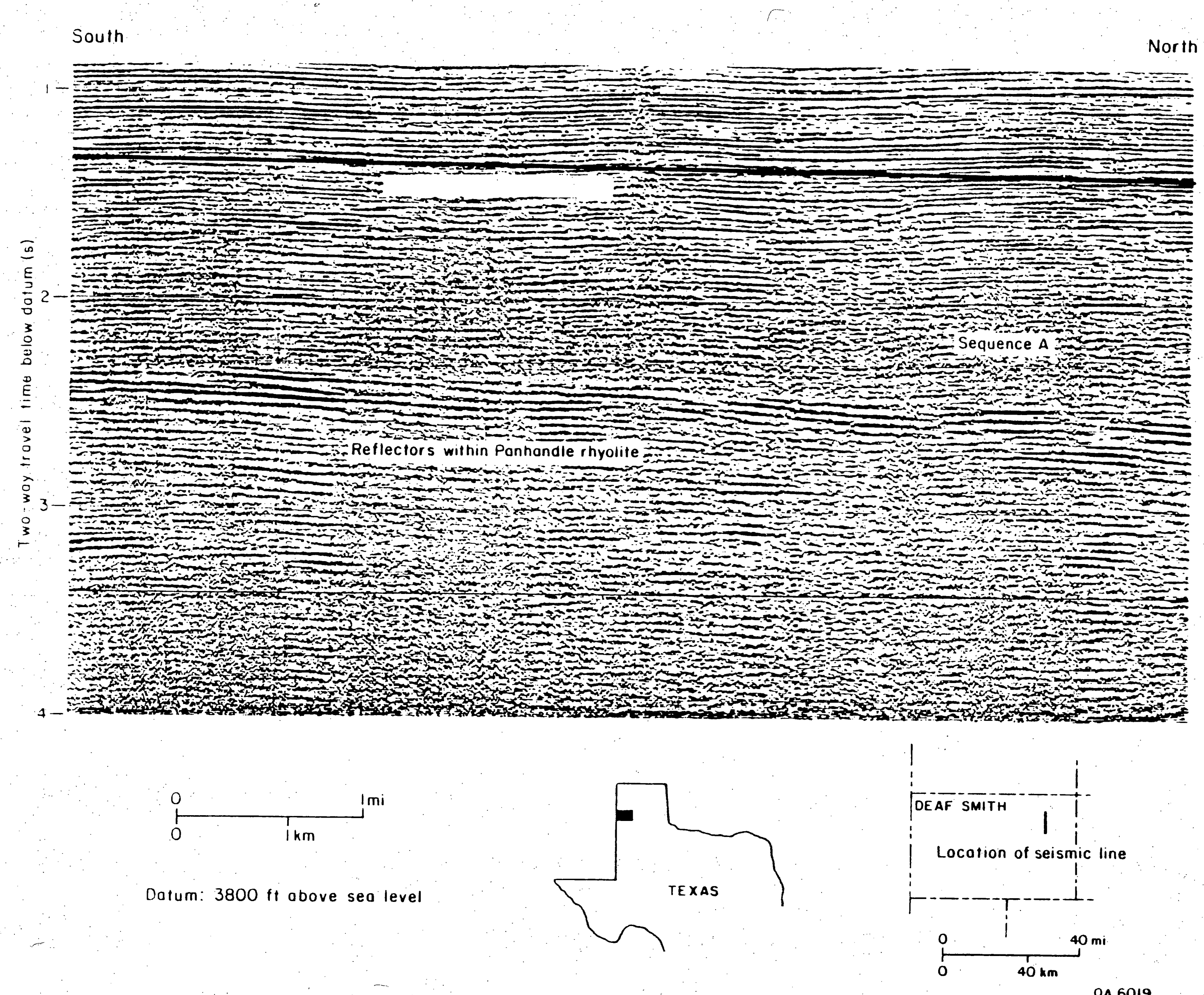

Figure 8. Northern part of seismic reflection profile SWEC-E, Deaf Smith County. Approximate top of basement indicated by dashed line. The prominent reflectors at about 2.5 S two-way travel time are probably caused by a mafic layer within the Panhandle rhyolite. Reflectors have been observed as much as 3.5 s TWTT below the top of basement on other seismic lines in the area. An average interval velocity of 18,000 ft/s (5,500 m/s) has been calculated for the rhyolite from seismic stacking velocities.

may be 1,350 to 1,400 Ma old (Thomas and others, 1984). Van Schmus and Bickford (1981) consider the younger dates to be minimum ages. The older dates are consistent with those obtained elsewhere in the midcontinent, suggesting that the Panhandle rhyolites are part of an extensive volcanic and plutonic province that extends from eastern New Mexico to northwestern Ohio (Van Schmus and Bickford, 1981). This vast belt of approximately 1,380- to 1,480-Ma-old volcanics separates rocks that are 1,600 Ma or older on the north from younger Proterozoic rocks (about 1,100 Ma old) on the south.

In the central part of the Palo Duro Basin the rhyolites are overlain by mafic rocks belonging to the Swisher diabasic sequence (fig. 6). This sequence consists of gabbro and diabase, intercalated with calcareous metasediments (Flawn, 1956). The Swisher sequence is relatively thin; wells drilled near its margin penetrated less than 600 ft (180 m) of mafic rocks before encountering felsic volcanics (fig. 9). Muehlberger and others (1967) correlated the Swisher diabase with the De Baca volcanic sequence in eastern New Mexico, which also consists of diabase and sedimentary rocks.

The age of the Swisher sequence is in dispute. A K-Ar date of 1,200 Ma was obtained from a low-potassium pyroxene in a diabase (Muehlberger and others, 1966). In the Franklin Mountains of West Texas, the correlative De Baca terrane is overlain by 900-Ma-old rhyolites (Muehlberger and others, 1966), suggesting at least a middle Proterozoic age for the Swisher/De Baca terrane. In contrast, Roth (1960) described Paleozoic microfossils from metasediments within the Swisher volcanics. Additional research is needed to resolve the age of the sequence.

There appears to be a coincidence between the geometry of the Palo Duro Basin and the distribution of Proterozoic lithologies in the underlying basement (compare figs. 4 and 6). In general, structurally low areas are underlain by volcanic rocks, whereas high areas are underlain by granitic rocks. A large part of the Palo Duro

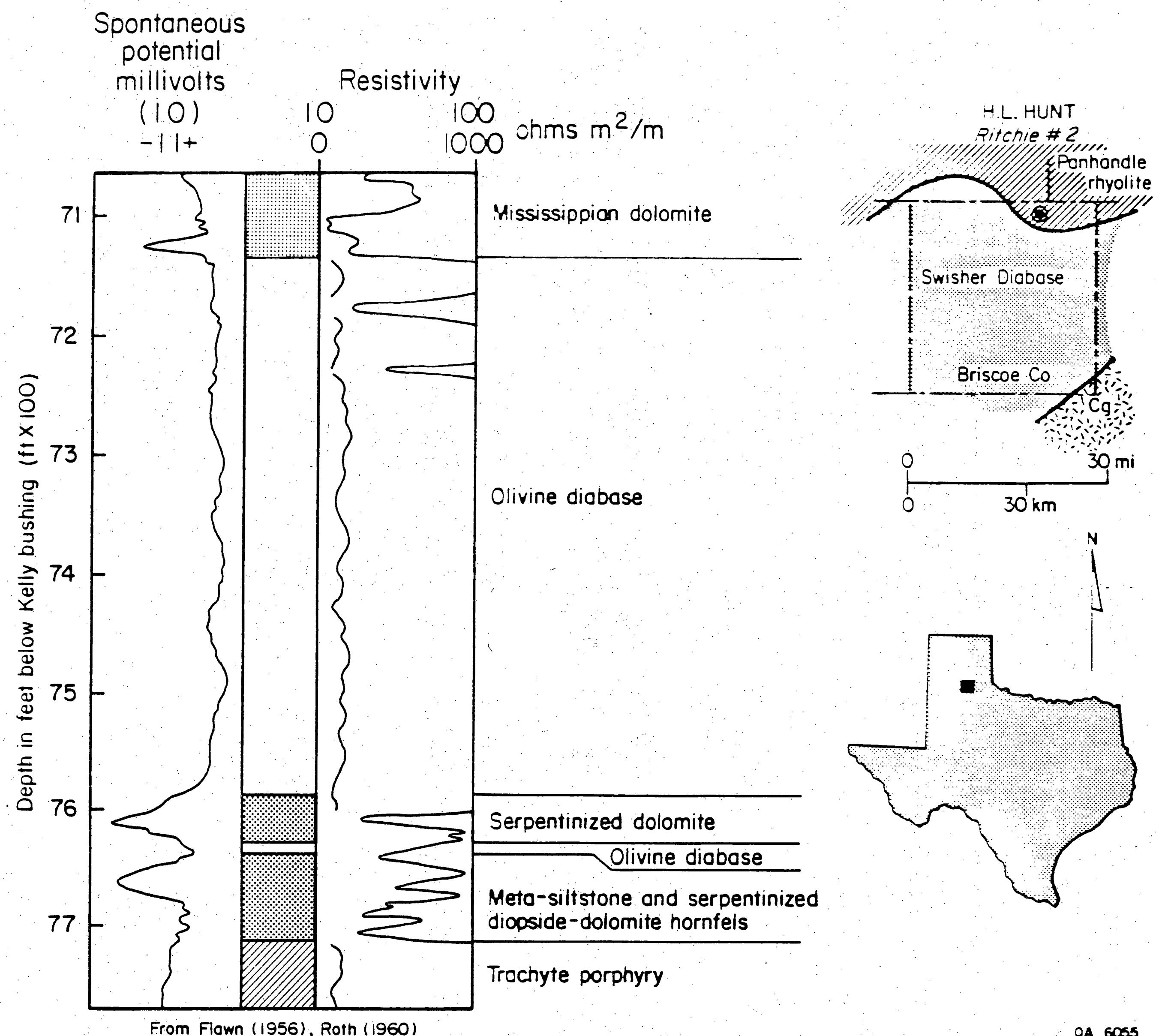

Figure 9. Basement lithologies in the H. L. Hunt Richie No. 2 well, Briscoe County. The well was drilled through diabase and metadolomite of the Swisher terrane and into trachyte of the Panhandle terrane.

Basin, as well as the Whittenburg Trough, is underlain by the Panhandle rhyolite or by rocks of the overlying Swisher sequence. The shallower, eastern part of the Palo Duro Basin, the Bravo Dome, and most of the Amarillo Uplift are underlain by granitic rocks. In several places (for example, along the northeastern side of the Bravo Dome and along the southwestern side of the Amarillo Uplift) contacts between basement lithologies coincide with faults, located on the basis of structural mapping of the basement surface (fig. 4). The rhyolites may have once covered the entire region but they eroded from structurally high areas prior to deposition of the overlying Arbuckle/Ellenburger Group. These upper Cambrian to lower Ordovician carbonates lie on granite on the Amarillo Uplift and on rhyolite in the Palo Duro Basin, suggesting that uplift and erosion of the volcanics took place prior to the late Cambrian.

An early phase of deformation in the Palo Duro Basin is also indicated by the arkosic sandstone and tuff that overlie the Swisher diabase in the Castro Trough. The clastics, which are approximately 100 ft (30 m) thick in the Sun Oil Company Herring No. 1 well (fig. 10; Roth, 1960), underlie a basal Cambrian(?) quartzose sandstone. The arkose may have been derived from the Panhandle rhyolite, present in the Arney positive to the northeast of the trough, during active faulting in the late Proterozoic or earliest Phanerozoic. The source of the tuff is unknown but may be related to the middle Cambrian volcanics (Gilbert, 1983) currently exposed in the Wichita Mountains to the east.

Early to Middle Paleozoic Deformation

A stable shelf occupied the area of the Palo Duro Basin during the early Paleozoic. Basal Cambrian(?) quartzose sandstones are overlain by carbonates of the Ellenburger Group (late Cambrian to early Ordovician; Ruppel, 1985). Sometime

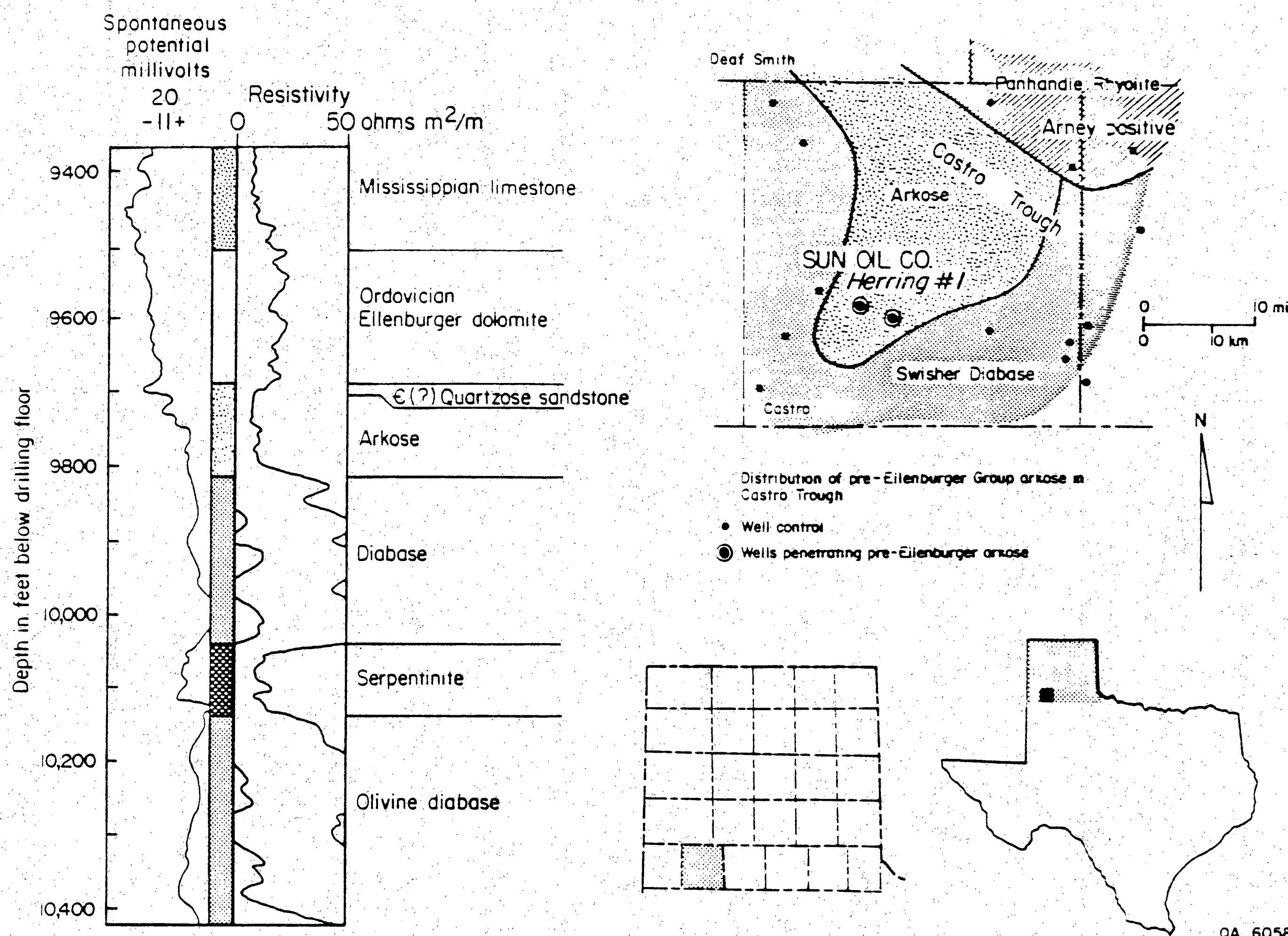

Figure 10. Basement lithologies in Castro County and in the Sun Oil Company Herring No. 1 well. Diabase of the Swisher terrane is overlain by a pre-Cambrian(?) quartzose sandstone. The arkose, which is projected to have been preserved in the Castro Trough, may have been derived from the Panhandle rhyolite in the northeastern part of the county.

between the middle Ordovician and early Mississippian, a northwest-trending area in the central Panhandle was uplifted to form the Texas Arch (fig. 11; Adams, 1954). Ellenburger Group carbonates and Cambrian(?) clastics eroded from the crest of the arch (Ruppel, 1985), except where preserved in downfaulted blocks such as the Castro Trough (Budnik, 1983). Silurian and Devonian sediments are present on the northeastern flank (Hardeman Basin; fig. 12a) and southwestern flank (Midland Basin) of the arch but are absent from the crest owing to erosion or nondeposition (Adams, 1954). Precise timing of uplift and accompanying faulting is unknown. However, on the eastern flank of the arch, in the Hollis Basin, units as young as early Devonian (Hunton Group) are unconformably overlain by upper Devonian and lower Mississippian strata (Tarr and others, 1965), suggesting a middle Devonian age of deformation (Eddleman, 1961; Ham and Wilson, 1967). The east side of the arch, in Armstrong, Briscoe, Hall, and Motley Counties, coincides with the boundary between volcanic and plutonic basement terranes (compare figs. 6 and 11), suggesting a reactivation of pre-Ordovician (Proterozoic?) structures in this area.

