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TECTONIC HISTORY OF THE PALO DURO BASIN, TEXAS PANHANDLE

by

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3.3.2 TECTONIC HISTORY

INTRODUCTION

The Palo Duro Basin is one of a dozen or more intracratonic basins formed as a result of large-scale plate motions in the Late Paleozoic (Goldstein, 1981; Kluth and Coney, 1981). The margins of the basin are defined by a series of uplifts that developed during the Pennsylvanian (fig. 1). The Palo Duro Basin is bounded on the northeast by the Amarillo-Wichita Uplift, on the northwest by the Bravo Dome, and on the west by the Sierra Grande and other smaller uplifts, all of which were imporant sources of sediment. To the south, the Matador Arch served as a sediment barrier and loci of carbonate buildups, as did a number of smaller, generally unnamed, uplifts to the east.

The Palo Duro Basin includes sediments deposited in two temporally separate but spatially overlapping basins (Budnik and Smith, 1982). The initial basin, a northwest extension of the Hardeman Basin (fig. 2), formed as a result of the foundering of a Mississippian shelf during the latest Mississippian or early Pennsylvanian (Budnik and Smith, 1982; Dutton and others, 1982). Up to 2,500 ft (750 m) of Pennsylvanian and a similar thickness of Wolfcampian (Lower Permian), primarily marine, sediments were deposited during this phase (Dutton and others, 1982). A second basin (effectively the northern shelf of the Midland Basin; fig. 3) formed in response to regional subsidence of the much larger Permian Basin. In excess of 4,000 ft (1,200 m) of restricted marine to non-marine sediments were deposited nearly continuously throughout the mid- and late Permian (Leonardian, Guadalupian, and Ochoan; Presley, 1980).

REGIONAL TECTONIC HISTORY

The distribution of Late Paleozoic sediments, as well as older and younger deposits within the Palo Duro Basin were influenced by movement along preexisting faults (Budnik and Smith, 1982; Dutton and others, 1982; McGookey and Goldstein, 1982; Budnik, 1983). These intrabasinal faults are related to a regional zone of crustal weakness that extends from Oklahoma and New Mexico into Colorado and Utah. Occupying this zone are the Amarillo-Wichita Uplift, the Cenozoic Rio Grande Rift and its precursors, and the central Colorado uplifts (fig. 4). The Amarillo Uplift is continuous with the Apishapa-Wet Mountain Uplift of southeastern Colorado (King, 1977) via the Freezeout Creek fault zone and other, previously unrecognized faults in northestern New Mexico and adjacent states. Recurrent movement along this three-pronged system of faults appears to have been the dominant controlling influence on the tectonic history of the Palo Duro Basin.

Precambrian

The origin of the regional system of faults can be traced back to the late Precambrian, when it may have formed as a result of deep mantle processes. The three-pronged configuration is very similar to plume-generated triple junctions recognized elsewhere (Burke and Dewey, 1973). Isotopic data from mafic volcanics near the apex of the system also suggest the presence of a mantle plume in that area approximately 1,800 to 1,900 mya (Condie and Budding, 1979). All three segments mark boundaries between contrasting basement terranes and/or include faults that exhibit evidence of Precambrian movement along them.

The southeast (Wet Mountain-Wichita Mountain) segment appears to delineate the northern edge of a Proterozoic (1,200 to 1,400 mya) basin (Brewer and others, 1983; Tweto, 1983). In the Hardeman Basin, south of the Wichita Uplift, COCORP seismic reflection surveys (Oliver and others, 1976; Brewer and others, 1981) revealed the presence of a thick (23,000 to 33,000 ft; 7 to 10 km) sequence of well-layered strata interpreted to be interbedded volcanic and sedimentary rocks of the Tillman Group (Flawn, 1956; Brewer and others, 1981; fig. 5). North of the Amarillo-Wichita Uplift, layering is absent within the crust. Brewer and others (1983) suggest on the basis of this contrast that the uplift formed as a result of Paleozoic reactivation of a fault zone that was in existence at the time of formation of the Proterozoic basin.

A similar relationship exists in southeastern Colorado. The Las Animas Formation, a low grade metasedimentary and bimodal metavolcanic sequence (Tweto, 1983) occurs south of the Apishapa fault and west of the Freezeout Creek fault zone (fig. 6). The unit appears to have been preserved in a graben within approximately 1,400 mya granites, which is truncated by basal Cambrian sandstones. Tweto (1983) correlated the Las Animas Formation with the Tillman Group on the basis of lithology, age, and structural setting. He believes the Apishapa fault originated in the Precambrian and formed the northern edge of the basin into which the Las Animas Formation was deposited (Tweto, 1980a).

The Proterozoic basin or basins inferred from the Las Animas and Tillman units may have covered a much larger area including parts of Oklahoma, Texas, Colorado, and New Mexico. These units, together with volcanics of the Panhandle (rhyolite) and Swisher (diabase) terranes, and the metaarkoses and metagraywackes of the De Baca and possibly Fisher terranes (Flawn, 1956) may define a Proterozoic basin that covered over 50,000 square miles (130,000 sq. km; fig. 7). Proprietary and nonproprietary seismic reflection surveys (fig. 8) and gravity data (Goldstein, 1982) confirm the presence of thick, well-stratified sequences beneath the Paleozoic of the Palo Duro and Tucumcari Basins. This large Precambrian basin was bounded on the north by the southeast segment of the regional fault system.

The Precambrian history of New Mexico is less well understood, as the area has been subjected to multiple major Phanerozoic deformations. Nonetheless, it appears that the southern segment of the regional fault zone also originated in the Precambrian. The zone parallels the western margin of the above-described Proterozoic basin, and appears to separate rocks greater than 1,400 mya on the west from younger rocks to the east (fig. 7).

Individual faults within this segment appear to have originated in the Precambrian. East of Albuquerque, the Tijeras fault separates Precambrian greenstones from gneisses. Aplite and pegmatite dikes associated with 1,400 to 1,800 mya plutonism are arranged en echelon to the fault in the greenstone indicating movement on the fault at that time (Lisenbee and others, 1979). To the north, in the southern Sangre de Cristo Mountains, the Picuris-Pecos fault zone may have also formed in the Precambrian (Miller and others, 1963). Schists, 1700 to 1800 mya (Robertson and Moench, 1979) are complexly deformed adjacent to the fault and are intruded by undeformed mafic dikes that parallel the fault.

There is a great deal of evidence to suggest that the northwest (Colorado) segment of the regional fault system originated in the Precambrian. Baars (1976) and Tweto (1980a) have summarized the evidence for individual faults within the segment (fig. 9). For example, the Ilse-Gore system, a major north-northwest trending fault zone, predated the emplacement of a 1,700 mya granite in the Wet Mountains (Tweto, 1980a). Also, in southwestern Colorado, the Coalbank Pass fault offsets 1,780 mya granite and is intruded by 1,400 mya granite (Baars, 1976). Tweto (1980b) defines at least two periods of faulting during the Precambrian: one at about 1,700 mya and another at about 1,400 mya based on these and other data.