During the Mississippian, the southern Panhandle was again the site of a carbonate platform with shallow-water carbonate (now dolomite) deposited on the Texas Arch, and relatively deeper water limestone deposited on the flanks of the arch (Ruppel, 1985). Carbonate deposition was interrupted briefly during the late Mississippian by an influx of clastics (Totten, 1956; Ruppel, 1985), which was possibly in response to initial uplift of the Ancestral Rocky Mountains (Budnik and Smith, 1982).

Pennsylvanian to Early Permian Deformation

During the Pennsylvanian Period, the Palo Duro Basin underwent three pulses of deformation (Ham and Wilson, 1967). Initially, the northern end of the Texas Arch

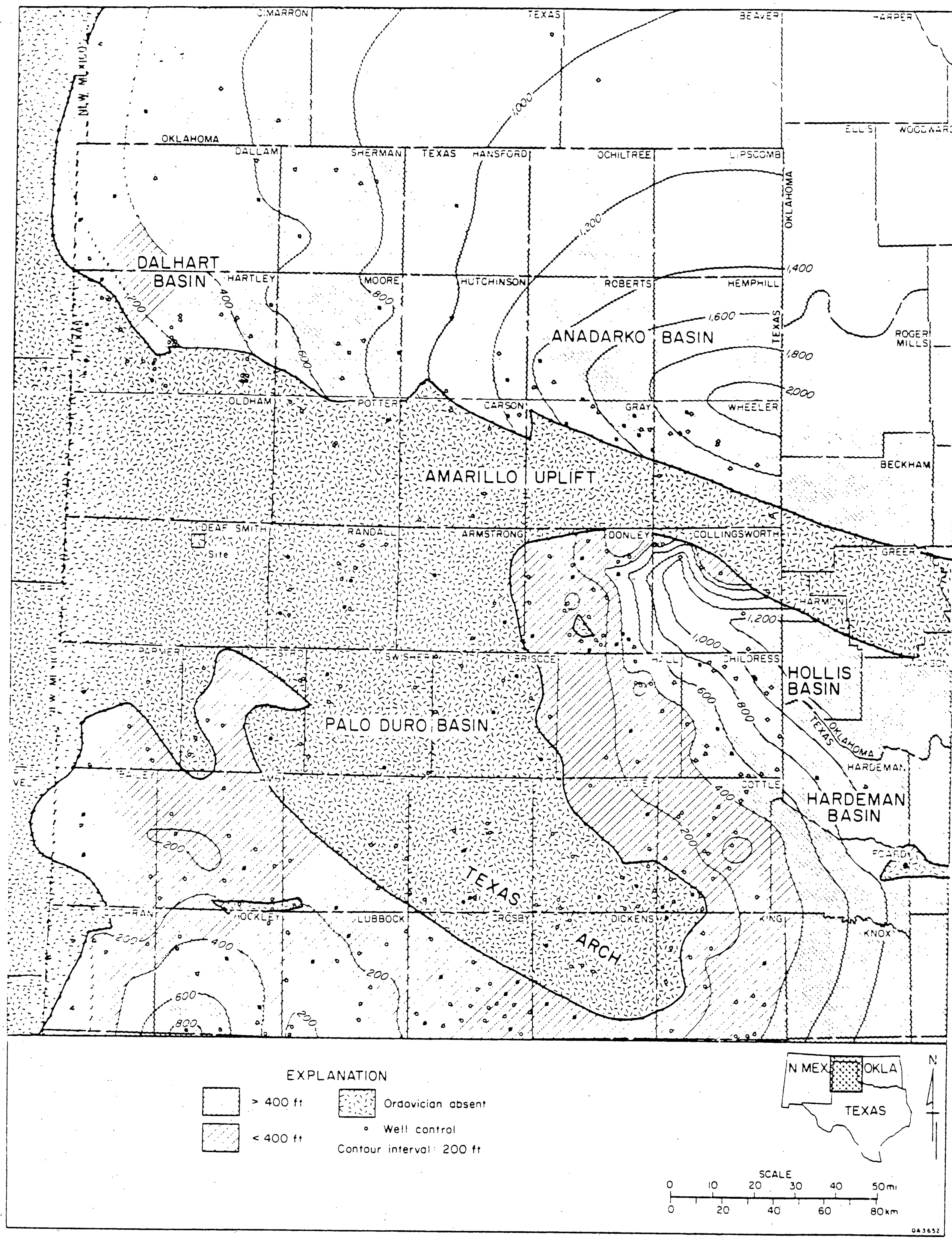

Figure 11. Isopach map of the Ellenburger Group, Palo Duro Basin (modified from Ruppel, 1985).

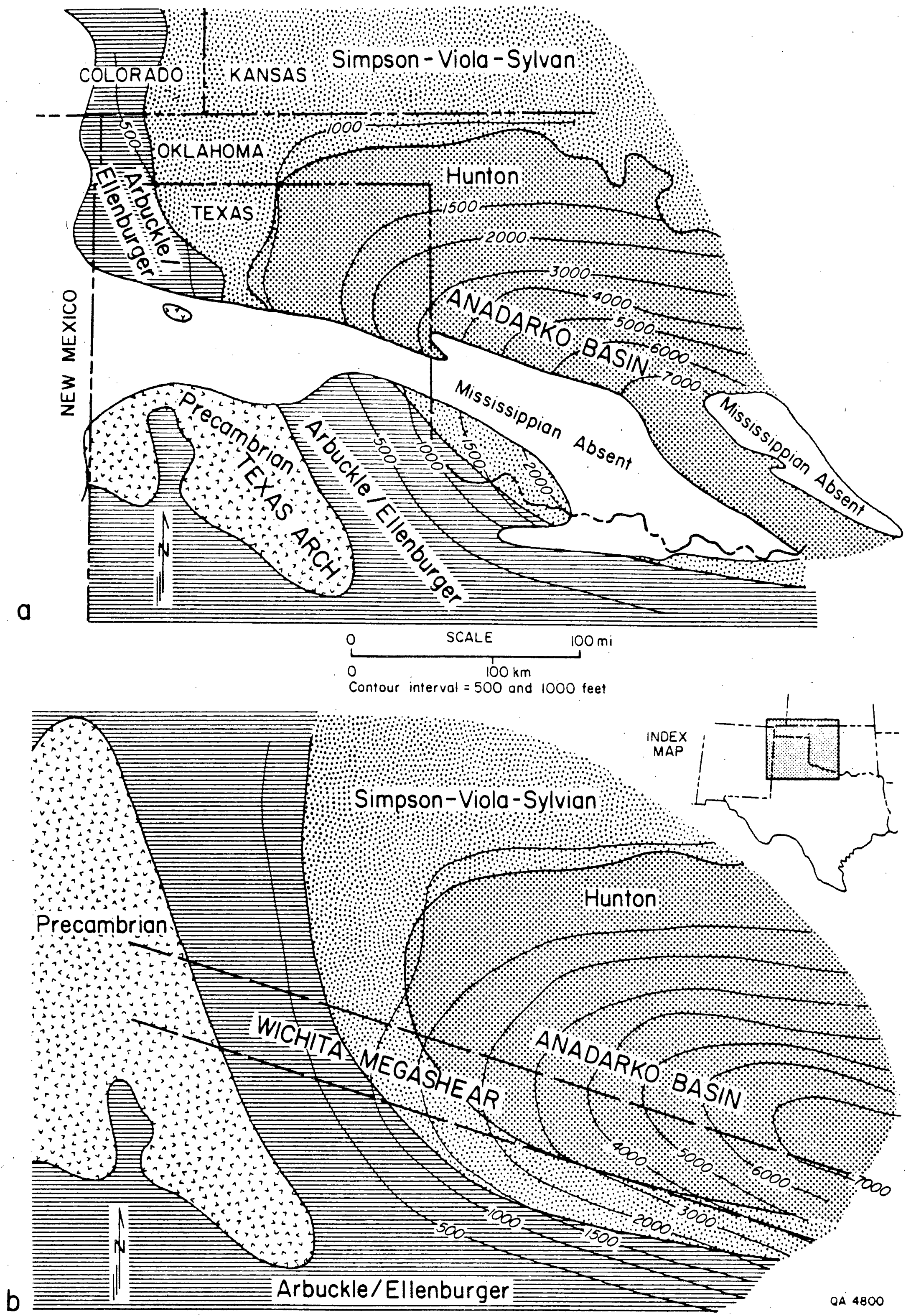

Figure 12. Upper Devonian/Mississippian subcrop and isopach map of the Arbuckle/Ellenburger Group (Maxwell, 1959; Bradfield, 1968; Panhandle Geological Society, 1969; Amsden, 1975, 1980). Contours in feet, contour interval: 500 and 1,000 ft. (a) Present configuration. Lower Devonian and older strata were downwarped into the Anadarko Basin prior to development of the regional middle Devonian unconformity. (b) Palinspastic reconstruction prior to Pennsylvanian faulting. A total of 75 mi (120 km) of left-lateral offset has been removed from the Amarillo Uplift.

was uplifted, tilting the Mississippian carbonate shelf to the south. During this phase, Mississippian and older strata eroded from a wide, east-west-trending band to the north of the present structural basin (fig. 12a), while lower Pennsylvanian (Morrowan) sediments deposited primarily in the southern part of the basin and in the Hardeman Basin to the east (Budnik and Smith, 1982).

The second and main period of deformation occurred during the middle Pennsylvanian (Desmoinesian; Dutton, 1982; Goldstein, 1982) Ancestral Rocky Mountain orogeny. It was during this time that the Amarillo Uplift and related structures formed as a result of left-lateral strike-slip faulting (see discussion under "Tectonic evolution of the Wichita megashear"). Most of the arkosic debris that shed to the south from the Amarillo Uplift was trapped in the Whittenburg Trough and in the Hollis Basin, although some of the clastics reached the Palo Duro Basin through lows in the Oldham-Harmon trend (fig. 13). Abrupt thickness changes exhibited by Desmoinesian sediments indicate that intrabasinal structures (for example, the Castro Trough) probably reached their greatest relief at this time. By the end of the Desmoinesian, bathymetric relief had been reduced and a carbonate shelf covered most of the area (fig. 14; Dutton, 1982).

During the third phase of deformation, in the late Pennsylvanian, the region was differentiated into a well-defined depositional basin as a result of rejuvenation of basement structures. Carbonate-shelf-margin complexes and basinal shale deposition were dominant during this period (Dutton, 1982). Carbonate buildups were localized on structurally high blocks, such as the central Randall high, within the basin, and along the Oldham-Harmon trend and the Matador Arch (fig. 15; Budnik and Smith, 1982). Subtle movement of basement structures throughout the late Pennsylvanian and earliest Permian (Wolfcampian) maintained these highstanding areas. This phase of deformation culminated with erosion or nondeposition, or both, of upper Pennsylvanian

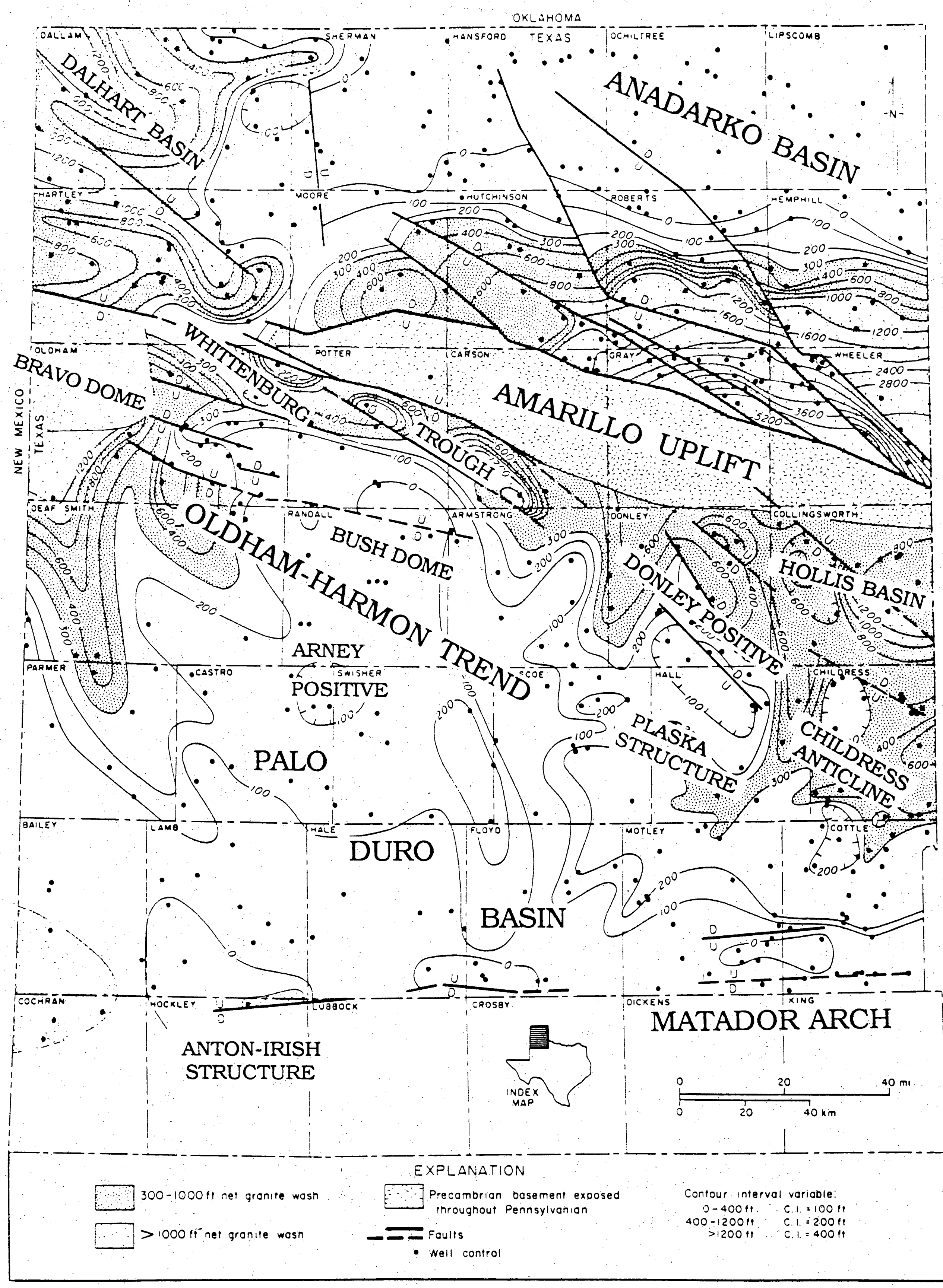

Figure 13. Isolith map of arkosic sediments in the Pennsylvanian and Wolfcampian of the Texas Panhandle (Dutton, 1982). Toward the south, sediments derived from the Amarillo Uplift were trapped within the Whittenburg Trough and the Hollis Basin.

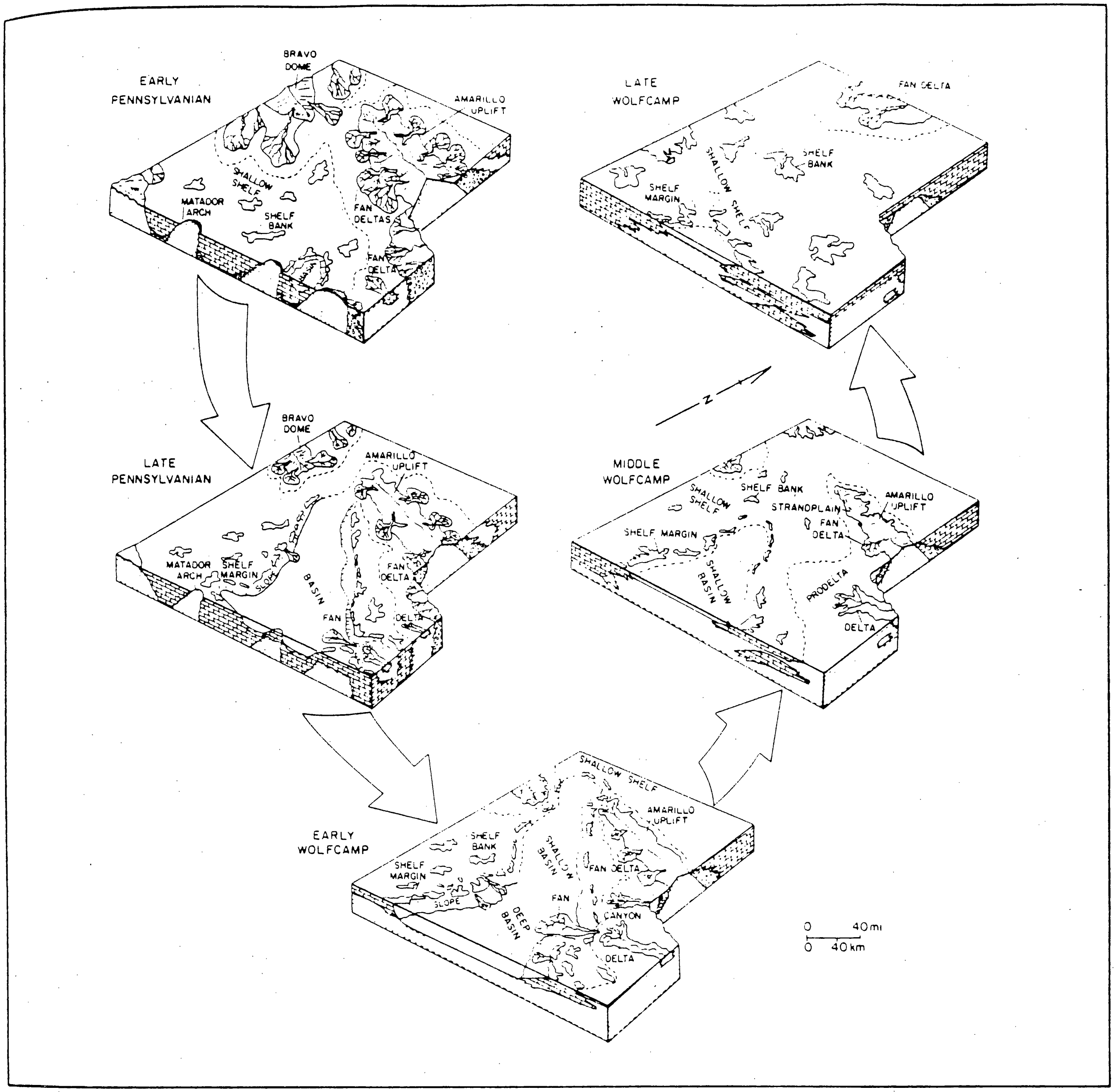

Figure 14. Block diagrams of paleogeographic evolution of the Palo Duro Basin during the Pennsylvanian and early Permian (Handford and Dutton, 1980). A well-defined depositional basin did not develop until the late Pennsylvanian.

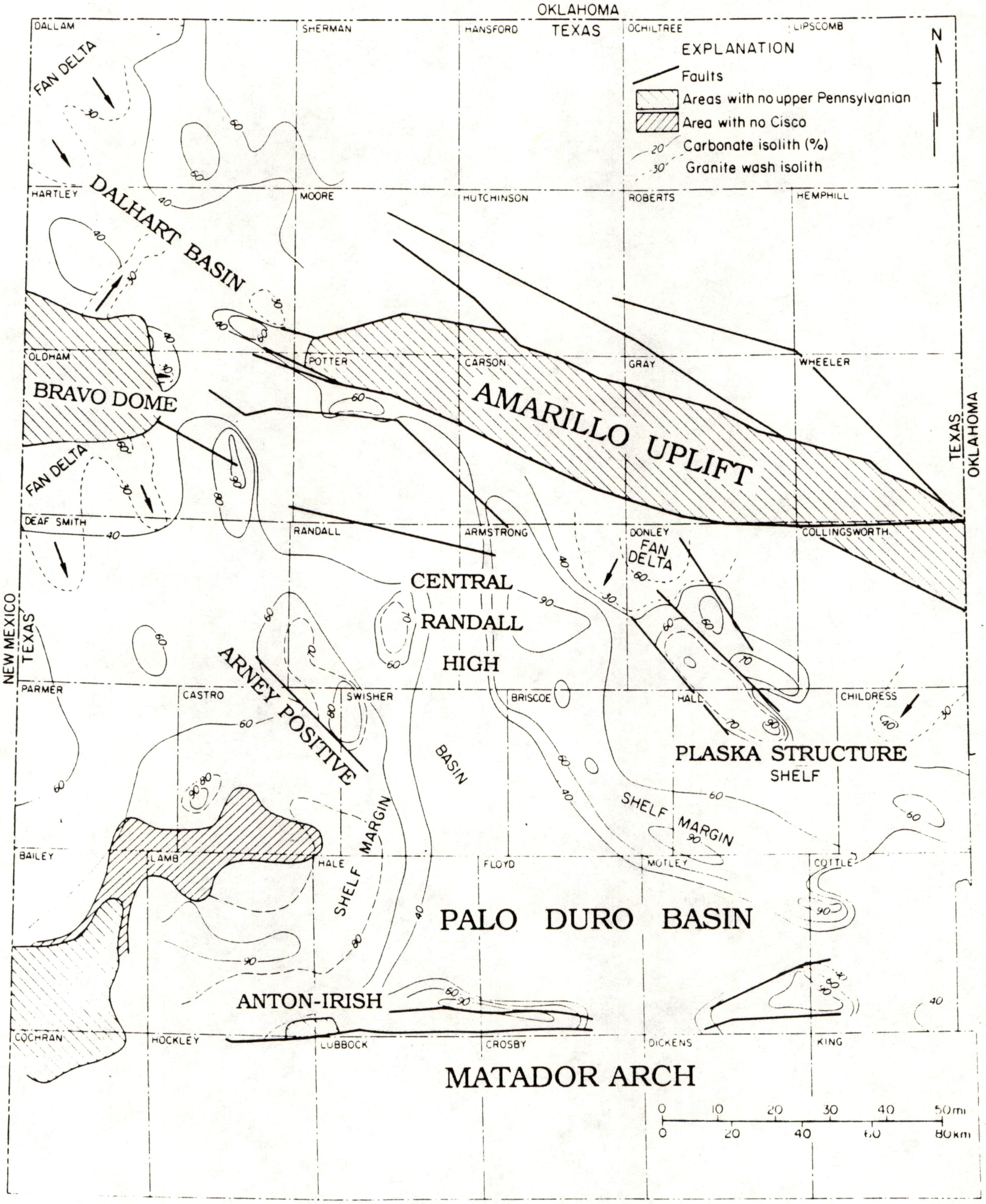

Figure 15. Isolith map of carbonate in the upper Pennsylvanian of the Palo Duro Basin (Budnik and Smith, 1982). Carbonate buildups are concentrated on structurally high areas, such as the Arney positive in northeastern Castro County.

(Virgilian, Cisco Series) deposits on structures in the southwestern part of the basin (Budnik and Smith, 1982), on the Amarillo Uplift, and on the Anton-Irish structure before deposition of the Wolfcamp Series (fig. 15). The pre-Permian isopach map (fig. 16) delineates a strong northwest-southeast trend to the axis of the basin at the end of the Pennsylvanian.

Permian Basin

The end of the Wolfcampian was a time of profound change in patterns of deformation and deposition in the Palo Duro Basin. During the Pennsylvanian and early Permian, relatively high local topographic relief existed within a well-defined normal-marine depositional basin. These conditions changed, however, near the end of the Wolfcampian, when the marine shelf margin and basin systems were replaced by a widespread carbonate shelf (Dutton, 1982). The basin axis shifted from northwest- to north-northwest-trending (compare figs. 16 and 17) during the early Permian. Deposition during the remainder of the Permian, primarily of evaporites and red beds, was controlled by regional subsidence associated with the larger Permian Basin (fig. 1). Distinction between the Palo Duro and surrounding depositional basins was reduced as a result of subsidence below sea level of the intervening uplifts (Goldstein, 1984).

Pennsylvanian structures continued to subtly influence depositional patterns during the middle and late Permian. These deposits thin over structural highs in the basin (the central Randall high, the Arney positive, and the Illusion Lake structure) and along the Matador Arch (fig. 18). The relationship between thickness and structure has been obscured by salt dissolution along the Oldham-Harmon trend. A correspondence between basement lows and areas of thick clastics in the middle

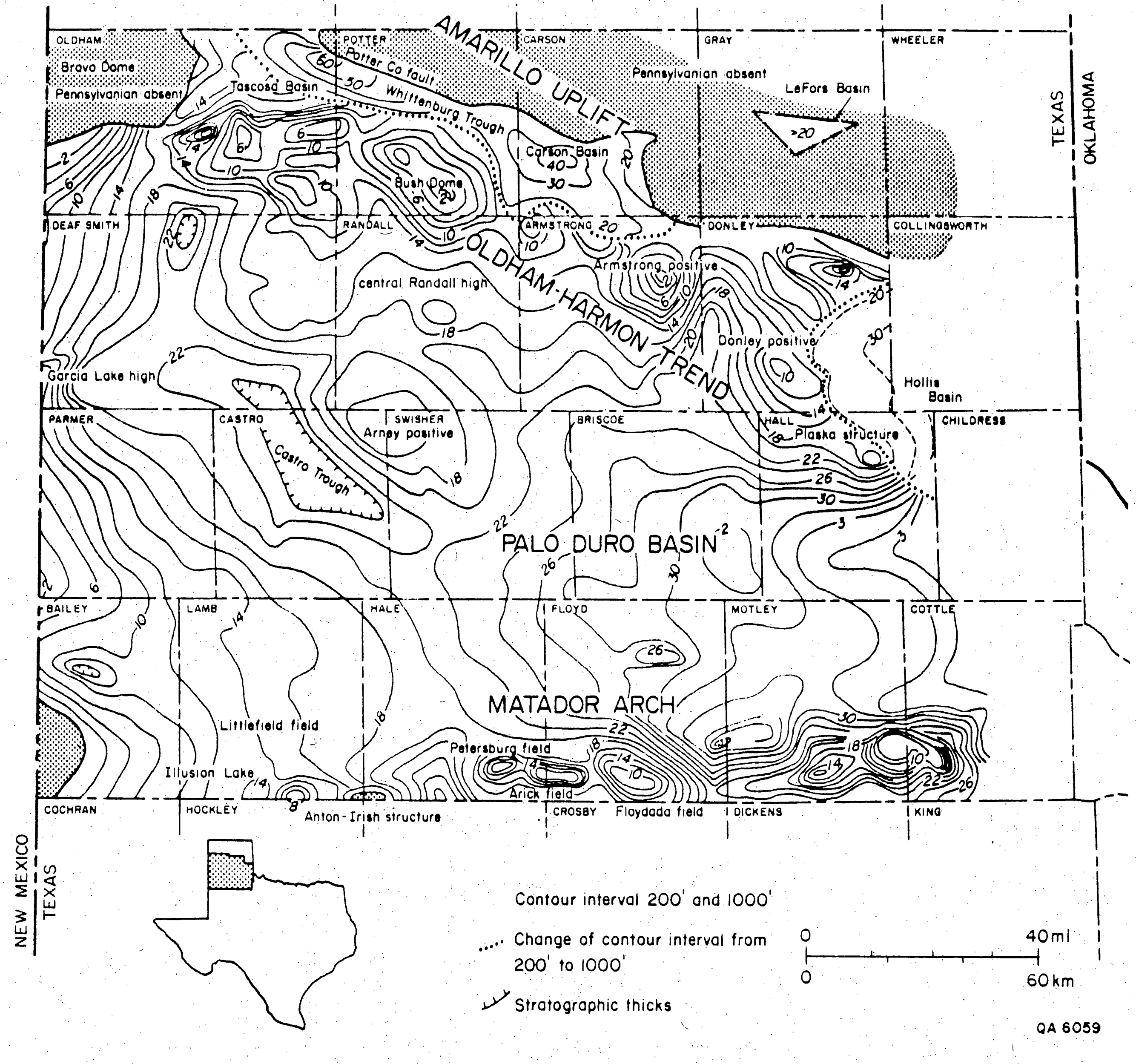

Figure 16. Pre-Permian isopach map of the Palo Duro Basin. Interval included is from the top of basement to the base of the Permian, but consists primarily of Pennsylvanian strata. The thickest deposits occur in the southeastern part of the basin, and in the Castro Trough.

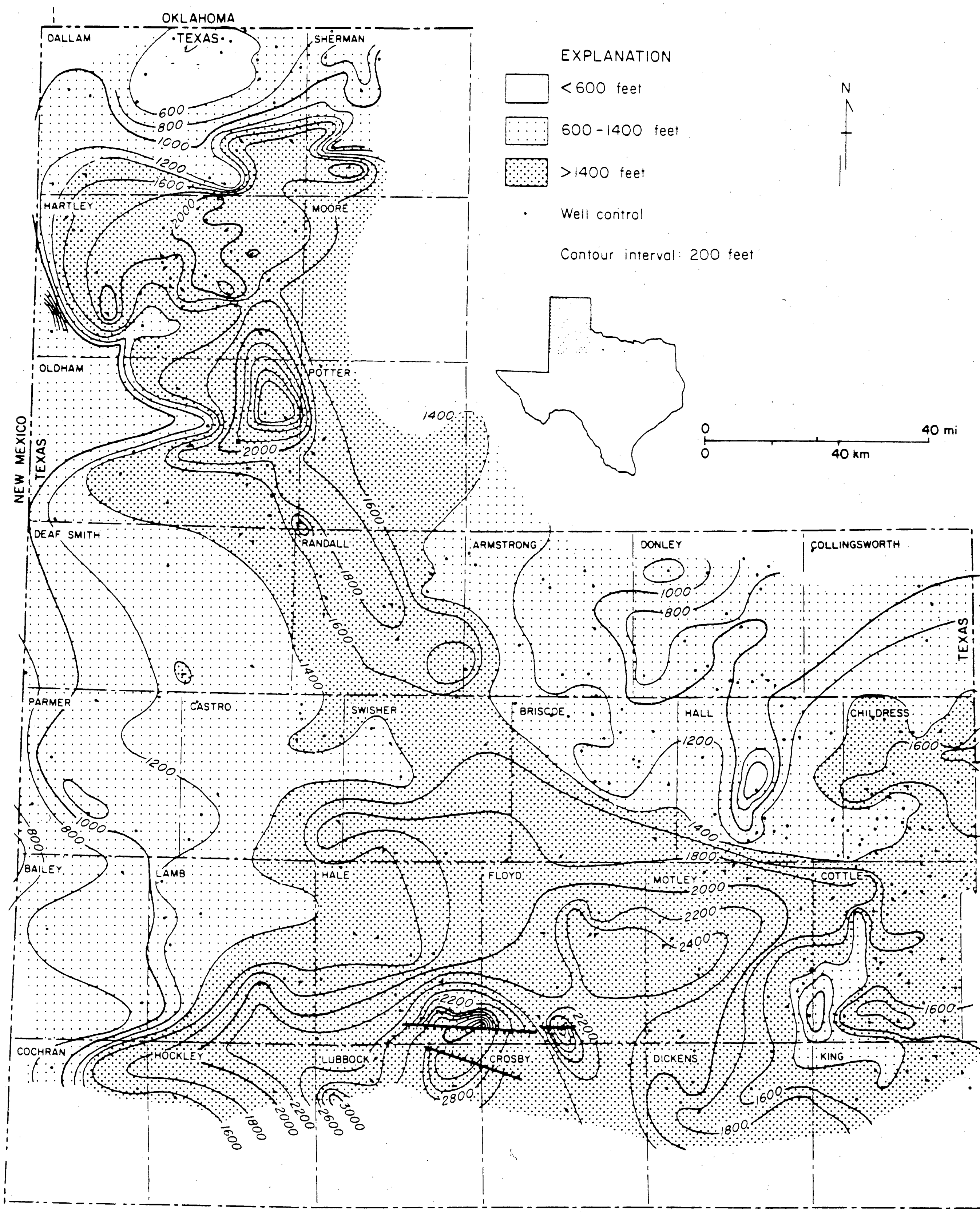

Figure 17. Isopach map of the Wolfcampian Series, Palo Duro Basin (Dutton, 1982). The basin axis, as defined by the thickest deposits, trends more north-northwesterly than that of the underlying Pennsylvanian.