Late Precambrian-Early Paleozoic

Deciphering the late Proterozoic and early Paleozoic tectonic history of the region is difficult because much of the section is missing due to erosion or nondeposition. Even so, there is evidence that the Precambrian faults along each segment of the system were reactivated during this period.

A major rifting event along the southeastern segment produced the southern Oklahoma aulacogen during the latest Precambrian and Early Cambrian (Hoffman and others, 1974). The resulting basin was filled with up to 20,000 ft (6,100 m) of bimodal volcanics and volcanoclastic sediments (Ham and others, 1964). The Precambrian faults were again reactivated during the Late Cambrian to Early Ordovician as indicated by anomalously high sedimentation rates and the distribution of lithofacies within the Arbuckle Group in the Ardmore Basin (Feinstein, 1981). The uppermost Devonian Woodford Formation overlies Devonian through Cambrian units on the flanks of the Wichita Uplift, indicating fault movement during the mid-Devonian (Tarr and others, 1965). Renewed uplift of the Amarillo Mountains, possibly accompanied by faulting, is suggested by rapid facies changes in the Kinderhook Series (Lower Mississippian) of the western Anadarko Basin (Mapel and others, 1979).

The early Paleozoic history of the southern (New Mexico) segment is largely unknown; in many areas Pennsylvanian or younger strata lie directly on basement. In south central New Mexico, an angular unconformity between Cambrian through Lower Devonian units and Upper Devonian strata (Kottlowski and others, 1956) suggests regional uplift, perhaps accompanied by localized faulting during mid-Devonian. There is good evidence for early Paleozoic faulting in the Sangre de Cristo Range to the north. The Del Padre Formation thickens and becomes conglomeratic against the Picuris-Pecos fault, which, as discussed above, also has evidence of Precambrian movement. The Del Padre is unfossiliferous and its age is unknown. Baltz and Read (1960) consider it and the overlying Espiritu Santo Formation to be Devonian (?) on the basis of lithologic correlation with Devonian units in Colorado. Armstrong (1979) indicates that both formations are middle Mississippian (Osagean) based on fossils found in the Espiritu Santo. In either case, the Picuris-Pecos fault was reactivated during the early Paleozoic.

Available data for the northwest (Colorado) segment indicate that the Precambrian faults were periodically reactivated during the early Paleozoic. In southwest Colorado, the Upper Cambrian Ignacio Formation, Upper Devonian Elbert Formation, and Lower Mississippian (Osagean) Leadville Formation all coarsen toward the margins of northwest-trending grabens (Baars and See, 1968). A similar pattern is seen in central Colorado in the Upper Cambrian Sawatch, Upper Devonian Parting and Leadville Formations (Baars, 1976; Tweto, 1980a).

Pennsylvanian

The most intense Paleozoic deformation along the regional system took place during the formation of the Ancestral Rockies in the Pennsylvanian and early Permian (Ham and Wilson, 1967; DeVoto, 1980; Dutton and others, 1982). During this time, preexisting faults were reactivated to produce a series of fault-bounded uplifts and rapidly subsiding basins along all segments. The following discussion applies to all segments and is based primarily on the work of Kluth and Coney (1981) and the above-cited authors.

The initial movement was one of minor uplift and erosion during the latest Mississippian or earliest Pennsylvanian. Mississippian and older strata were stripped off broad areas that were then broken into horsts and grabens during the Pennsylvanian. These epeirogenic movements were followed by three pulses of deformation: one in the early Pennsylvanian (Morrowan-Atokan; Wichita Orogeny), one in the middle Pennsylvanian (Desmoinesian; Ouachita Orogeny), and one in the late Pennsylvanian to early Permian (Virgilian to Wolfcampian; Arbuckle or Marathon Orogeny). Thousands of feet of arkosic sediment accumulated in basins adjacent to basement-cored source terranes. Each succeeding pulse deformed sediments deposited during the previous episode. While the whole region was undergoing deformation at this time, the areas of greatest structural relief were confined to the regional fault system (fig. 10).

Permian

Tectonic activity decreased during the middle and late Permian, although preexisting structures continued to influence depositional patterns (McGookey, 1981; McGookey and Goldstein, 1982; fig. 11). The uplifts along the southeast segment subsided along with the adjoining basins to form the northern part of the Permian Basin (fig. 12). The Amarillo Uplift was completely covered by Wolfcampian shelf carbonate (Dutton and others, 1982). The Wichita Uplift continued to be a source of coarse arkosic sediment (the Pontatoc Formation) as late as mid-Permian. Younger Permian strata in the Anadarko Basin become clastic-rich in the vicinity of the uplift as well (Fay, R. O., 1964).

Deformation over the Apishapa Uplift was apparently intermittent during the mid-Permian. East of the Freezeout Creek fault zone, there is a complete section of Pennsylvanian and Lower Permian strata. West of the fault, the Pennsylvanian, upper Wolfcamp and lower Leonard are absent (fig. 13; Rascoe and Baars, 1972). Coarse arkosic sediments were deposited along the eastern side of the Front Range of Colorado and the Sangre de Cristo Mountains of New Mexico through the mid-Permian. Widespread unconformities within upper Permian strata are present throughout the region, indicating continued epeirogenic movement (Rascoe and Baars, 1972).

Mesozoic

Early and Middle Mesozoic deformation is difficult to document because of a general lack of Triassic and Jurassic strata within the regional fault system. In the Uncompaghre Mountains, Precambrian faults were reactivated during the Late Permian or early Triassic. The Cutler Formation (Permian) was folded and faulted prior to deposition of the Dolores Formation (Upper Triassic; Weimer, 1980). Along the southern extension of the Freezeout Creek fault zone, there appear to have been at least two episodes of deformation during the mid-Mesozoic. In northeastern New Mexico, Upper Triassic strata (Dockum Group) were folded prior to deposition of the Jurassic Exeter Formation (Baldwin and Muehlberger, 1959, fig. 14a). A few miles to the east, in northwestern Oklahoma, the Jurassic is folded beneath the Cretaceous (Stovall, 1943; fig. 14b).

Early Tertiary

The western parts of North and South America underwent major deformation during the Laramide Orogeny (latest Cretaceous and early Tertiary). Many Precambrian faults within the southern and northwestern segments of the regional system were again reactivated to form major uplifts and basins (Miller and others, 1963; Tweto, 1980b). The effects of this orogeny were much less pronounced along the southeastern segment. The Dakota Sandstone (lower Cretaceous) and older rocks were folded and faulted over the Apishapa and Freezeout Creek fault zones (Scott, 1968). The Dockum Group may have been downfaulted against the Permian along the south side of the Amarillo Uplift during this time (Barnes, 1969). Upper Permian strata are faulted at the surface along the north side of the Wichita Uplift (Carr and Bergman, 1976). The age of faulting is unknown, but may be related to the Laramide Orogeny.