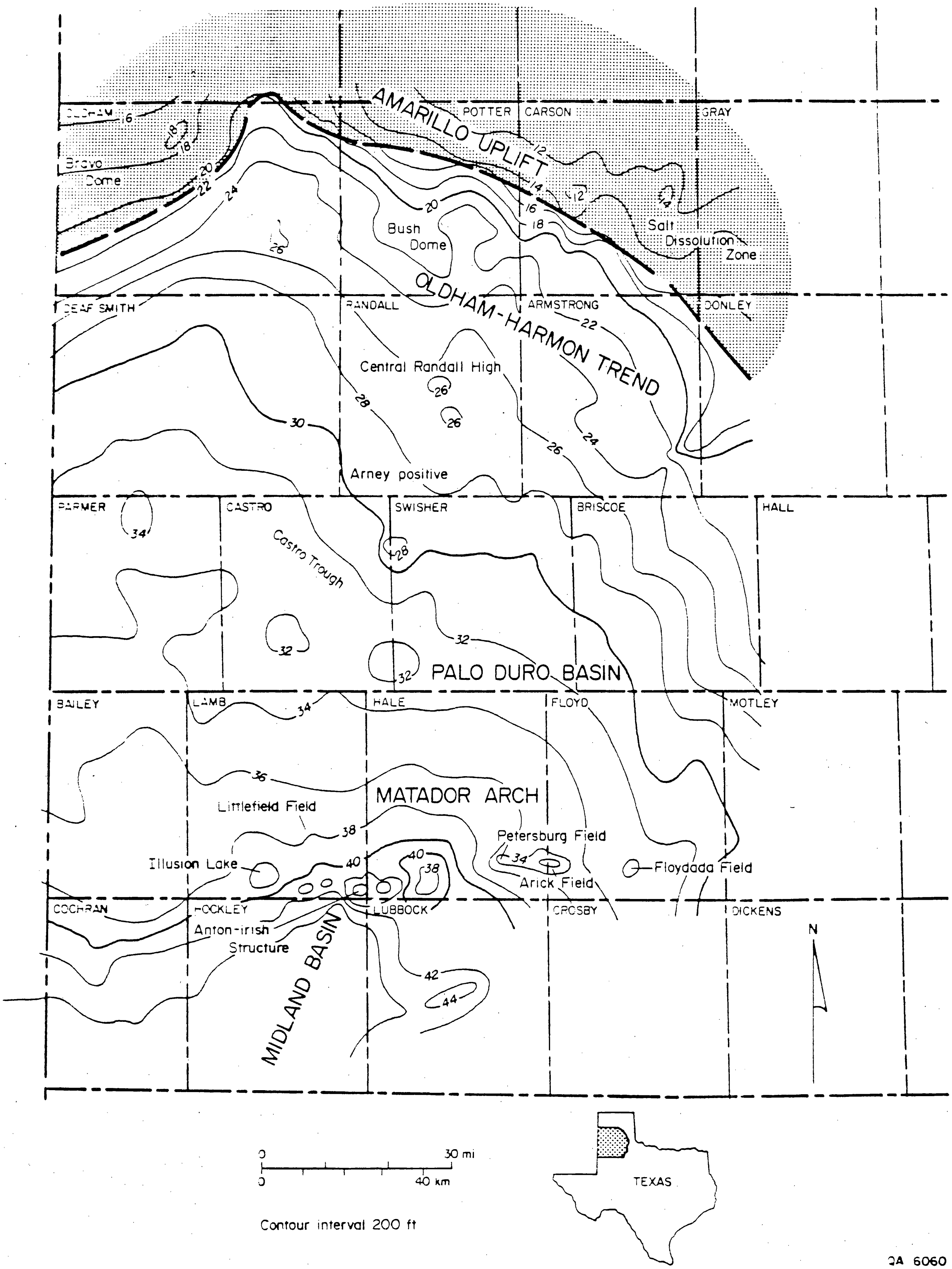

Figure 18. Isopach map of the middle and upper Permian, Palo Duro Basin. Interval mapped is from the top of the Tubb Formation (Leonardian) to the top of the Alibates Formation (Ochoan).

Permian Glorieta Formation was noted by Presley and McGillis (1982) and in the upper Permian Salado/Tansill Formations by McGillis and Presley (1981). Structural influence continued through the end of the Permian, as is suggested by the thinning of the Alibates Formation over the Arney positive and the Littlefield and Illusion Lake structures (McGillis and Presley, 1981).

The relationship between thickness of Permian strata and basement structure is probably the result of recurrent movement on the older structures, not merely the effect of differential compaction. The best evidence of this is the episodic influence of structures on depositional patterns. For example, the lower and upper salt-bearing intervals of the middle Permian San Andres Formation thin over structural highs, whereas the middle, non-salt-bearing interval shows no correspondence between structure and thickness (Fracasso and Hovorka, 1984). The change in lithology and coincident change in effect of local structure on thickness suggest that there may have been a large-scale but subtle tectonic influence on depositional patterns in the San Andres. In addition to the influence of local structure on the thickness of Permian strata, a change in regional subsidence patterns occurred. A progressive shift to the southwest of the axis of thickest sediment accumulation is evident from a comparison of isopach maps of the pre-Permian, Wolfcampian, and upper Leonardian through Ochoan (figs. 16, 17, and 18).

The Palo Duro Basin has been deformed since the Paleozoic, as indicated by the folding of the Alibates Formation (uppermost Permian) over structures within the basin and over elements of the Amarillo Uplift to the north and the Matador Arch to the south (fig. 19; Budnik, 1984). For example, there has been more than 200 ft (60 m) of differential uplift of blocks along the Matador Arch since the Permian (Budnik, 1984). Folding of the Alibates Formation at Palo Duro Canyon took place

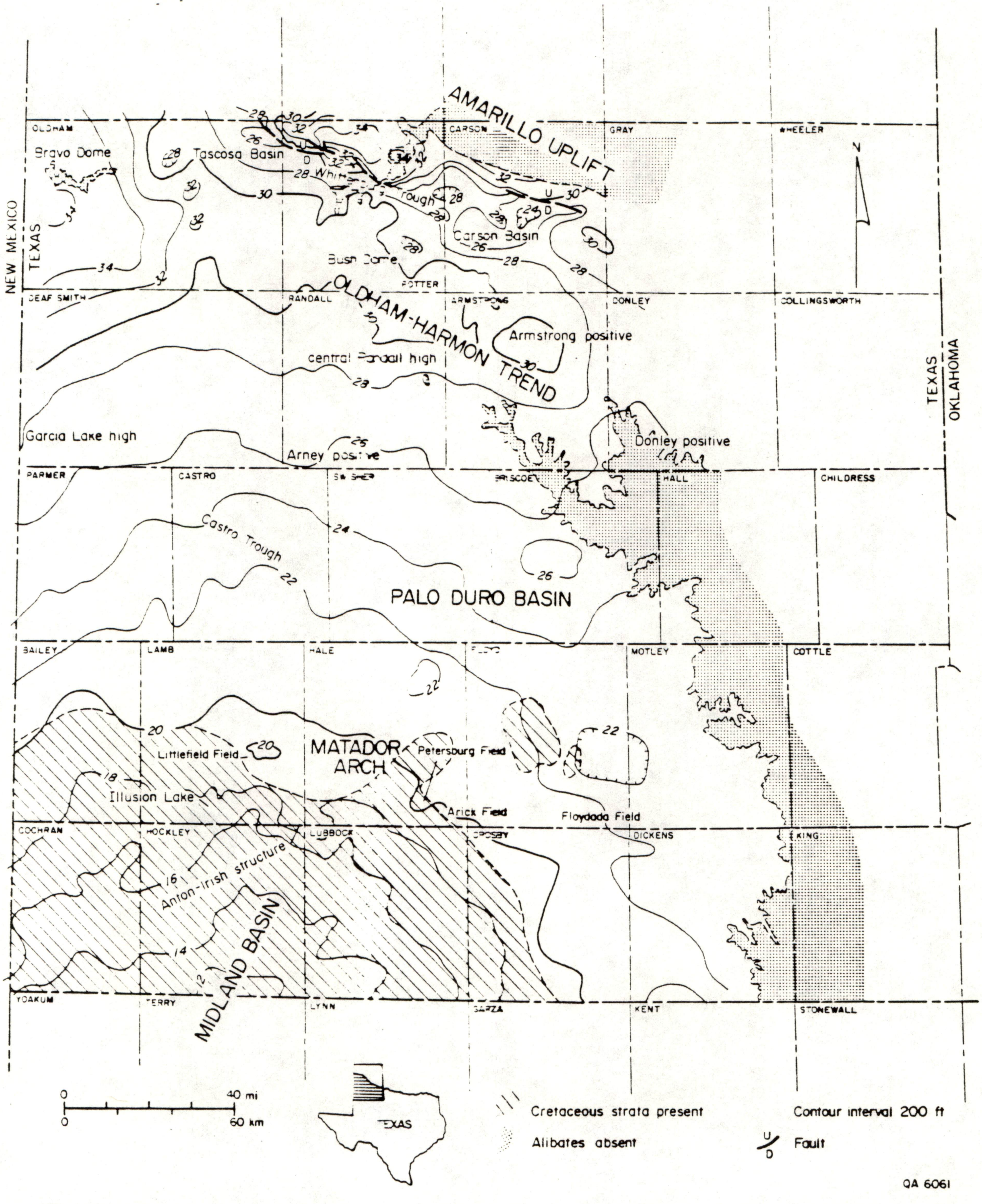

Figure 19. Structure-contour map on the top of the Alibates Formation, Palo Duro Basin. Distribution of Cretaceous strata from Seni (1980) and Knowles and others (1982).

prior to deposition of the Dockum Group in the late Triassic (Collins, 1984). However, along the western part of the Amarillo Uplift, folding of the Alibates Formation occurred during deposition of the lower part of the Miocene Ogallala Formation (see discussion under "Cenozoic deposition and deformation").

Structural Controls on Triassic Deposition

During the late Triassic, depositional patterns were influenced by some of the same basement structures that affected Permian and earlier deposition. Regionally, the Dockum Group is primarily of lacustrine origin within the center of the Permian Basin, whereas fluvial/deltaic deposits are more common around the margins (McGowen and others, 1979), indicating that regional subsidence continued to be the dominant structural influence in the area into the Triassic. Local structures (for example, the Castro Trough) appear to have influenced the distribution of sand in the lower Dockum Group (Budnik, 1984). Johns (1985) also noted that thick accumulations of sand in the Dockum Group occupy structurally low areas along the Matador Arch and elsewhere in the basin. Patton (1923) reported intraformational angular unconformities within the Dockum Group on the northern flank of Bush Dome, suggesting that elements of the Oldham-Harmon trend were undergoing active deformation during the late Triassic.

Structural Influence on Cretaceous Deposition

Cretaceous strata are absent from all but the southernmost (fig. 19) and northwesternmost parts of the Panhandle as a result of erosion or nondeposition. Sufficient data are not available to determine if sediments were deposited elsewhere in the basin and later eroded or if the present distribution approximates the original extent of the deposits. The Panhandle may have been the site of a stable shallow shelf during the Cretaceous, with the shoreline to the northwest and deeper water to the southeast (Scott, 1977). Lower Cretaceous (Aptian through lower Cenomanian) marine strata onlap Triassic and older units northwestward of the Gulf Coast toward the Texas Panhandle (Adkins, 1932). Northwest of the Palo Duro Basin, in northeastern New Mexico and adjacent areas, lower and upper Cretaceous (upper Albian to Campanian) fluvial/deltaic clastics overlie Jurassic nonmarine clastics (Kauffman, 1977).

Lower Cretaceous units are preserved beneath the Ogallala Formation in Hale, Lamb, and Floyd Counties along the structural axis of the Palo Duro Basin (fig. 19; Budnik, 1984). Cretaceous strata are absent from the Petersburg structure, part of the Matador Arch (fig. 19) that may have been a topographic high during the early Cretaceous or was uplifted, or both, and the Cretaceous strata eroded prior to deposition of the Ogallala Formation in the late Tertiary.

Cenozoic Deposition and Deformation

During the late Miocene and early Pliocene, the western Great Plains, including the Texas Panhandle, was the site of deposition of the Ogallala Formation, a vast alluvial apron that spread eastward from uplifts along the Rio Grande rift in central New Mexico and Colorado (fig. 20; Schultz, 1977; Seni, 1980). Deposition of the Ogallala Formation in Texas was initiated during the late Miocene (Clarendonian, approximately 10 Ma ago) based on vertebrate fossil data (Schultz, 1977; Winkler, 1985). Ogallala deposition ended during the late Miocene to early Pliocene (Hemphillian, 4 to 5 Ma ago; Izett, 1975). Isotopic ages of 4.7 and 6.6 Ma were

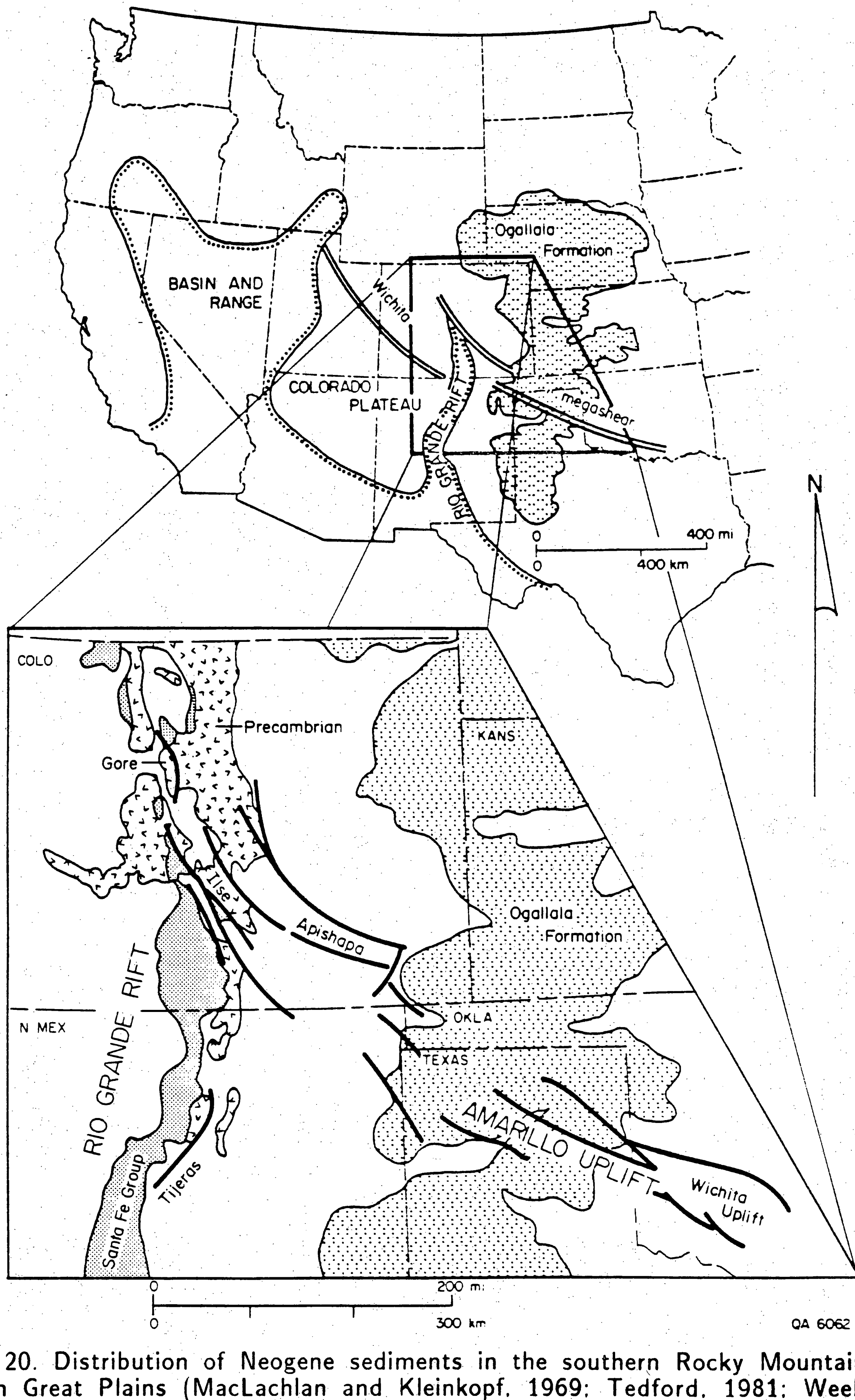

Figure 20. Distribution of Neogene sediments in the southern Rocky Mountains and western Great Plains (MacLachlan and Kleinkopf, 1969; Tedford, 1981; Weeks and Gutentag, 1981). BR - Basin and Range province; CP - Colorado Plateau; RGR - Rio Grande rift; Og - Ogallala Formation. The Santa Fe Group fills the Rio Grande rift.

obtained from an ash bed near the top of the Ogallala Formation in Hemphill County, Texas (Izett, 1975). Basalt flows dated 2 to 3 Ma old occupy stream valleys that eroded into the Ogallala in northeastern New Mexico (Stormer, 1972). In the Texas Panhandle, the Ogallala is locally overlain by Blancan (Pliocene, >2.8 Ma old) lacustrine deposits (Schultz, 1977).

Although the midcontinent was relatively stable during the Tertiary, compared with the Rocky Mountains to the west, parts of the Texas Panhandle were tectonically deformed during this time, as indicated by facies patterns and folding in the Ogallala Formation. Regionally, the distribution of the Ogallala was influenced primarily by paleotopography and by collapse structures that formed as a result of the dissolution of deeper Permian evaporites (Frye and Leonard, 1959; Seni, 1980). However, structural and stratigraphic studies in the Texas Panhandle indicate that the Ogallala has been tectonically deformed at least locally, most notably where it overlies the Amarillo Uplift.