Late Tertiary

A second major tectonic event occurred during the Tertiary in the western United States. The Basin and Range province formed as a result of extension during the Neogene (King, 1977). The eastern edge of this province, delineated by the Rio Grande Rift, lies along the southern and northwestern segments of the regional system. Many of the faults that bound the Neogene grabens within the Rio Grande Rift originated in the Precambrian, including the Tijeras and Picuris-Pecos faults in New Mexico (Kelley, 1979; Lisenbee and others, 1979) and the Ilse and Gore faults in Colorado (fig. 15; Taylor, 1975; Tweto, 1979, 1980b). Rift basins bounded by these and other reactivated faults are filled with up to 13,000 ft (4,000 m) of syntectonic deposits of the Sante Fe Formation (Kelley, 1977).

The southeast segment of the regional system was generally unaffected by Basin and Range deformation. The Ogallala Formation, coeval with the Sante Fe Formation, was deposited as a vast, relatively thin sheet east of the rift (fig. 15). In the Texas Panhandle, the Ogallala Formation averages about 300 ft (100 m) in thickness (Seni, 1980, fig. 16). Locally, however, there are areas of anomalous thickening. Along the south side of the Amarillo Uplift, the Ogallala is in excess of 800 ft (250 m) thick. This thick Ogallala section is in the Carson County Basin, part of the Whittenburg Trough (Soderstrom, 1968) (fig. 17).

The Carson County basin lies within the zone of Quaternary dissolution of Permian evaporites (Gustavson and others, 1980; fig. 18) and may be related to Neogene dissolution. However, the similarity of post-salt (Ogallala) and pre-salt (Tubb, Wolfcampian, and basement) structures in the basin (fig. 19) suggests that it is of tectonic origin. A proprietary seismic line across the eastern end of the basin confirms the presence of a pre-salt graben in this area. The Carson County basin is interpreted to be a rhomb graben formed as the result of local strike-slip faulting during Basin and Range deformation in the Neogene.

TECTONIC HISTORY OF THE PALO DURO BASIN

The history of deformation within the Palo Duro Basin is closely related to that of the surrounding region. The effects of each deforming event were more subtle, however, in the basin than along the regional fault system.

The dominant structural grain of the Palo Duro Basin is northwest (Nicholson, 1960; Budnik and Smith, 1982; Dutton and others, 1982), as defined by the orientation of numerous fault-bounded blocks within and adjacent to the basin (fig. 20). This trend is parallel to that of individual faults within the Amarillo Uplift and Matador Arch, but oblique to the overall strike of these two features.

Precambrian

Timing of the initiation of faulting within the basin is difficult to document. As discussed above, the Palo Duro Basin was part of a larger Proterozoic basin or series of basins (fig. 7). Proterozoic basin fill within the Palo Duro Basin consists of rhyolite (Panhandle terrane), diabase and intercalated calcareous and siliceous metasediments (Swisher Terrane) and coeval granite (Amarillo terrane) onto which the volcanics were extruded (Flawn, 1956; Muehlberger and others, 1967; Goldstein, 1982). The volcanics were originally believed to be approximately 1,100 my old (Muelhberger and others, 1966); however, recent age determinations place them at about 1,300 mya (W. Muehlberger, personal communication). The bimodal basalt-rhyolite association, indicative of a rift environment (Hoffman and others, 1974; Condie and Budding, 1979), implies contemporaneity of faulting and volcanism. Where contacts between terranes are relatively well-defined, they coincide with faults. Tweto (1980b) and Brewer and others (1983) observed similar relationships between basement terranes and faults along the southeast segment of the regional system and postulated a Precambrian origin for those faults. Faults within the Palo Duro Basin may also have formed 1,300 mya.

Late Precambrian-Early Paleozoic

Evidence for Late Precambrian-Early Cambrian deformation within the Palo Duro Basin is tenuous. An arkosic sandstone occurs beneath basal Cambrian(?) quartzose sandstone in a few wells within the basin. This arkose is generally considered on sample logs to be weathered basement. However, in the Sun Oil Company #1 Herring well in Castro County (BEG #Castro 11, fig. 21), Roth (1960) described the unit as consisting of slightly metamorphosed arkosic sandstone and interbedded pyroclastics. This unit, which lies on diabase of the Swisher terrane in the Sun Oil well appears to be preserved in the deepest part of the Castro Trough (named by Birsa, 1977; figs. 22, 23, and 24). The age of the arkose is unknown. Other sandstone units in the Proterozoic basin are primarily graywackes (Tillman) or quartzites (DeBaca; Muehlberger and others, 1967). The Las Animas Formation (Tweto, 1983) consists of two distinct phases (1) gray quartzite and graywacke similar to the Tillman Group and (2) arkose, graywacke, and phyllite, all maroon in color, some limestone, and thin interbeds of volcanics. The two phases are found in wells 40 miles (65 km) apart. Tweto (1983) interprets the arkosic phase to be the upper part of the formation. However, the arkose may be a younger unit and it and the Castro County arkose may reflect faulting during the opening of the southern Oklahoma aulacogen.

A stable shelf occupied the area of the Palo Duro Basin during the Late Cambrian to Early Ordovician (Dutton and others, 1982). Sometime between mid-Ordovician and early Missisippian time, a northwest trending area in the central Panhandle was uplifted to form the Texas Arch (fig. 25; Adams, 1954). Ellenburger (Ordovician) carbonates and Cambrian(?) clastics were eroded from the crest of the arch, except where preserved in downfaulted blocks, such as the Castro Trough (fig. 22). Silurian and Devonian sediments present on the flanks of the arch are absent over the crest due to erosion or non-deposition. 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 Devonian (Hunton Group) are truncated below Upper Devonian and Lower Mississippian strata (Tarr and others, 1965), suggesting a mid-Devonian age of deformation (Ham and Wilson, 1967).

Pennsylvanian

The formation and major deformation of the Palo Duro Basin coincided with the development of the Ancestral Rockies (Goldstein, 1982). During this time, the Palo Duro Basin underwent three pulses of deformation (Ham and Wilson, 1967). Initially, the basin formed in the latest Mississippian to earliest Pennsylvanian as a result of the breakup of the Mississippian shelf along preexisting faults. Mississippian and older strata were eroded off fault blocks within the basin and surrounding uplifts (Dutton and others, 1982). Lower Pennsylvanian sediments were deposited primarily in the southeastern part of the basin, which was an extension of the Hardeman Basin (fig. 26; Budnik and Smith, 1982). The main period of deformation occurred during the mid-Pennsylvanian (Dutton and others, 1982). The basin axis shifted westward and became oriented parallel to the northwest trending structural grain (fig. 26). A series of deep grabens (the Whittenburg Trough; Soderstrom, 1968) developed along the south flank of the Amarillo Uplift and separated the uplift from the Palo Duro Basin (fig. 20). The trough trapped most of the arkosic sediment shed off the south side of the uplift (fig. 27). Intrabasinal fault blocks were important sources of sediment. Lower Pennsylvanian deposits thin by up to 50 percent across upfaulted blocks, and in some cases are absent on the higher structures (fig. 28). By the end of the Desmoinesian (middle Pennsylvanian), many of the structural highs had been eroded down and most of the area was covered by a carbonate shelf (Dutton, 1980; Handford and others, 1981).

Renewed movement during the Late Pennsylvanian differentiated the region into a well-defined basin and shelf-margin complex (Dutton and others, 1982). Carbonate buildups were localized on structurally high blocks (figs. 29 and 30; Handford and others, 1981; Budnik and Smith, 1982). Episodic movement throughout the Late Pennsylvanian and Early Permian (Wolfcampian) maintained the high standing areas. This phase culminated in the Wolfcampian with erosion of Upper Pennsylvanian (Cisco) strata from fault blocks in the southwestern part of the basin (Budnik and Smith, 1982) and a westerly shift of the basin axis (figs. 26 and 31). The remainder of the Wolfcampian was marked by a filling of the basin and development of a carbonate shelf over the entire region (Handford, 1980).

Permian

A second basin formed in the mid-Permian (Leonardian) under the influence of regional subsidence associated with the larger Permian Basin (fig. 12; Budnik and Smith, 1982). The Palo

Duro Basin subsided nearly continuously during the remainder of the Paleozoic, eventually being filled with over 4,000 ft (1,200 m) of evaporites and related strata, which were deposited at or near sea level (fig. 32; Presley, 1980).

Basement structures continued to subtly influence depositional patterns during this phase. The entire evaporitic interval thins over basement highs. In the Castro Trough, for example, which apparently existed during the pre-Paleozoic, the pre-Mississippian, and the Pennsylvanian, Permian deposits were also affected by basement structure (fig. 33). Mid-Permian (Leonardian) strata (Wichita Group and Glorieta Formation) are more clastic-rich in the trough than on the flanking highs (figs. 34 and 35; Presley and McGillis, 1982; Handford, unpublished data). Upper Permian (Guadalupian) units exhibit similar trends. Salt in the San Andres Cycle 4 thickens into the trough (fig. 36) as does the clastic portion of the Salado-Tansill Formation (fig. 37; McGillis and Presley, 1981). The uppermost Permian evaporitic unit (the Alibates Formation) thins over the basement high northeast of the Castro Trough (McGillis and Presley, 1981). In central Randall County, the Permian thins over a basement high and units as young as the Alibates are deformed over a basement fault (fig. 8). In Palo Duro Canyon, intraformational angular unconformities in the Quartermaster Formation (fig. 38) indicate that deformation continued into the latest Permian.

Mesozoic

Minor deformation continued into the Mesozoic. Locally, there is an angular unconformity at the base of the Dockum Group (fig. 39). Depositional patterns in the Dockum Group (Upper Triassic) fluvial-lacustrine deposits (McGowen and others, 1979) were influenced by basement structures. In the Castro Trough, for example, the Dockum is thicker and more sand-rich than in adjacent areas (figs. 40 and 41).

Cenozoic

Evidence for Laramide deformation is lacking within the Palo Duro Basin, primarily because of the absence of deposits of the appropriate age. The Ogallala Formation (Neogene) rests unconformably upon pre-Tertiary strata (fig. 42; Seni, 1980; Barnes, 1968). In the Neogene, the basement structures again subtly influenced depositional patterns. Major channel systems in the Ogallala tend to overlie basement lows, whereas interchannel areas correspond to structural highs (fig. 43). The Ogallala Formation is thicker and has a higher percentage of sand in the Castro Trough than it does over the basement high to the northeast (fig. 44). In the southwestern parts of Deaf Smith and Randall Counties, Dockum strata crop out from beneath a thin veneer of Ogallala on top of basement highs (fig. 43).

SUMMARY

The tectonic history of the Palo Duro Basin and surrounding region has been dominated by recurrent motion on a regional fault system. This three-pronged system, extending from Oklahoma and New Mexico into Colorado may have originated as a result of deep mantle processes 1,800 to 1,900 mya. Faults along this system were reactivated several times during the Precambrian and formed the boundaries of a large Proterozoic basin in eastern New Mexico, West Texas, and southwestern Oklahoma. The southern Oklahoma aulacogen opened along the southeast segment of the system during the Late Precambrian to early Cambrian.

Where evidence exists, it appears that the system underwent renewed movement during the Late Cambrian, Middle Devonian, and mid-Mississippian. The Ancestral Rockies formed in the Pennsylvanian as a series of uplifted blocks within the regional fault zone, flanked by rapidly subsiding basins. Three pulses of deformation during the Pennysivanian and Early Permian maintained the relative relief between uplifts and basins.

Regionally, relief was subdued during the Permian and Mesozoic, although individual faults were reactivated periodically. The southern and northwestern segments of the regional system underwent major deformation in the Laramide Orogeny. Evidence of deformation along the southeastern segment at this time consists primarily of local faults and unconformities within the Mesozoic and upper Permian section. The Neogene Basin and Range event affected the same segment of the regional system as the Laramide. A rhomb graben developed along the southeastern segment during deposition of the Ogallala Formation.

The tectonic history of the Palo Duro Basin closely followed that of the regional system. The dominant northwest-trending fault set in the basin parallels the regional fault pattern. The intrabasinal faults probably originated at the time of formation of the Proterozoic basin. Although the evidence is sketchy, it appears that the faults may have been reactivated during the Late Precambrian to Early Cambrian and in the mid-Devonian.

Deformation during the remainder of the Phanerozoic is best documented by facies changes within the stratigraphic section. The initial Palo Duro Basin formed in the Early Pennsylvanian as a result of the reactivation of basement faults during uplift of the Ancestral Rockies. The basin axis shifted westward and became better defined with each succeeding pulse of deformation. Intrabasinal fault blocks localized carbonate buildups and deposition of clastic sediments.

Filling of the basin at the end of the Wolfcampian was followed by the formation of a second basin in the Leonardian. Depositional patterns within the predominantly evaporite section of this basin were subtly influenced by basement structures. Within a given unit, structural lows tend to contain thicker salt beds and a greater percentage of clastics than adjoining highs.

Mesozoic and Cenozoic terrestrial deposits demonstrate the same subtle basement control on facies distribution. The Dockum Group and the Ogallala Formation are thicker and more sand-rich in structural lows.

The Palo Duro Basin exhibits the effects of recurrent deformation beginning in the Precambrian and continuing through to at least the Neogene.

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Figure Captions

Figure 1. Structural elements of the Texas Panhandle. After Nicholson (1960).

Figure 2. Isopach of the Pennsylvanian system. After Dutton and others (1982).

Figure 3. Position of shelf margins during Pennsylvanian, and Early and Middle Permian. After Ramondetta (1982).

Figure 4. Tectonic map of Texas Panhandle and surrounding region modified from King (1969) and Budnik and Smith (1982).