Almost all of the structural relief between the Amarillo Uplift and adjacent basins developed during the Pennsylvanian and early Permian, as evidenced by the large quantity of syntectonic arkose shed into the basins (Dutton, 1982). However, reactivation of basement structures resulted in the folding and faulting of upper Permian and Triassic strata and the lower part of the Ogallala Formation along the western part of the Amarillo Uplift (fig. 21; Budnik, 1984). The upper (Hemphillian) part of the Ogallala is only broadly folded, indicating that deformation took place during Ogallala deposition.

Within the basin, reactivation of Paleozoic structures has had a subtle but recognizable effect on Cenozoic strata. These effects have been masked in part by erosion and by late Cenozoic salt dissolution, processes that have been more active

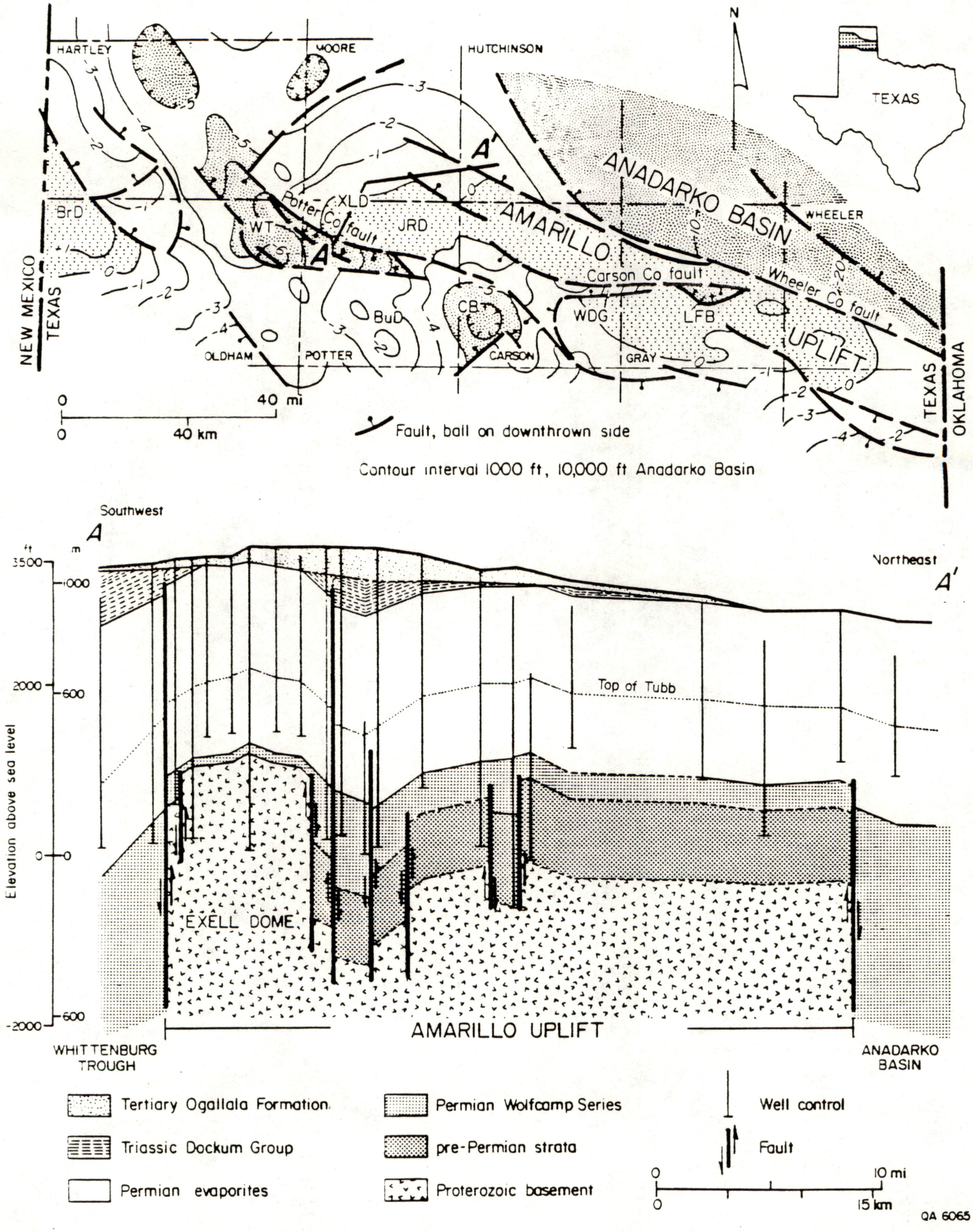

Figure 21. Basement-structure-contour map and cross section of the Amarillo Uplift. Triassic Dockum Group was folded by post-Paleozoic uplift of the Exell Dome. Upper part of the Ogallala Formation is broadly warped.

along the margins of the basin than in the basin interior. Depositional patterns, as defined by isopachous and sand trends in the Ogallala Formation (Seni, 1980), appear to reflect the position of large-scale basement structures in the Panhandle. Major distributary channel systems occupied the axes of the Anadarko and Palo Duro Basins (Budnik, 1984), indicating that the structures had enough topographic expression in the Neogene to influence drainage patterns. Baker (1932) also recognized that the Ogallala Formation was thickest in the axis of the Anadarko Basin and that it thinned over the Amarillo Uplift; he attributed this change in thickness to uplift during deposition.

Post-Ogallala deformation has continued along the western Amarillo Uplift. At present, the formerly flat-lying Pliocene lacustrine deposits (the Rita Blanca beds; Anderson and Kirkland, 1969; Schultz, 1977) dip as much as 10 degrees off the uplift in Hartley County (Budnik, 1984). Microseismicity in that area (Acharya, 1984, 1985) suggests that the Whittenburg Trough to the west of the Amarillo Uplift is currently undergoing tectonic deformation.

Extent of late Cenozoic surface faulting in the region is not well documented, except to the west of the Palo Duro Basin in New Mexico. Barnes (1977) indicates that the northeast-trending Alamosa Creek fault in Roosevelt County, New Mexico (fig. 4), displaces the Ogallala Formation. Lovelace (1972) and Barnes (1977) indicate that, to the north, the Bonita fault in Quay County, New Mexico, offsets Quaternary deposits. North of the Palo Duro Basin, in Potter and Carson Counties, abrupt thickening of the Ogallala Formation across basement structures (Budnik, 1984, his figs. 18 and 20) suggests that movement along the Potter County fault (fig. 4) may have occurred during deposition of the unit. Although post-Paleozoic faults have not been recognized within the Palo Duro Basin, Finch and Wright (1970) suggested, based on the deflection of topographic contours from Curry County, New Mexico, to Crosby County, Texas, that late Cenozoic tectonic deformation offset the surface of the Southern High Plains.

In addition to differential uplift of basement blocks during the Tertiary, regional southeastward tilting of the Texas Panhandle and adjacent areas has occurred since the early Cretaceous. Lower Cretaceous strata to the south of the Palo Duro Basin, which were deposited at or near sea level, currently have a southeastward dip of 8 ft/mi (1.5 m/km; Brand, 1953). McGookey (1984) noted that Cretaceous strata were about 3,000 ft (910 m) above sea level in Lubbock County, south of the basin, and 4,800 ft (1,450 m) above sea level in Quay County, New Mexico, west of the basin, indicating a slope of about 12 ft/mi (2.3 m/km) southeastward.

The timing of this tilting is not closely constrained but most likely coincided with regional orogenic movements either (1) in the late Cretaceous to Eocene (Laramide orogeny) or (2) in the Miocene during opening of the Rio Grande rift and deposition of the Ogallala Formation. Paleogene sediments are absent from the Texas Panhandle as a result of erosion or deposition or both, so no record exists from which to evaluate the possibility of early Tertiary uplift. Tilt of the Cretaceous strata is approximately equal to that of the present High Plains surface (8 to 10 ft/mi, or 1.5 to 2 m/km; Brand, 1953), which is about the same gradient as that of the surface of modern alluvial-fan analogs of the Ogallala (Seni, 1980). Uplift and tilting may have occurred during the opening of the Rio Grande rift, just prior to or during the onset of Ogallala deposition in the late Miocene, and provided the initial slope upon which the unit was deposited. Gable and Hatton (1983) projected 300 to 3,000 ft (100 to 1,000 m) of epeirogenic uplift of the western Great Plains, including the Texas Panhandle, in the past 10 Ma, suggesting that tilting of the region may have occurred during deposition of the Ogallala Formation.

Summary

The Palo Duro Basin and surrounding region have had a long history of tectonism, beginning in the Precambrian. The Palo Duro Basin was the site of a tremendous outpouring of rhyolite ignimbrites during the middle Proterozoic. Deformation of the area in the latest Proterozoic - earliest Phanerozoic locally produced interbedded arkosic sandstone and tuff. Relative stability during the late Cambrian through middle Devonian allowed development of a carbonate-dominated shelf. Uplift of the Texas Arch in the middle Devonian occurred along preexisting faults. A carbonate shelf was reestablished in the Mississippian, with shallow-water carbonates deposited along the axis of the Texas Arch and deeper water sediments deposited along the flanks.

The area underwent major deformation during the late Paleozoic, beginning with a southward tilting of the carbonate shelf in the late Mississippian to early Pennsylvanian. Recurrent uplift in the Pennsylvanian and early Permian maintained highstanding basement blocks. Subsidence, related to the development of the larger Permian Basin, and subtle deformation continued episodically to the end of the Paleozoic. Older structures, reactivated during the Triassic, influenced depositional patterns in the Dockum Group. The present distribution of Cretaceous strata suggests that basement blocks along the Matador Arch may have formed topographic highs during the early Cretaceous or have been uplifted since then. Parts of the Amarillo Uplift and smaller structures within the Palo Duro Basin were reactivated during the deposition of the Ogallala Formation in the Miocene; at approximately the same time the entire region was uplifted and tilted eastward. Faulting in eastern New Mexico and possibly along the Amarillo Uplift may have occurred since deposition of the Ogallala.

TECTONIC EVOLUTION OF THE WICHITA MEGASHEAR

The tectonic history of the southwestern United States, including the Palo Duro Basin, appears to have been influenced by the recurrent activation of the Wichita megashear, a fundamental zone of weakness extending from southern Oklahoma to eastern Utah (figs. 2 and 3). The tectonic history of the Palo Duro Basin reflects the history of this larger tectonic feature; timing of deformation in the basin closely corresponds to the timing of deformation along the megashear.

The existence of a throughgoing zone of weakness from southern Oklahoma to eastern Utah has been postulated by a number of authors (Hunt, 1963; Sales, 1968; Walper, 1970; Baars, 1976; Larson and others, 1985), although others, for example Kluth and Coney (1981), have recognized no evidence of a throughgoing megashear in the region. The megashear can be subdivided into three parts for ease of discussion: (1) an eastern segment in Oklahoma and the Texas Panhandle; (2) a middle segment in northeastern New Mexico and southeastern and central Colorado; and (3) a western segment in southwestern Colorado and eastern Utah (fig. 3). The eastern segment of the Wichita megashear consists of a complex zone of uplifts and basins that includes the Amarillo-Wichita and Arbuckle Uplifts and related structures in southern Oklahoma and the Texas Panhandle. The middle segment is composed of major faults in northeastern New Mexico and southeastern and central Colorado (fig. 3) that have been collectively called the Apishapa and Gore-Ilse fault systems by Tweto (1980a). Faults within and adjacent to the Apishapa/Sierra Grande Uplift align with, or are en echelon to, faults along the western edge of the Frontrange Uplift (the Gore-Ilse fault system) and eastern edge of the central Colorado Trough (fig. 3; Maher, 1953; Anderman, 1961; Lewis and others, 1969; DeVoto, 1980; Tweto, 1980a, 1980b).

The western segment of the Wichita megashear is occupied by the Uncompahgre Uplift (fig. 3) in southwestern Colorado and eastern Utah. This segment forms a major part of the Olympic-Wichita lineament of Baars (1976). The extent of the Wichita megashear is unknown beyond the Uncompahgre Uplift because pre-Mesozoic strata are allochthonous to the northwest (Roberts and others, 1965). However, included in Laramide thrust sheets in Utah are as much as 5 mi (8 km) of Pennsylvanian and lower Permian strata that were deposited in the Oquirrh Basin (Roberts and others, 1965). Dickinson (1977) proposed that the Oquirrh Basin formed during late Paleozoic rifting of the western Great Basin; it is possible that the megashear formed the eastern limit of this rifting. Baars (1976) and Baars and Stevenson (1981) projected the zone of weakness northwestward to connect with the Olympic-Wallowa lineament in Washington (Raisz, 1945; Wise, 1963); however, the present Pacific Northwest of the United States was probably beyond the edge of the North American continent until the Mesozoic (Burchfiel and Davis, 1972).

Proterozoic Origin of the Wichita Megashear

The Wichita megashear appears to have formed as a zone of weakness across the southwestern part of the North American craton during the Precambrian. Each of the three segments of the system marks boundaries between contrasting basement lithologies or has other evidence of Proterozoic faulting or both (fig. 5).

The eastern (Amarillo-Wichita-Arbuckle) segment appears to delineate the northern edge of a local accumulation of 1,200- to 1,400-Ma-old volcanic and sedimentary rocks within the regionally extensive middle Proterozoic terrane (Brewer and others, 1983). South of the segment, geological and geophysical evidence (fig. 8) indicates the presence of a thick (at least 30,000 ft, or 9,100 m) sequence of volcanic and possibly sedimentary rocks, which exhibit distinct layering on seismic reflection profiles (Brewer and others, 1981). These rocks include the Tillman Group in southwestern Oklahoma (Flawn, 1956; Brewer and others, 1981), the Panhandle rhyolite sequence of the Texas Panhandle (fig. 5; Flawn, 1956; Muehlberger and others, 1967), and the Las Animas Formation of southeastern Colorado (Tweto, 1983). North of the segment the basement apparently consists primarily of granitic rocks (Muehlberger and others, 1967) that do not appear layered on seismic reflection data (Brewer and others, 1983). On the basis of this contrast in the nature of the basement, Brewer and others (1983) suggested that the distribution of the Proterozoic units was in part controlled by faulting in the area of the present Wichita Uplift.

Faults that form the middle and western (Colorado) segments of the Wichita megashear also originated in the Proterozoic (Baars, 1976; Tweto, 1980a). For example, the Las Animas Group is preserved in an east-west-trending graben along the Apishapa fault system in southeastern Colorado, which developed prior to the deposition of upper Cambrian strata, probably in the late Proterozoic (Tweto, 1983). To the northwest, the north-northwest-trending Gore-Ilse fault system (fig. 5) predated the emplacement of a 1,700-Ma-old granite in the Wet Mountains (Tweto, 1980a). In southwestern Colorado, the Coalbank Pass fault (one of a number of faults along the front of the Uncompahgre Uplift; fig. 5) offsets a 1,780-Ma-old granite and is in turn intruded by a 1,400-Ma-old granite (Baars, 1976). Thus the eastern, central, and western segments of the Wichita megashear all exhibit evidence of formation during the Proterozoic.

Another fault zone, which includes the Picuris-Pecos and Tijeras faults (fig. 5; Miller and others, 1963; Kelley, 1979) in central New Mexico, has had a significant influence on the tectonic development of the region. These north-northeast-trending faults are apparently unrelated to the Wichita megashear. The Tijeras fault, which lies along the east side of the Sandia Range near Albuquerque, separates Precambrian greenstones from gneisses. Aplite and pegmatite dikes associated with 1,400- to 1,800-Ma-old plutonism are arranged en echelon to the fault in the greenstone, indicating movement of the fault at that time (Lisenbee and others, 1979). To the north, in the southern Sangre de Cristo Mountains, the Picuris-Pecos fault zone also may have formed during the Precambrian (Miller and others, 1963). Schists, 1,700 to 1,800 Ma old (Robertson and Moench, 1979), are complexly deformed adjacent to the fault and are intruded by undeformed mafic dikes of probable Precambrian age that parallel the fault.

Latest Proterozoic - Earliest Phanerozoic Rifting

Deciphering the latest Proterozoic - earliest Phanerozoic tectonic history of the region is difficult because much of the section is missing owing to erosion or nondeposition. Even so, evidence exists that the previously described faults along each segment of the system were reactivated during this period.

A major rifting event along the eastern segment produced the Southern Oklahoma Aulacogen approximately 525 to 570 Ma ago (fig. 5; Hoffman and others, 1974; Gilbert, 1983). The location and orientation of the rift were controlled by the preexisting Proterozoic faults (Brewer and others, 1981). The resulting trough was filled with up to 20,000 ft (6,100 m) of bimodal volcanics and volcaniclastic sediments (Ham and others, 1964). These are underlain and possibly intruded by a large volume of mafic and granitic plutonic rocks (Gilbert, 1983).