Figure 5. COCORP seismic reflection profile, Hardeman Basin, Oklahoma. p€: top of basement, A, B, and C are reflectors within basement. Note truncation of Precambrian layering at east end of line. Precambrian fault probably caused truncation, and was reactivated by Pennsylvanian movements as Burch Fault. (Brewer and others, 1981). See figure 7 for location.

Figure 6. Distribution of Las Animas Formation, southeastern Colorado. (Tweto, 1983).

Figure 7. Distribution of basement terranes. Vertical ruling-Proterozoic basin fill, LA-Las Animas Formation, PV-Panhandle volcanics, SD-Swisher diabase, DB-DeBaca terrane, TG-Tillman Group, FT-Fisher terrane; blank-granitic rocks less than 1400 mya; diagonal ruling-rocks older than 1400 mya. Stippled rocks younger than 600 my. From Edwards (1966); Muehlberger and others (1966, 1967); Denison and Hetherington (1969); Olson and others (1977); Condie and Budding (1979); Condie (1982); Tweto (1983). H-location of figure 5, S-location of figure 8.

Figure 8. Seismic reflection profile, Palo Duro Basin. IP-top of Pennsylvanian, p€-top of basement; A and B are reflectors within basement. Termination of reflectors at C and D probably due to Precambrian faults that were reactivated in the Pennsylvanian. See figure 7 for location.

Figure 9. Precambrian-aged faults in Colorado. From Tweto (1980a) and Baars (1976).

Figure 10. Distribution of arkosic sandstone and basement uplifts of the Ancestral Rocky Mountains. (McKee and others, 1975).

Figure 11. Isopach map of lower Glorieta (Leonardian). Sandstone bed pinches out against flank of Amarillo Uplift. (McGookey, 1981).

Figure 12. Outline of Permian Basin. (McKee and Oriel, 1967, plate 19).

Figure 13. East-west cross section across Freezeout Creek fault. (Rascoe and Baars, 1972).

Figure 14a. East-west cross section, Union County, New Mexico, showing angular unconformity below Jurassic. (Baldwin and Muehlberger, 1959).

Figure 14b. Northwest-southeast cross section, Cimarron County, Oklahoma, showing angular unconformity between Jurassic (Morrison Formation) and Cretaceous (Purgatoire Formation) (Stovall, 1943).

Figure 15. Distribution of syntectonic Neogene sediments, High Plains and Rio Grande Rift. (Robinson, 1972; Scott, 1975; Weeks and Gutentag, 1981). Faults from Tweto (1979) and Kelley (1979).

Figure 36. Net salt map, Cycle 4, lower San Andres Formation, Castro County (Presley, unpublished data).

Figure 37. Net-clastic map, Salado-Tansill Formation. Mudstone-siltstone beds and mudstone are intercalated with salt. Northwest-trending depositional axes define strike-oriented mud flats. Values determined from gamma ray logs (McGillis and Presley, 1981).

Figure 38. Photograph of intraformational angular unconformity within Quartermaster Formation, Palo Duro Canyon State Park. Photo by E. Collins.

Figure 39. Photograph of angular unconformity between Quartermaster Formation and Dockum Group at Capital Peak, Palo Duro Canyon State Park. Photo by E. Collins.

Figure 40. Isopach map of Dockum Group (Triassic) and Dewey Lake Formation (uppermost Permian), Castro County, contour interval: 50 ft.

Figure 41. Percent sand, lower Dockum Group (McGowen, unpublished data). Contour interval: 5 percent.

Figure 42. Photograph of angular unconformity between Dockum Group and Ogallala Formation. South side of Palo Duro Canyon, looking east from State Highway 207, Armstrong County.

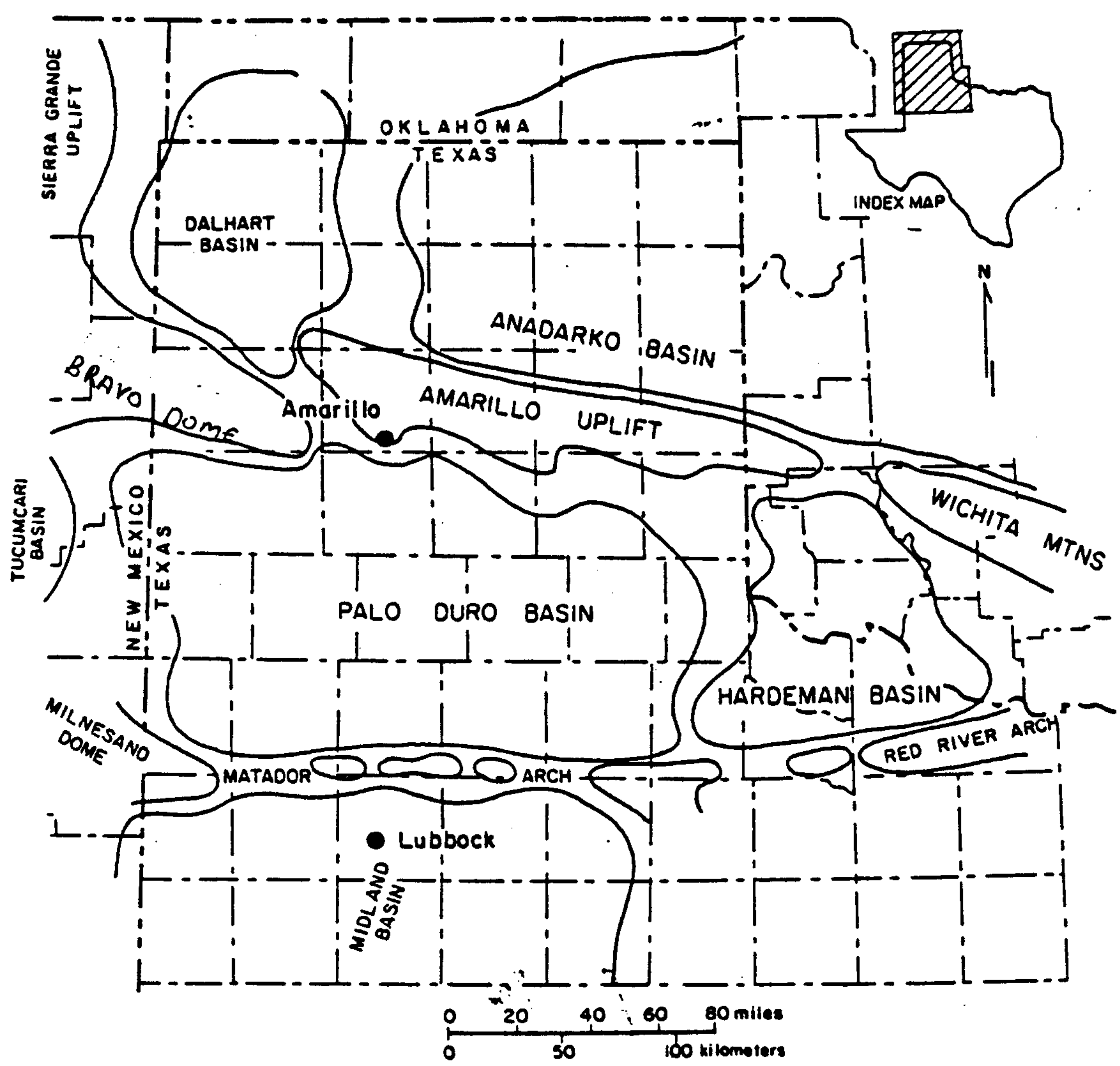
Figure 43. Schematic illustration of Ogallala depositional facies and sediment dispersal systems. Width and length of arrows indicate relative intensity of fluvial processes. Facies not time-equivalent (Seni, 1980). Vertical ruling = Dockum outcrops (Barnes, 1977).