To the northwest, in south-central Colorado, alkalic dikes and small intrusives were emplaced parallel to the Ilse and related faults (fig. 5) 495 to 535 Ma ago (Singewald, 1966; Olsen and others, 1977). Along the Uncompahgre Uplift in western Colorado similar intrusives yield ages of 497 and 570 Ma (Olsen and others, 1977; Larson and others, 1985). This igneous activity coincides with that in the Southern Oklahoma Aulacogen, indicating that the entire megashear was reactivated during the Cambrian (Larson and others, 1985).

Early to Middle Paleozoic Deformation

Along the eastern segment of the Wichita megashear, post-rifting cooling and resulting crustal thickening at the site of the Southern Oklahoma Aulacogen initiated subsidence and formation of the Anadarko Basin in the late Cambrian, about 525 Ma ago (fig. 12a; Feinstein, 1981). During this phase of deposition, which continued into the early Devonian (Ham and Wilson, 1967), as much as 15,000 ft (4,500 m) of shallow-water carbonates and clastics of the Timbered Hills Group (upper Cambrian), the Arbuckle Group (Ellenburger equivalent; upper Cambrian and lower Ordovician), the Simpson and Viola Groups and Sylvan Formation (Ordovician), and the Hunton Group (Silurian and lower Devonian) were deposited in the basin (Feinstein, 1981). Basement faults were reactivated briefly during the latest Cambrian to earliest Ordovician, as indicated by an anomalous increase in the subsidence rate, which was followed by a resumption of subsidence at a rate predicted by the typical post-rifting thermal-decay model until the early Devonian (Feinstein, 1981).

A regional erosion surface developed across the midcontinent during the middle Devonian (Ham and Wilson, 1967). Pre-middle Devonian strata were downwarped into the Anadarko Basin and truncated by erosion at this time, so that upper Devonian and Mississippian strata onlap Cambrian through lower Devonian units around the margins of the basin (fig. 12a). Mississippian strata rest on Proterozoic basement on the crest of the Texas Arch to the southwest of the basin (Adams, 1954; Ruppel, 1985) and on the flanks of the Transcontinental Arch to the northwest (Craig and Conner, 1979). Abrupt facies changes in the Kinderhook Series along the north side of the Amarillo Uplift suggest renewed fault activity during the early Mississippian (Mapel and others, 1979; Ruppel, 1985).

Available data for the central and western segments of the Wichita megashear indicate that Proterozoic faults were reactivated at about the same time as those in Oklahoma and Texas. The coarsening of clastic sedimentary rocks of the Sawatch (upper Cambrian) and Parting (upper Devonian) Formations and the presence of clastic rocks in the dominantly carbonate Leadville Formation (lower Mississippian) in the vicinity of the Gore fault suggest episodic reactivation of the central segment (Baars, 1975; Tweto, 1980b). Similarly, in southwest Colorado, abrupt facies changes in the Ignacio (upper Cambrian), Elbert (upper Devonian), and Leadville Formations at the margins of northwest-trending grabens indicate concurrent tectonism on the western segment during deposition of those units (Baars and See, 1968).

Late Paleozoic Deformation

The most intense Paleozoic deformation along the Wichita megashear took place during the formation of the Ancestral Rocky Mountains during the Pennsylvanian and early Permian (ver Wiebe, 1930; Ham and Wilson, 1967; Mallory, 1972). Proterozoic faults were reactivated and new faults formed to produce a series of uplifts and basins along all segments of the system (fig. 3; Tweto, 1980b; Baars and Stevenson, 1981; Kluth and Coney, 1981; Brewer and others, 1983; Larson and others, 1985).

Although all major faults within the eastern segment exhibit large-scale vertical separation (Ham and others, 1964), motion along the segment appears to have been dominantly left-slip. This interpretation is supported by the primarily northwest trend of en echelon folds and faults and the presence of displaced lower Paleozoic subcrop and facies trends (Ham, 1950; Tanner, 1967; Carter, 1979; Evans, 1979; Booth, 1981; Haas, 1981, Axtmann, 1983; Harding, 1985).

Determining the amount of offset along the eastern segment of the Wichita megashear has been difficult owing to a lack of unique geologic relationships (piercing points) to correlate across the zone. Pennsylvanian strata exhibit abrupt lateral facies changes that do not intersect but instead parallel the megashear (Frezon and Dixon, 1975; Dutton, 1982); hence they provide no information about the amount of horizontal movement. Similarly, Mississippian strata, which were deposited on a broad carbonate shelf and slope (Ruppel, 1985), contain only gradual lateral changes in facies that are difficult to define precisely enough to use as piercing points. However, the displaced intersection of lower Paleozoic units with the middle Devonian erosion surface to the north and south of the Amarillo-Wichita Uplift provides an opportunity to calculate the amount of horizontal offset along the megashear.

Below the middle Devonian unconformity north of the Amarillo Uplift, Cambrian through lower Devonian strata strike north-south and dip eastward into the Anadarko Basin from the Sierra Grande Uplift (fig. 12a; Panhandle Geological Society, 1969). South and east of the uplift, Ordovician units dip northeastward off the Texas Arch in the Texas Panhandle into the Hollis and Hardeman Basins (Adams, 1954). In addition, regionally the Arbuckle/Ellenburger Group (Cambro-Ordovician) thickens toward the center of the Anadarko Basin (Huffman, 1959). However, the subcrop pattern and isopachous trends north of the megashear do not line up with those to the south of the megashear (fig. 12a), but instead appear to be horizontally offset

75 mi (120 km) in a left-lateral sense. Removal of this offset aligns the subcrops in the Anadarko Basin with those in the Hollis-Hardeman Basins (fig. 12b) and also realigns isopachous trends within the Arbuckle/Ellenburger Group across the megashear. This estimate of the amount of offset across the entire Amarillo Uplift is consistent with estimates of as much as 20 mi (30 km; Carter, 1979) and 40 mi (65 km; Tanner, 1967) of left-slip on individual faults along the Arbuckle Uplift (fig. 3) at the eastern end of the segment. An alternative interpretation has been presented by Nielsen and Brown (1984), who attribute the apparent strike-slip offset in the Arbuckle Uplift to reverse dip-slip on the faults.

Although the preservation of thick sequences of syntectonic sediments (Mallory, 1958, 1972, 1975) provides evidence of dip-slip on fault zones, large-scale Pennsylvanian strike-slip faulting of approximately 60 mi (100 km) or more has not been recognized or proposed for the middle and western segments of the Wichita megashear. In part this may be because the older structures have been overprinted by younger tectonism (Tweto, 1980c) or buried beneath younger deposits (Baars and Stevenson, 1984). As noted by Reading (1982), however, dip-slip movement commonly occurs along transcurrent faults, and, in the case of ancient strike-slip fault zones, may be the only provable direction of motion. However, evidence of at least a component of Pennsylvanian strike-slip faulting occurs along the middle and western segments. For example, the Gore-Ilse fault system, part of the middle segment of the Wichita megashear, is similar to other strike-slip fault zones (Reading, 1980) in that it is a linear zone of closely spaced, en echelon to subparallel, high-angle faults (DeVoto, 1980; Tweto, 1980a). Tweto (1980a) interprets this zone to have originated as a strike-slip fault during the Precambrian, which was reactivated with mainly dip-slip in the Pennsylvanian. A large amount of vertical separation (as much as 10,000 ft, or

3,000 m; DeVoto, 1972) occurs between the Frontrange Uplift and the central Colorado Trough across the fault system. However, this relief may not have developed as a result of simple block faulting. The presence of small fault-bounded basins that were filled with syntectonic deposits that exhibit abrupt facies changes and complex onlap and overlap relations (DeVoto, 1972) suggests lateral movement as well.

Pennsylvanian left-lateral strike-slip faulting has also been proposed along the western segment of the Wichita megashear (Szabo and Wengerd, 1975; Stone, 1977). However, this faulting may have been preceded and followed by right-lateral movement during the Precambrian (Baars, 1976; Baars and Stevenson, 1981) and the Laramide orogeny (Hite, 1975) along the same trend. Northwest-trending faults along the front of the Uncompahgre Uplift and within the adjacent Paradox Basin had reverse offset during the Pennsylvanian (Stone, 1977; White and Jacobson, 1983) when more than 3,000 ft (900 m) of arkosic sediments were deposited adjacent to the uplift (Clair, 1958; Mallory, 1975). However, a left-lateral component of movement is suggested by the en echelon arrangement and north-northwest orientation of folds within the Paradox Basin (Szabo and Wengerd, 1975) and within and to the north of the uplift (Stone, 1977).

The architecture of the entire Wichita megashear also is compatible with left-lateral strike-slip faulting. The eastern and middle segments are in a right-stepping en echelon arrangement, whereas the middle and western segments form a left-stepping en echelon pattern (fig. 3). Under a left-lateral regime, this geometry would be predicted (Rodgers, 1980) to produce an uplift between the eastern and middle segments (the Sierra Grande Uplift) and a basin between the middle and western segments (the central Colorado Trough). Thus, although it is difficult to prove that the Ancestral Rocky Mountains formed in response to large-scale left-lateral strike-slip faulting, major and minor structures found all along the feature support the hypothesis.

Several phases of late Paleozoic deformation are recognized along the Wichita megashear. Initially, the region along the Wichita megashear was broadly folded during the latest Mississippian or earliest Pennsylvanian, at which time Mississippian and older strata eroded from large areas (Ham and Wilson, 1967; DeVoto, 1980). These epeirogenic movements were followed by a series of pulses of deformation (van der Gracht, 1931; Tomlinson and McBee, 1962; Ham and Wilson, 1967; DeVoto, 1972), which included (1) differentiation of the region into discrete uplifts and basins in the early Pennsylvanian (Morrowan-Atokan); (2) rapid uplift to maximum topographic relief during the middle Pennsylvanian (Desmoinesian), accompanied by strike-slip faulting; and (3) rejuvenation of structures in the late Pennsylvanian and early Permian (Virgilian to Wolfcampian; Ham and Wilson, 1967; DeVoto, 1972; Mallory, 1975; Kluth and Coney, 1981). In Oklahoma, the earliest and latest pulses have been named, respectively, the Wichita and Arbuckle orogenies (van der Gracht, 1931; Tomlinson and McBee, 1962; Ham and Wilson, 1967); the intermediate pulse was the culmination of the Ancestral Rocky Mountain orogeny (Mallory, 1958, 1972, 1975; Martin, 1965; Ohlen and McIntyre, 1965; DeVoto, 1972, 1980; Stone, 1977; Casey, 1980; Kluth and Coney, 1981; Goldstein, 1982).

Tectonic activity decreased during the middle and late Permian; however, preexisting structures continued to influence depositional patterns (Budnik, 1984). Uplifts along the eastern segment of the megashear subsided during the formation of the Permian Basin (Goldstein, 1984), although subdued uplifts on all segments remained sources of arkosic sediments (Rascoe and Baars, 1972). Widespread unconformities within upper Permian strata are present throughout the region, indicating that epeirogenic movements continued (Rascoe and Baars, 1972).

Post-Paleozoic Deformation

Although the early and middle Mesozoic were times of relative stability, some evidence exists that minor deformation on the Wichita megashear continued. Along the western segment, Proterozoic faults were reactivated during the late Permian or early Triassic. The Cutler Formation (Permian) was deformed as a result of movement on faults along the Uncompahgre Uplift prior to deposition of the Dolores Formation during the late Triassic (Weimer, 1980). Minor folding also occurred in the latest Triassic and again in the latest Jurassic along the Apishapa fault system in northeasternmost New Mexico and in adjoining states (Stovall, 1943; Baldwin and Muehlberger, 1959).

Two major post-Paleozoic orogenic events affected the region: (1) the Laramide orogeny in the late Cretaceous and early Tertiary and (2) the Basin and Range event in the late Tertiary. Many of the preexisting structures, primarily along the central and western segments of the megashear, were reactivated as a result of these events (Tweto, 1980b). During the Laramide orogeny the region was subjected to east-northeast compression (Chapin and Cather, 1981; Price and Henry, 1985), resulting in reverse offset on older faults in Colorado (fig. 22; Tweto, 1980c). Rotation of the stress field in the Eocene resulted in later right-lateral strike-slip faulting (Chapin and Cather, 1981) along the central segment of the megashear and along the previously mentioned preexisting zone of weakness in central New Mexico. The Cordilleran orogenic belt to the west of the megashear underwent large-scale thrusting at this time (Coney, 1972). The eastern segment of the Wichita megashear does not appear to have been reactivated during the Laramide orogeny, although this may be more apparent than real because of the lack of post-Paleozoic strata in much of the area.

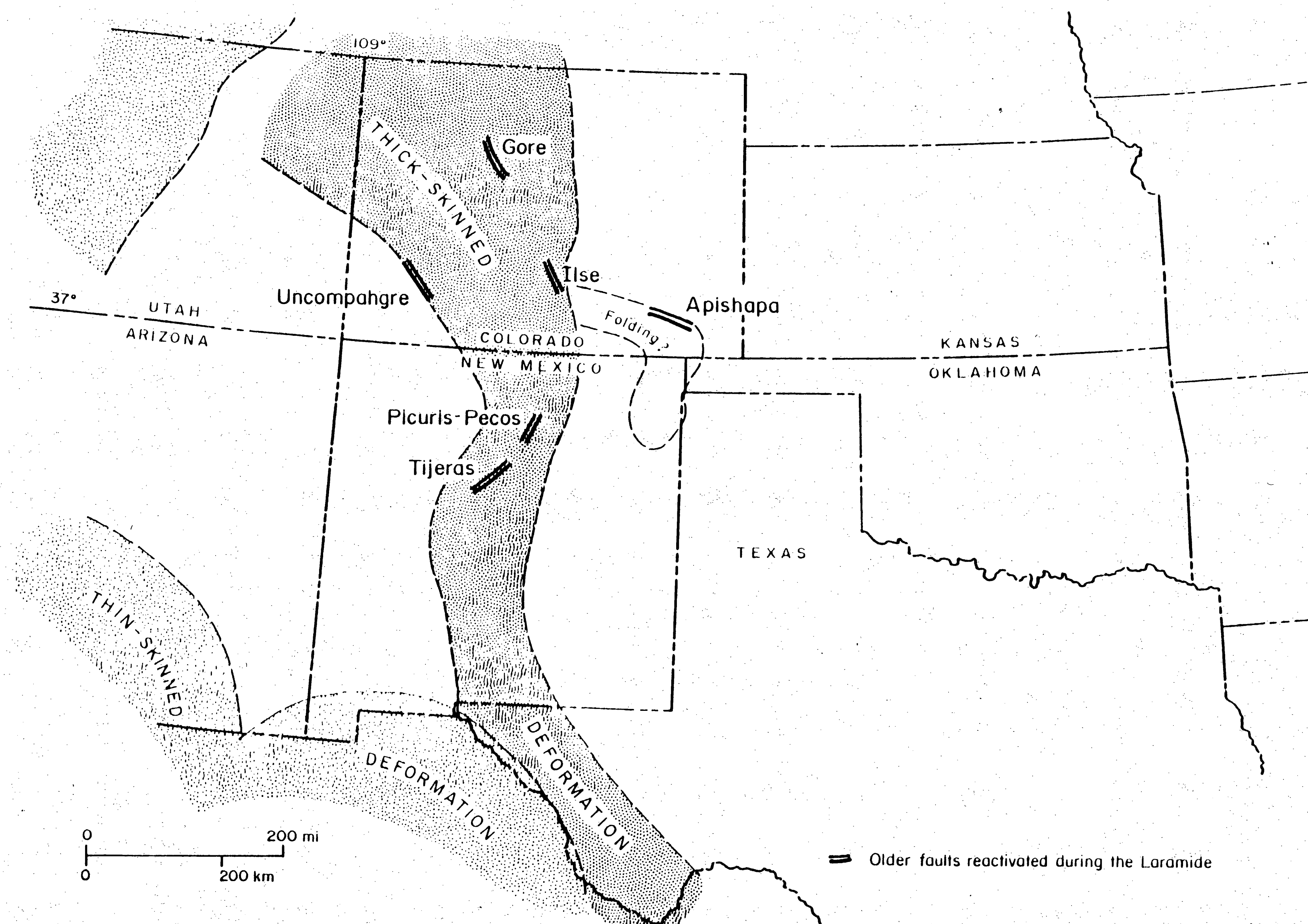

Figure 22. Laramide tectonic elements of the southwestern United States (Miller and others, 1963; Drewes, 1978; Lisenbee and others, 1979; Tweto, 1979). Proterozoic faults in Colorado and New Mexico were reactivated primarily as high-angle reverse during the Laramide orogeny. Horizontal tectonic transport was probably less than 5 mi (8 km) in the area labeled "thick-skinned" and between 5 and 50 mi (8 and 80 km) in the area labeled "thin-skinned." There is no evidence of reactivation of older structures in the Texas Panhandle or Oklahoma at that time.

Where Triassic and Cenozoic strata are present in the Texas Panhandle, however, no evidence of post-Triassic, pre-Miocene folding or faulting exists.