Figure 44. Net sand, Ogallala Formation, Castro County (Knowles and others, 1982). Contour interval: 20 ft.

TABLE 1

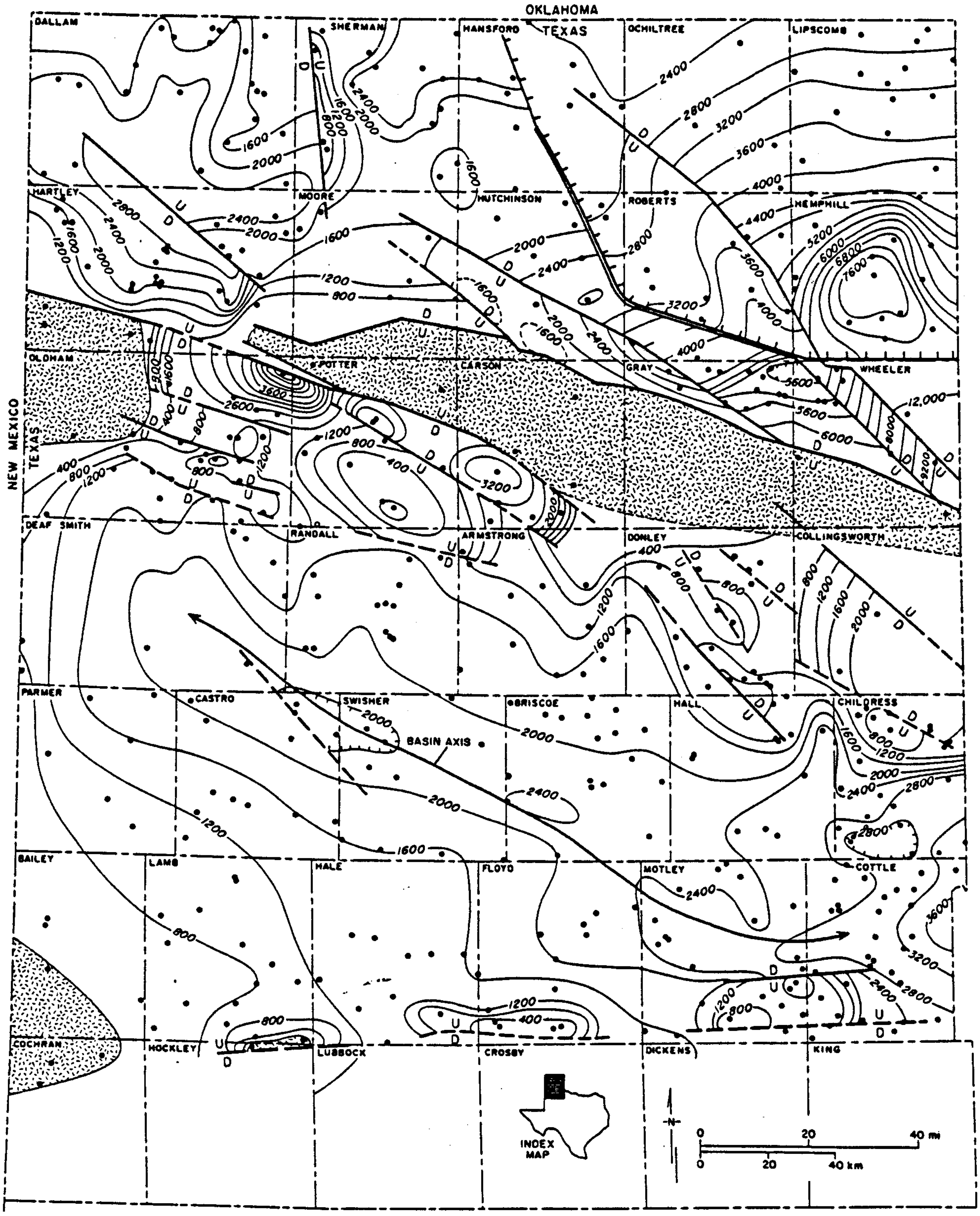
County B.E.G. #	
Bailey	
8	Lion Oil Company, Birdwell #1
17	Phillips Petroleum Company, Stephens A #1
Castro	
6	Ashmum and Hilliard, Formwalt #1
8	I. A. Stephens, I. C. Little #1
9	Ashmum and Hilliard, Willis #1
11	Sun Oil Company, L. C. Boothe, #1
13	Amarillo Oil Company, L. C. Boothe #1
14	Sun Oil Company, A. L. Habenen #1
Parmer	
10	Sunray, Kimbrough #1
Swisher	
3	Frankfort Oil Company, Culton #1

Figure 1



SIERRA GRANDE UPLIFT
OKLAHOMA
TEXAS
DALHART BASIN
INDEX MAP
N
ANADARKO BASIN
BRAVO DOME
Amarillo
AMARILLO UPLIFT
WICHITA MTNS
TUCUMCARI BASIN
NEW MEXICO
TEXAS
PALO DURO BASIN
HARDEMAN BASIN
MILNESAND DOME
MATADOR
ARCH
RED RIVER ARCH
Lubbock
MIDLAND BASIN
0 20 40 60 80 miles
0 50 100 kilometers

Figure 2



EXPLANATION

Precambrian basement exposed throughout Pennsylvanian

Faults

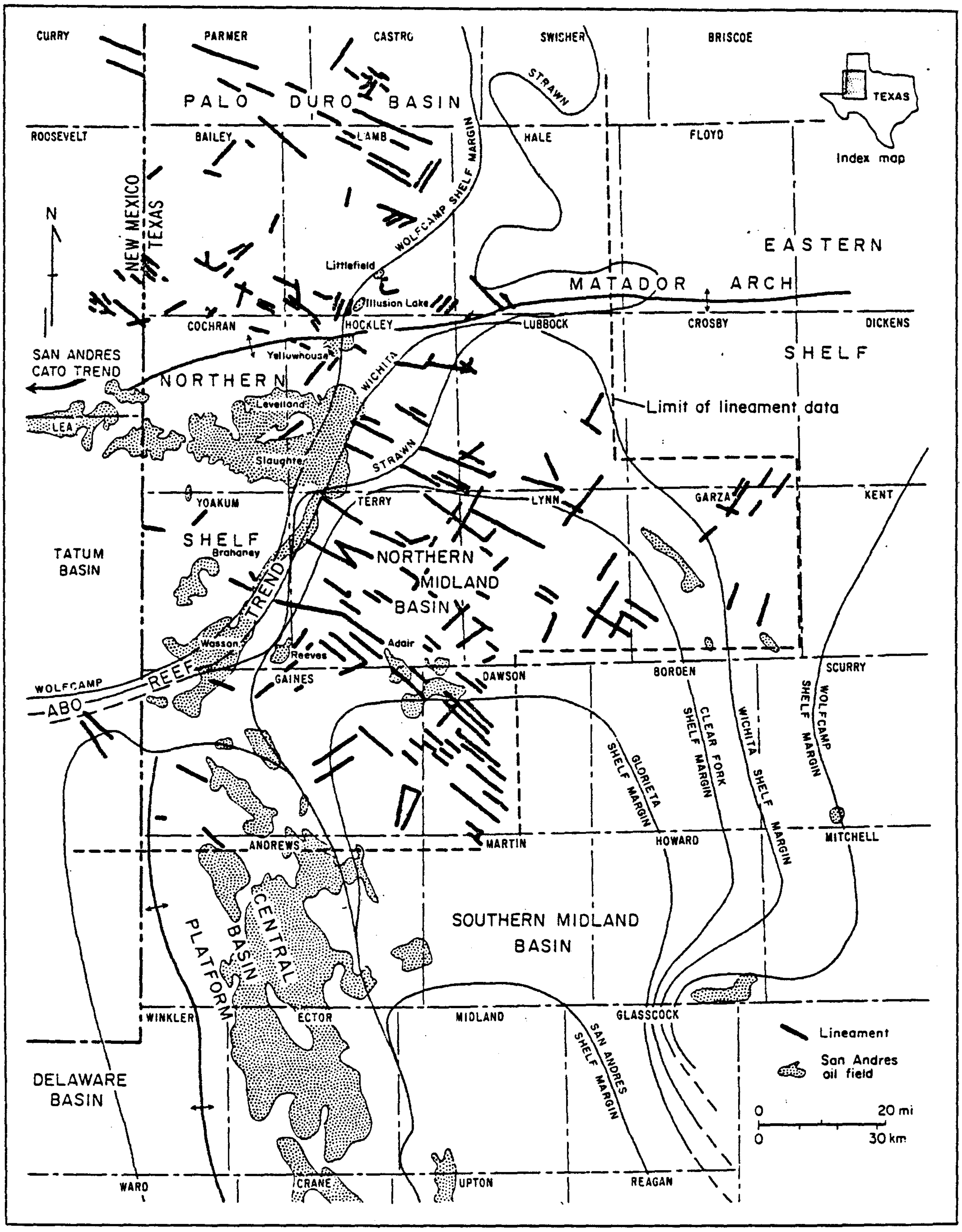
Well control

Contour interval = 400 ft

Axis of basin

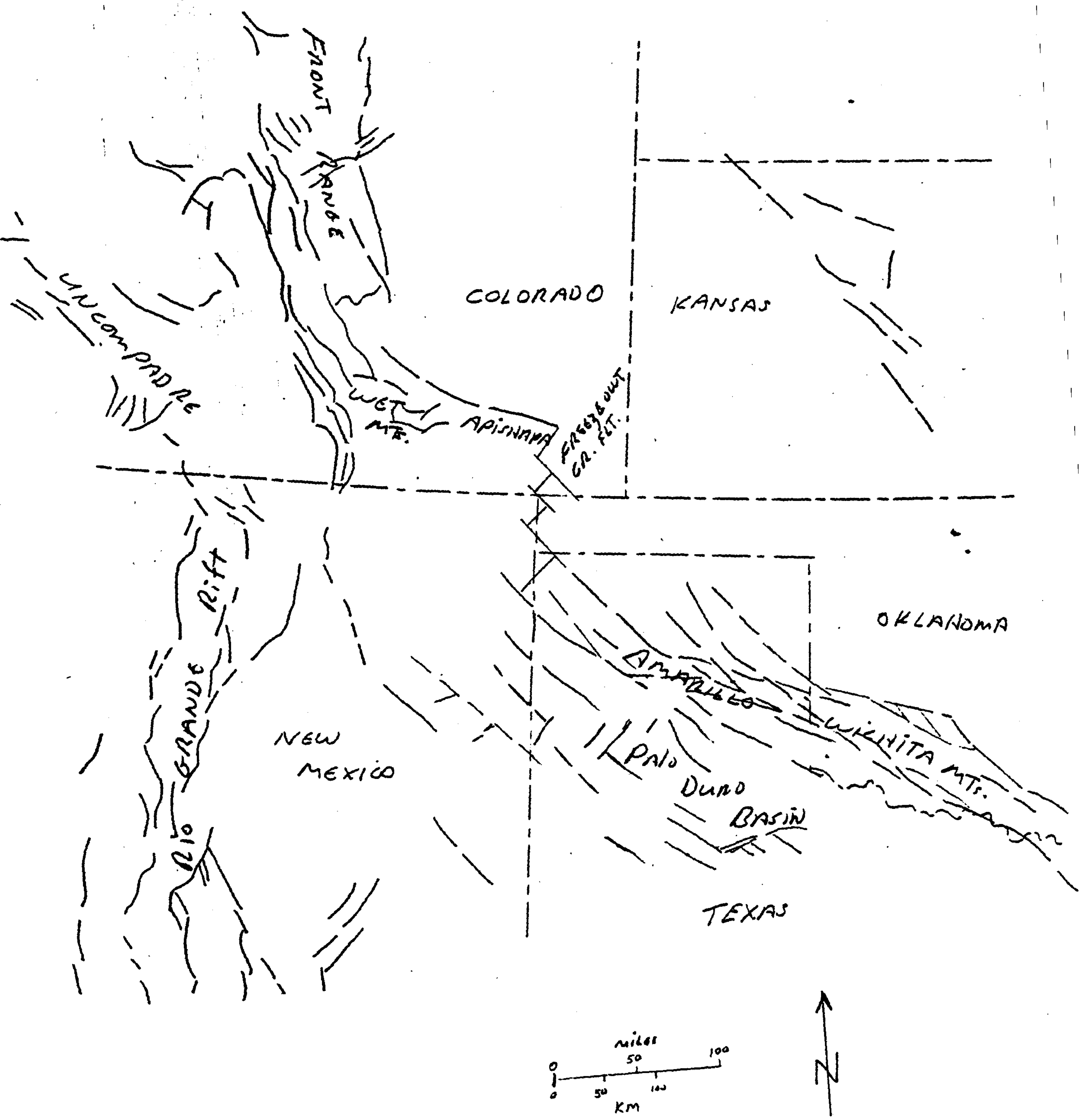
Area northeast of hachured line shows thickness from top of Mississippian to top of Missourian Series.