The dominant stress direction in the region during the middle Tertiary (31 to 12 Ma ago) was east-northeast-oriented extension (Price and Henry, 1985). Under this stress regime, the Rio Grande rift, a narrow zone of crustal extension, formed in central New Mexico and Colorado (fig. 20; Chapin, 1979, Cordell, 1982; Baldridge and others, 1984). Three phases of deformation have been recognized along the rift (Chapin and Seager, 1975; Golombek and others, 1983): (1) initial downwarping and formation of broad basins from about 30 Ma ago until 10 or 12 Ma ago (Zoback and others, 1981; Morgan and Golombek, 1984); (2) the beginning of active rifting with the formation of narrow fault-bounded basins and marginal uplifts accompanying a change in stress orientation to WNW-ESE extension (Zoback and others, 1981) about 10 to 12 Ma ago; and (3) reduced fault activity resulting in more subdued topography and development of throughgoing axial drainage from about 4 to 5 Ma ago to the present.

Extension across the Rio Grande rift was accommodated in part through the reactivation of preexisting fault zones (Eaton, 1979; Tweto, 1979; Cordell, 1982; Baldridge and others, 1984). Older structures associated with the north-northwest-trending Gore-Ilse fault system (fig. 20) influenced the location of rift basins in central and northern Colorado (Taylor, 1975; Tweto, 1979). Similarly, the Tijeras and other north-northeast-trending faults in northern and central New Mexico were reactivated during rifting (Miller and others, 1963; Chapin and Seager, 1975; Kelley, 1979; Tweto, 1979; Cordell, 1982). However, the character of axial basins changes along the length of the rift; in central Colorado the rift basins are small and discontinuous (Chapin, 1979; Tweto, 1979), whereas to the south they are wider, deeper, and relatively continuous (Kelley, 1979; Tweto, 1979). Basins along the entire rift were filled with syntectonic fluvial, eolian, and lacustrine deposits (the Santa Fe Group and related units; fig. 20) derived from bordering uplifts primarily during the late Miocene to early Pliocene (Clarendonian and Hemphillian; Galusha and Blick, 1971; Tedford, 1981). The decrease in fault activity about 4 to 5 Ma ago is indicated by the presence of relatively undeformed basalt flows and Blancan (Pliocene) ancestral Rio Grande fluvial deposits that overlie faulted, strongly tilted, and eroded strata of the Santa Fe Group (Chapin and Seager, 1975; Seager and others, 1984).

As previously discussed, evidence from the Ogallala Formation suggests that the Texas Panhandle was also undergoing deformation in the late Miocene to early Pliocene. Basement blocks along the Amarillo Uplift were elevated about 500 ft (150 m) relative to adjoining blocks during initial deposition of the Ogallala Formation in the Clarendonian. Deformation there appears to have ended in the Hemphillian because the upper part of the Ogallala is only broadly warped over these blocks. Basement structures elsewhere in the basin also were subtly rejuvenated at this time. The timing of deposition and deformation of the Ogallala Formation in the Texas Panhandle coincides with the most active phase of faulting along the Rio Grande rift to the west about 10 until 4 Ma ago and suggests that both the eastern and middle segments of the Wichita megashear were reactivated at that time (fig. 20).

The pattern of deformation that was established in the late Tertiary continued to the present. The Rio Grande rift appears to be the focus of Quaternary faulting (fig. 23; Nakata and others, 1982) and recent seismicity (fig. 24; Kirkham and Rodgers, 1981; Sanford and others, 1981). However, evidence of Quaternary faulting along the Meers fault in Oklahoma (fig. 23; Donovan and others, 1983) and seismicity in the Texas Panhandle (fig. 24; Woollard, 1958; Acharya, 1984, 1985) indicate that the eastern segment of the Wichita megashear also has remained tectonically active up to the present.

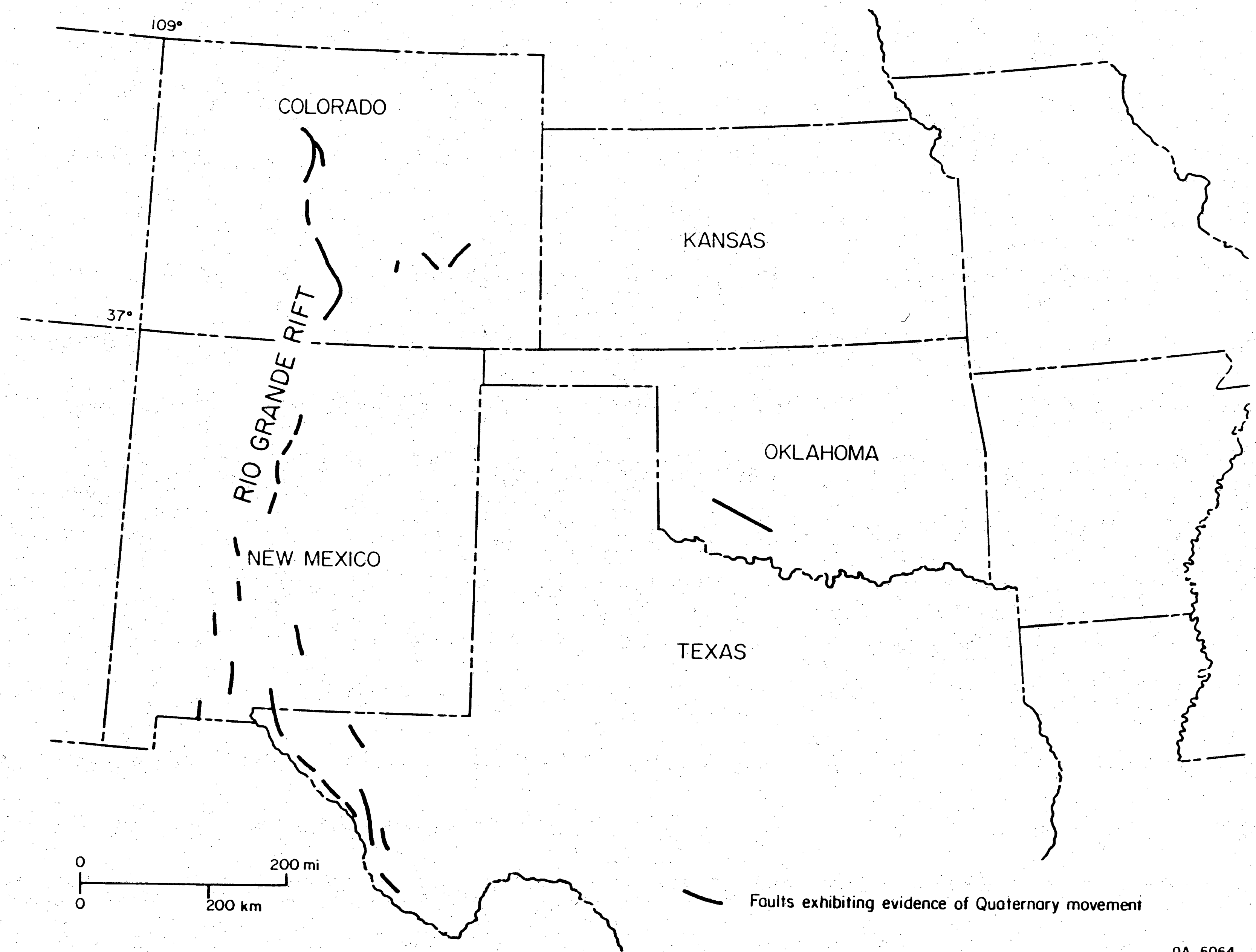

Figure 23. Distribution of faults exhibiting Quaternary offset (Nakata and others, 1982; Donovan and others, 1983).

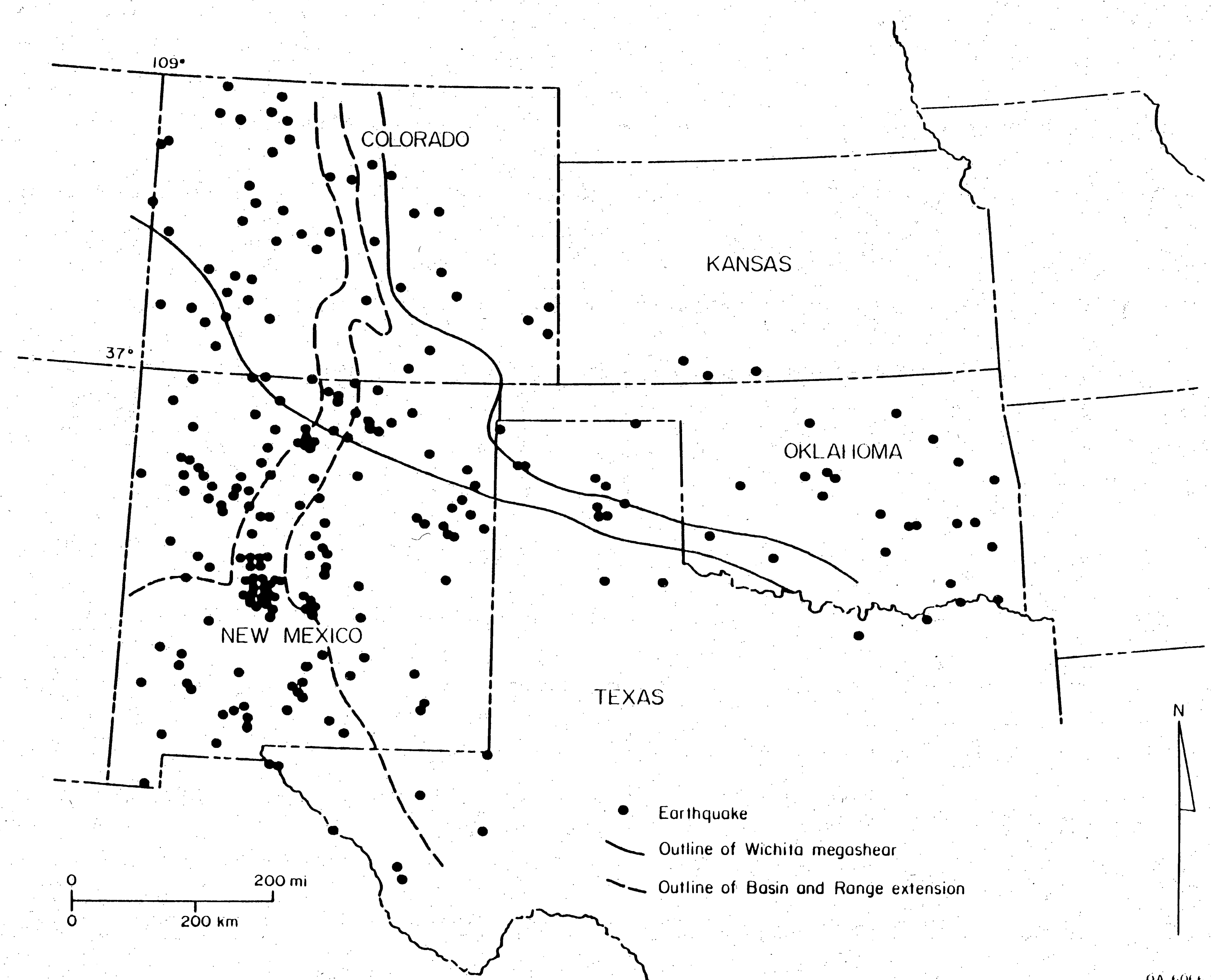

Figure 24. Seismicity in the southern Rocky Mountains and southern Great Plains (Docekal, 1970; Kirkham and Rodgers, 1981; Sanford, 1981; Reagor and others, 1982).

Summary

The tectonic history of the southwestern United States has been characterized by recurrent deformation along the Wichita megashear, a network of faults that extends from Oklahoma northwestward into eastern Utah. Each of the three segments of the megashear exhibits evidence of deformation beginning in the Proterozoic, at least 1,400 Ma ago. Rifting about 525 to 570 Ma ago produced the Southern Oklahoma Aulacogen along the eastern segment and scattered igneous activity along the central and western segments. The area was again deformed in the latest Cambrian to earliest Ordovician and in the middle Devonian. The major Phanerozoic deformation occurred in the Pennsylvanian to early Permian, when the Ancestral Rocky Mountains were formed. The central and western segments were reactivated during the Laramide orogeny (late Cretaceous to early Tertiary); effects of this event have not been recognized along the eastern segment. The Rio Grande rift formed by extension, in part along the central segment of the megashear. Parts of the eastern segment also were reactivated during the late Tertiary as a result of extension to the west. Seismicity and evidence of Quaternary faulting along all three segments indicate that currently the megashear is locally undergoing deformation.

TECTONIC MODELS

The geologic evolution of the Palo Duro Basin has been influenced by large-scale plate tectonic interactions and resulting intraplate deformation. Although the nature of these interactions, especially prior to the Mesozoic, is not well understood, it is appropriate to set the Palo Duro Basin in the context of plate tectonics.

The southwestern United States has been cited as a classic example of continental accretion (Condie, 1982). The age of the Precambrian rocks at the top of the basement becomes progressively younger to the southeast (fig. 5), from Archean (>2,500 Ma old) in southern Wyoming to late Proterozoic (Grenville, 1,000 Ma old) in the Llano area of Texas (Van Schmus and Bickford, 1981; Condie, 1982). The basement terranes form east-northeast-trending belts across the midcontinent (Van Schmus and Bickford, 1981). Van Schmus and Bickford (1981) and Condie (1982) suggested that the accretion of the continental crust formed as a result of episodic subduction along a convergent plate margin. Condie (1982) proposed a model for the southern edge of the continent involving cyclic back-arc rifting and convergence followed by collapse of back-arc basins approximately 1,760 to 1,800 Ma, 1,720 to 1,760 Ma, 1,650 to 1,720 Ma, and 1,100 to 1,200 Ma ago. He did not specifically address the origins of the Panhandle rhyolite sequence.

The tectonic setting of this tremendous pile of 1,380- to 1,480-Ma-old, predominantly siliceous volcanics that in part underlie the Palo Duro Basin is enigmatic. As pointed out by Van Schmus and Bickford (1981), the position of the terrane between areas of older and younger basement suggests that the volcanics formed at a plate margin. However, there is a conspicuous lack of intermediate and basic rocks usually associated with such a setting. On the basis of the acidic nature of the rocks, the volcanics may have formed in a continental rift environment. If this interpretation were correct, however, older rocks would be present both north and south of the terrane and the volcanics would have more chemical variation, neither of which has been noted. Van Schmus and Bickford (1981) concluded that the Panhandle and related volcanics of the midcontinent are on the average much more acidic than rocks being formed at modern continental margins, and therefore it is difficult to determine the tectonic setting at the time of formation 1,400 Ma ago.

As previously discussed, faults associated with the Wichita megashear in Colorado (Baars, 1976; Tweto, 1980a) and in Oklahoma (Brewer and others, 1983) appear to have developed by at least 1,400 Ma ago. The origin of the megashear may be related to that of the Panhandle volcanics, but a model for the origin of an initial throughgoing zone of weakness has not been formulated.

The Wichita megashear was reactivated episodically during the Paleozoic, beginning in the Cambrian. The Southern Oklahoma Aulacogen (fig. 5) represents a failed rift that formed at a triple junction during continental separation about 570 Ma ago (Hoffman and others, 1974; Walper, 1977; Gilbert, 1983). The location of the rift appears to have been controlled by the presence of the Wichita megashear, which is consistent with the observation of Burke and Dewey (1973) and Rankin (1976) that preexisting zones of weakness strongly influence the geometry of the plate margins during breakup. Evidence of igneous activity along the eastern (Gilbert, 1983), central (Gore-Ilse), and western (Uncompahgre) segments (Olsen and others, 1977; Larson and others, 1985) of the megashear suggests that the entire zone of weakness was reactivated at this time.

A relatively minor reactivation of the Wichita megashear in the latest Cambrian to early Ordovician is indicated by an increase in subsidence rates in the Anadarko Basin (Feinstein, 1981) and an abrupt increase in grain size in the Ignacio (Baars and See, 1968) and Sawatch (Tweto, 1980b) Formations in the vicinity of the Gore-Ilse and Uncompahgre fault zones. This movement on the megashear may be related to a change in plate motions from that of continental separation in the Cambrian to continental convergence in the Ordovician (Bird and Dewey, 1970).

The late Devonian to early Mississippian was a time of major tectonic activity along the eastern (Acadian orogeny; Rodgers, 1967) and western (Antler orogeny, Nilsen and Stewart, 1980) margins of the North American plate. An increase in grain size of the upper Devonian Elbert (Baars and See, 1968) and Parting (Tweto, 1980b) Formations in the vicinity of faults associated with the Wichita megashear indicates contemporaneity of deformation within the plate. The uplift of the Transcontinental and Texas Arches in the middle Devonian (Ham and Wilson, 1967) probably occurred in response to initial orogenic activities at the plate margins. Facies changes in the Leadville Formation (Baars and See, 1968; Tweto, 1980b) along preexisting faults in Colorado and in equivalent strata in the Anadarko Basin (Mapel and others, 1979) indicate that there was minor rejuvenation of structures along the megashear in the early Mississippian at the end of the Antler and Acadian orogenies (Rodgers, 1967; Nilsen and Stewart, 1980).

During the Pennsylvanian, major tectonic activity took place (fig. 25) along the eastern (Alleghenian orogeny) and southern (Ouachita orogeny) margins of North America and along the Wichita megashear (Ancestral Rocky Mountain orogeny). The Ouachita and Alleghenian orogenies occurred during the collision between the northern part of Gondwana (South America and Africa) and Laurussia (including North America and Europe) in the late Paleozoic (Hatcher, 1972; Graham and others, 1975; LeFort and van der Voo, 1981; Pindell and Dewey, 1982). It has been previously suggested (Walper, 1977; Kluth and Coney, 1981) that the Ancestral Rocky Mountains also formed as a result of this collision. The Ouachitas are thought to represent continental margin deposits (Keller and Cebull, 1973; Morris, 1974) that were deformed during plate convergence (Wickham and others, 1976; Viele, 1979), whereas it has been proposed (Kluth and Coney, 1981) that the Ancestral Rocky Mountains were formed as the continental block south of the Wichita megashear was pushed northwestward by South America. The Kluth and Coney (1981) model, however, is not consistent with the apparent middle Pennsylvanian left-lateral displacement and east-northeast compression along the megashear, but instead requires right-lateral

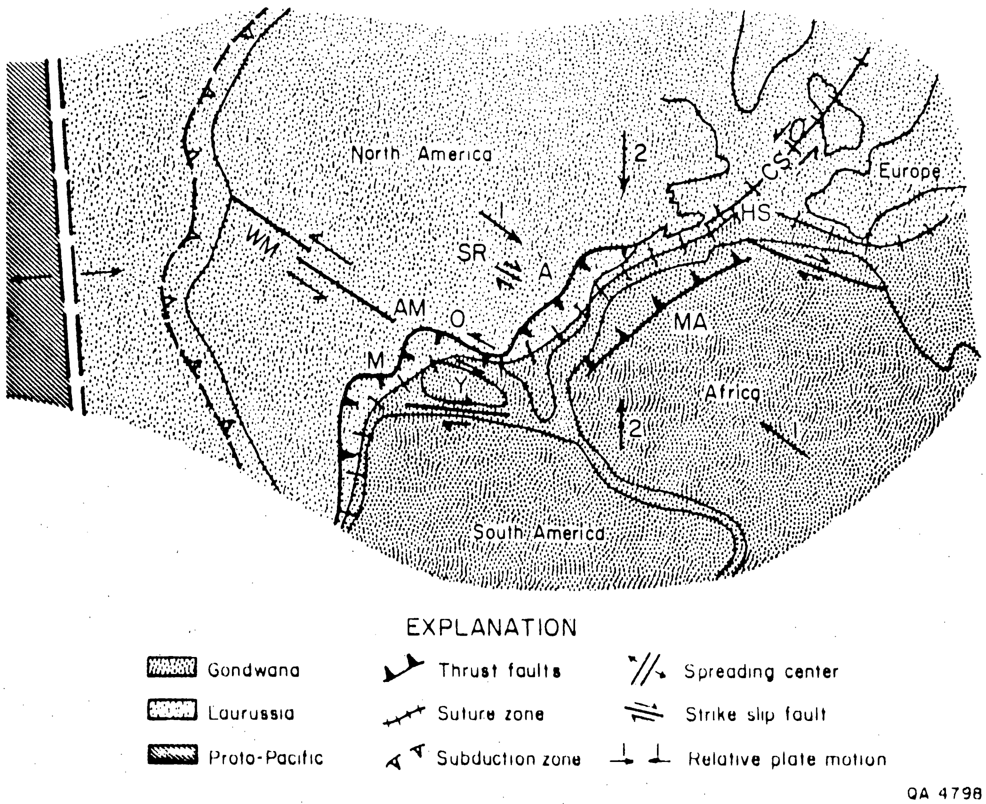

Figure 25. Plate configuration during the late Paleozoic. From Badham and Halls (1975), LeFort and van der Voo (1981), Dewey (1982), and Thomas (1983). Symbols: A - Appalachian belt; AM - Arbuckle Mountains; CS - Caledonian suture; HS - Hercynian suture; M - Marathon belt; MA - Mauritanide belt; O - Ouachita belt; SR - Shawneetown - Rough Creek fault zone; WM - Wichita megashear; Y - Yucatan. Relative motion between Gondwana and Laurussia is indicated by numbered arrows: (1) early to middle Pennsylvanian and (2) late Pennsylvanian to early Permian. A spreading ridge formed the western edge of the North American plate until closure of the proto-Atlantic, at which time an east-dipping subduction zone must have developed between the ridge and the continent.

movement and north-northwest-oriented compression. Kluth and Coney (1981) suggested that any left-lateral movement in southern Oklahoma was caused by thrusting in the Marathon region, presumably in the latest Pennsylvanian to early Permian.

Middle Pennsylvanian left-lateral motion along the megashear can be explained, however, by an alternative model in which the Appalachians, not the Ouachitas, formed the main impingement zone between Gondwana and Laurussia (fig. 25). The collision would have imparted an east-west maximum principal compressive stress across the megashear, resulting in left-lateral strike-slip movement. The relative magnitude of deformation in the Appalachian and Ouachita orogenic belts is difficult to assess because of the complexity of the areas and the lack of surface exposures in most of the Ouachitas. The Appalachians appear to have undergone hundreds of kilometers of shortening during the Alleghenian orogeny (Roeder and others, 1978; Harris and Bayer, 1979; Cook and others, 1981), although at least some of the shortening may have taken place during earlier orogenic events (Hatcher, 1978). In western Africa, a similar amount of shortening (Arthaud and Matte, 1977) took place across the Mauritanides (fig. 25) as a result of eastward-directed, thin-skinned deformation (Graham and others, 1975; Lecorche and others, 1983) in the late Mississippian to middle Pennsylvanian (Michard and Pique, 1979). In contrast, total shortening across the part of the Ouachitas in Arkansas may have been approximately 60 mi (100 km) (Viele, 1979; Lillie and others, 1983; Lillie, 1985) and less than 30 mi (50 km) across the part adjacent to the Llano Uplift of Texas (fig. 2; Rosendal and Erskine, 1971).

The kinematics of the interaction between Gondwana and Laurussia have yet to be completely resolved (Mosher, 1983); therefore all models are highly speculative. The following, much simplified model is proposed to explain the late Paleozoic tectonic history of the Wichita megashear; other models may fit the data as well or better. The proposed model suggests that, during the late Paleozoic, Laurussia was moving eastward from a spreading ridge to the west. Paleomagnetic and paleoclimatologic data indicate that Gondwana was moving northward at this time (Bambach and others, 1980), although geologic data (Arthaud and Matte, 1977; Badham, 1982) suggest that Africa had a relative westward component of motion as well at the time of collision in the Pennsylvanian. A continent-continent collision between North America and Africa began in the late Mississippian to early Pennsylvanian (LeFort and van der Voo, 1981), possibly reaching maximum east-west shortening in the middle Pennsylvanian.

During the late Pennsylvanian and early Permian, relative movement between Africa and North America became primarily oblique to left-lateral strike-slip (LeFort and van der Voo, 1981; Badham, 1982). In Morocco, at the northern end of the Mauritanides, the early phase of deformation was followed in the late Pennsylvanian to early Permian by right-lateral motion along east-west-trending strike-slip faults (Arthaud and Matte, 1977), possibly in response to the northwestward movement of Africa against North America and Europe (LeFort and van der Voo, 1981). This northwestward motion also induced strike-slip movement on the former (Taconic-Acadian-Caledonian) suture between North America and Europe (fig. 25; LeFort and van der Voo, 1981; Bradley, 1982; Dewey, 1982; Mosher, 1983).

To the west, along the Ouachitas, the above-described plate motions would result in primarily west- to northwest-directed convergence during the middle Pennsylvanian, with a component of right-oblique-slip (transpression) along the eastern part of the orogenic belt (Cebull and others, 1976; Thomas, 1983; Owen and Carozzi, 1986). The lack of evidence of major shortening on the same scale as that proposed for the Appalachians suggests that deformation along the western part of the suture may have been taken up primarily by fragmentation of the northern part of South America (fig. 25). These fragments of South America later formed the Yucatan, Florida Straits, and other smaller blocks during the opening of the Gulf of Mexico in the Mesozoic (Pindell, 1985).

The eastward progress of the part of North America to the north of the megashear would have been slowed by its collision with Africa (Yamano and Uyeda, 1985), whereas the block of continental crust to the south would have continued eastward, deforming the northern part of South America, possibly along preexisting zones of weakness. This change in relative velocities of the two parts of the plate may have reactivated the Wichita megashear with left-lateral motion (fig. 25). As pointed out by Kluth and Coney (1981), intraplate deformation during the middle Pennsylvanian was concentrated along the Ancestral Rocky Mountains because of the presence of a preexisting zone of weakness. Elsewhere, for example in southern New Mexico and Trans-Pecos Texas (Crosby and Mapel, 1975; Greenwood and others, 1977) and in the midcontinent (Prichard, 1975; Stewart, 1975; Wanless, 1975a, 1975b), the North American plate was broadly folded in the middle Pennsylvanian.

Late Pennsylvanian to early Permian deformation within the North American plate was produced by relative northward movement of Gondwana, resulting in thrusting in the Marathon region (Marathon orogeny) and along the eastern end of the Wichita megashear (Arbuckle orogeny). Uplift of the Central Basin Platform and related structures in Trans-Pecos Texas and southern New Mexico (Greenwood and others, 1977; Ross, 1979) also coincided with this change in direction of convergence.

Following the consolidation of Pangea in the early Permian, the Palo Duro Basin and the Wichita megashear lay far from a plate margin. The dominant influences on deposition during the middle and late Permian were regional subsidence associated with the Permian Basin and continued broad uplift of Pennsylvanian structures in

Colorado (Peterson, 1980). No satisfactory plate tectonic model has been proposed to explain the formation of the Permian Basin. Dewey and Pitman (1982) suggested that the basin may have formed as a result of post-rifting cooling, however Bally (in Dewey and Pitman, 1982) pointed out that no evidence of late Paleozoic rifting exists in the area. The Permian Basin may have formed in response to stretching of the crust prior to breakup of Pangea in the Triassic. This process would have continued into the late Triassic, thus explaining the coincidence between the Permian and Dockum Basins. Dickinson (1981), on the other hand, proposed that the Dockum depositional basin developed as a result of the uplift of central Texas during the separation of North and South America.

Although faults associated with the central and western segments of the Wichita megashear were reactivated during the late Cretaceous through Eocene Laramide orogeny (fig. 22; Tweto, 1979), the eastern segment exhibits no evidence of deformation at this time, suggesting that the megashear itself was not reactivated, possibly because of an inappropriate orientation of stresses. The transition from Laramide compression to Basin and Range tension resulted from a change in stress orientations related to a change in plate motions in the North Atlantic (Coney, 1972; Chapin and Cather, 1981; Zoback and others, 1981). During Basin and Range deformation, older structures associated with the central segment of the Wichita megashear in Colorado and preexisting faults in New Mexico underwent extension to form the Rio Grande rift.

Evidence for reactivation of structures in the Texas Panhandle during the Miocene is consistent with a pattern of recurrent deformation along the Wichita megashear in response to plate interaction along the eastern or western margins of the North American plate (Kluth and Coney, 1981; Larson and others, 1985). In the case of late Tertiary deformation, the coincidence in timing between reactivation of the megashear and Basin and Range extension to the west suggests that the two are interrelated.

As previously noted, the Rio Grande rift, which is a relatively wide and continuous feature in New Mexico and southern Colorado, becomes narrower and less continuous to the north (fig. 20). This change in character occurs at the intersection of the rift and the Wichita megashear. The preexisting north-northwest-trending faults in central Colorado were reactivated during Basin and Range extension (Tweto, 1979), implicitly with a right-lateral strike-slip component. During the opening of the Rio Grande rift, the Wichita megashear formed a boundary between the area of no extension to the northeast and the area that underwent extension to the southwest (fig. 26), forming, in essence, an intracratonic transform fault with apparent left-lateral offset.

The magnitude of WNW-ESE extension of the central segment of the rift has been estimated to be approximately 5 to 10 mi (10 to 15 km) (Cordell, 1982). The amount of WNW-ESE extension on the northern segment could be expected to be much less because the motion would be translated into oblique-slip along the north-northwest-trending faults. The net horizontal slip on the Wichita megashear, therefore, could have been 5 mi (10 km) or more. This is a necessarily crude estimate because many of the details of the fault motions at that time are still unknown. Also, this assumes that the Colorado Plateau remained relatively fixed and that all of the extension across the rift was produced by an eastward shift of the eastern part of New Mexico and the Texas Panhandle. Alternatively, it has been proposed that eastern New Mexico remained fixed (with no movement along the Wichita megashear) and that the Colorado Plateau rotated clockwise as the Rio Grande rift opened (Eaton, 1979). However, the deformation of the Ogallala Formation in the Texas Panhandle suggests that there had to have been some eastward component of rifting.

Although relatively stable at the present time, the midcontinent is undergoing low-level seismic activity, primarily along older basement structures (Woollard, 1958;

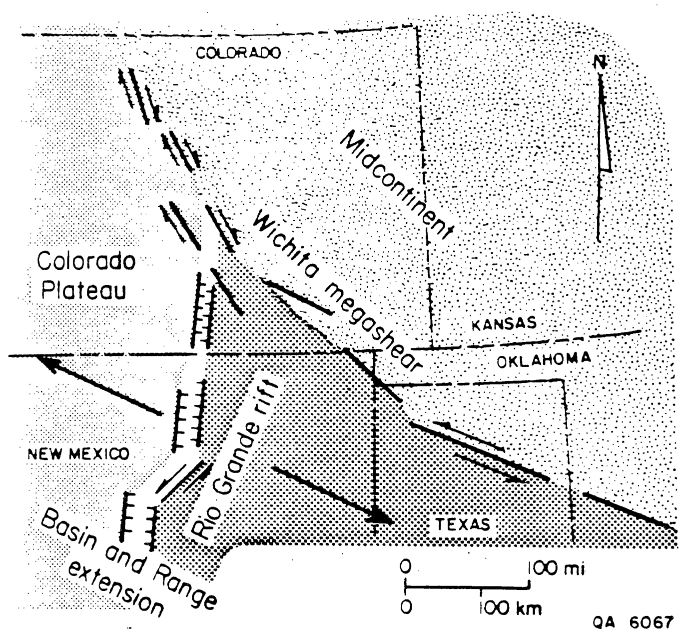

Figure 26. Neogene tectonic setting of the southern Rocky Mountains and southern Great Plains. Large arrows indicate direction of extension; small arrows indicate predicted direction of movement on faults. The Wichita megashear east of the Rio Grande rift formed an intraplate transform fault during Neogene extension.

Docekal, 1970; Acharya, 1984, 1985), including the Wichita megashear. This intraplate activity is occurring in response to large-scale plate motions (Sbar and Sykes, 1973; Hinze and others, 1980; Zoback and Zoback, 1980), possibly caused by either ridge-push or drag on the base of the lithosphere (Zoback and Zoback, 1980).

CONCLUSIONS

The tectonic history of the Palo Duro Basin is closely related to that of large regional structures, especially the Wichita megashear. Analysis of the southern Rocky Mountains and southern Great Plains has allowed a more precise definition of the tectonic history of the Panhandle, including the Palo Duro Basin. Although the effects are generally subtle, timing of this episodic intraplate deformation closely coincides with changes in plate motions.

The earliest record preserved in the Palo Duro Basin is that of widespread extrusion of rhyolites, possibly near a plate margin, about 1,400 Ma ago. The northwest structural trend associated with the later Amarillo Uplift may have originated at this time. Reactivation of the Wichita megashear occurred during continental breakup and formation of the Southern Oklahoma Aulacogen about 570 Ma ago. Structures within the Palo Duro Basin (for example, the Castro Trough) may have formed at this time.

The Palo Duro Basin remained relatively stable until the middle Devonian, when regional folding produced the Texas Arch, possibly in response to plate interactions along the eastern and western margins of North America. With the exception of minor activity along the megashear, the region was tectonically quiescent during the Mississippian. Formation of the Palo Duro depositional basin and major uplifts adjoining the basin occurred in the Pennsylvanian as a result of the collision of North America and Africa during the assemblage of Pangea. Stretching of the continental crust prior to the separation of North and South America may have produced the Permian and Dockum depositional basins. The Palo Duro Basin was again tectonically stable during the early Tertiary; however, structures along the Amarillo Uplift and possibly within the Palo Duro Basin were reactivated in the late Miocene in response to Basin and Range extension to the west. Present seismicity in the region may be related to large-scale plate motions.

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