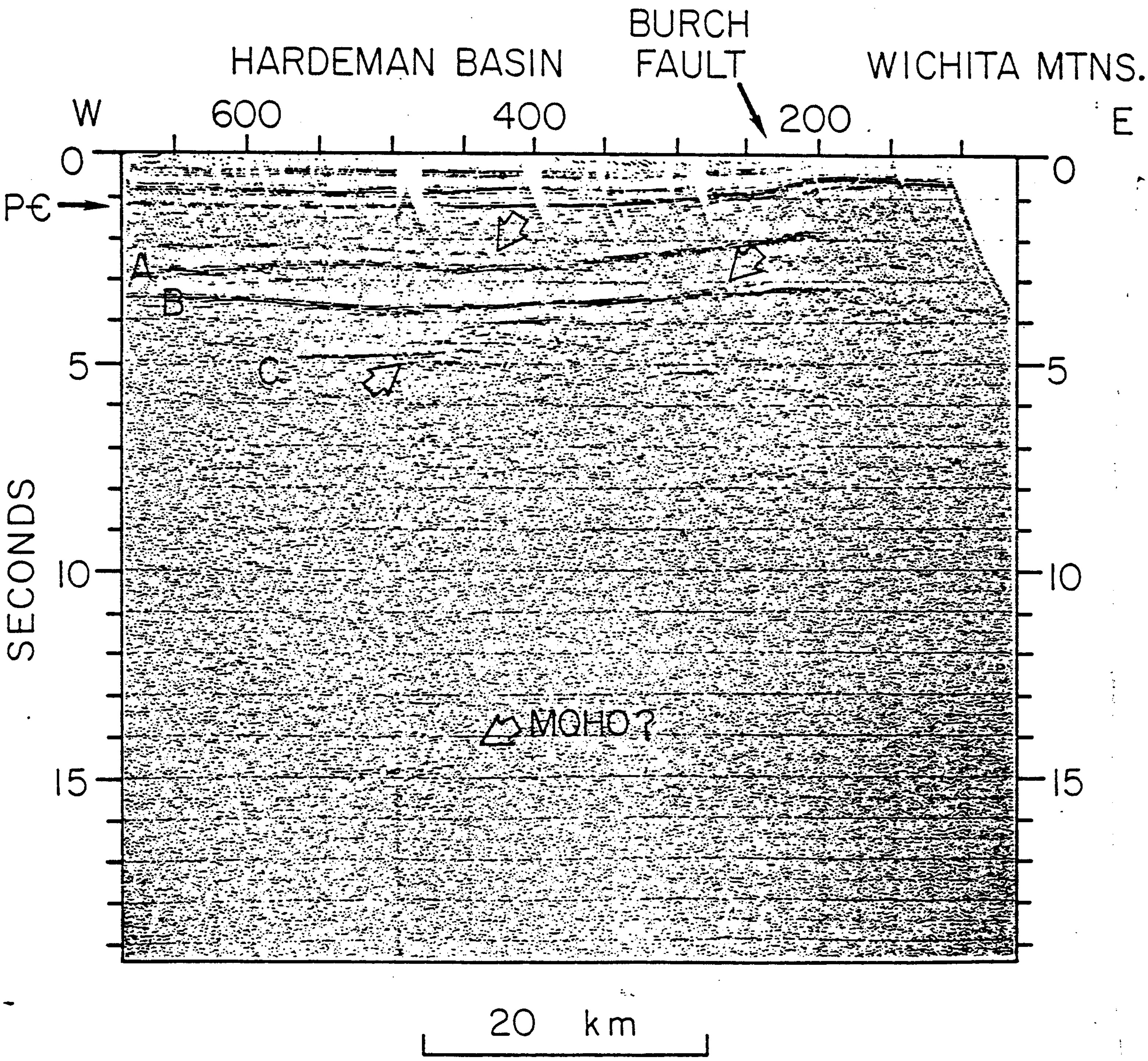
Isopach map of Pennsylvanian System. After Dutton and others (1982).



Map of study area in Texas showing San Andres oil production, shelf margins, and surface lineaments. Surface lineaments are from Finley and Gustavson (1981), and shelf-margin positions are from J. H. Nicholson (personal communication, 1980).

Figure 4


FRONT RANGE
UNCOMPADRE
COLORADO
KANSAS
WET MT.
APISHAPA
FREEZEOUT CR. FLT.
OKLAHOMA
AMARILLO
WICHITA MTS.
PALO DURO BASIN
NEW MEXICO
RIO GRANDE RIFT
TEXAS
MILES
0
50
100
0
50
100
KM
N


BURCH
FAULT
HARDEMAN BASIN
WICHITA MTNS.
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B
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15
SECONDS
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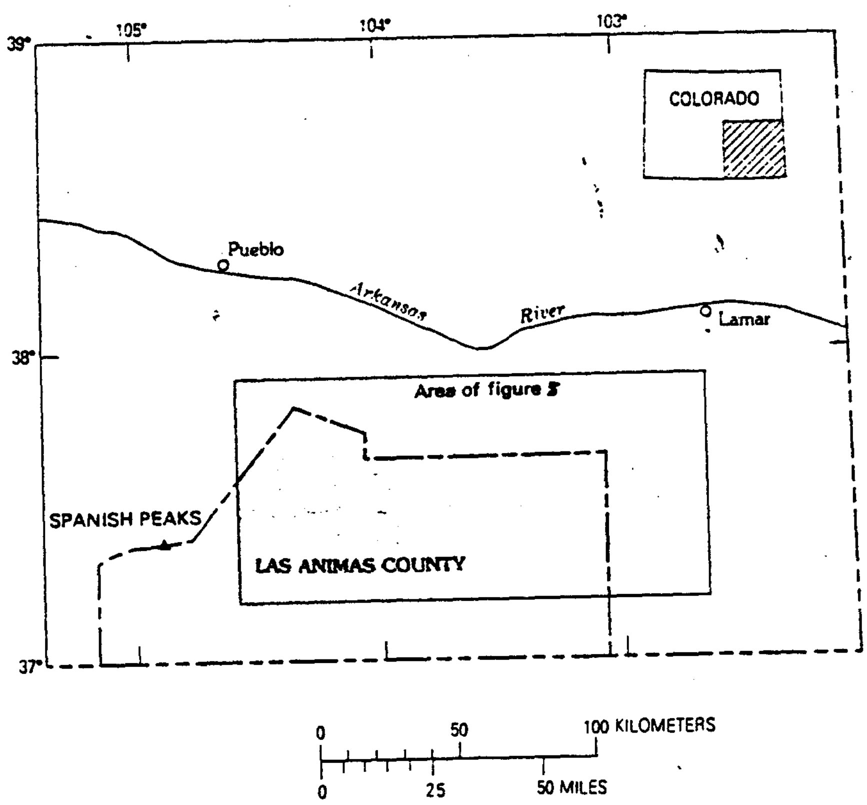
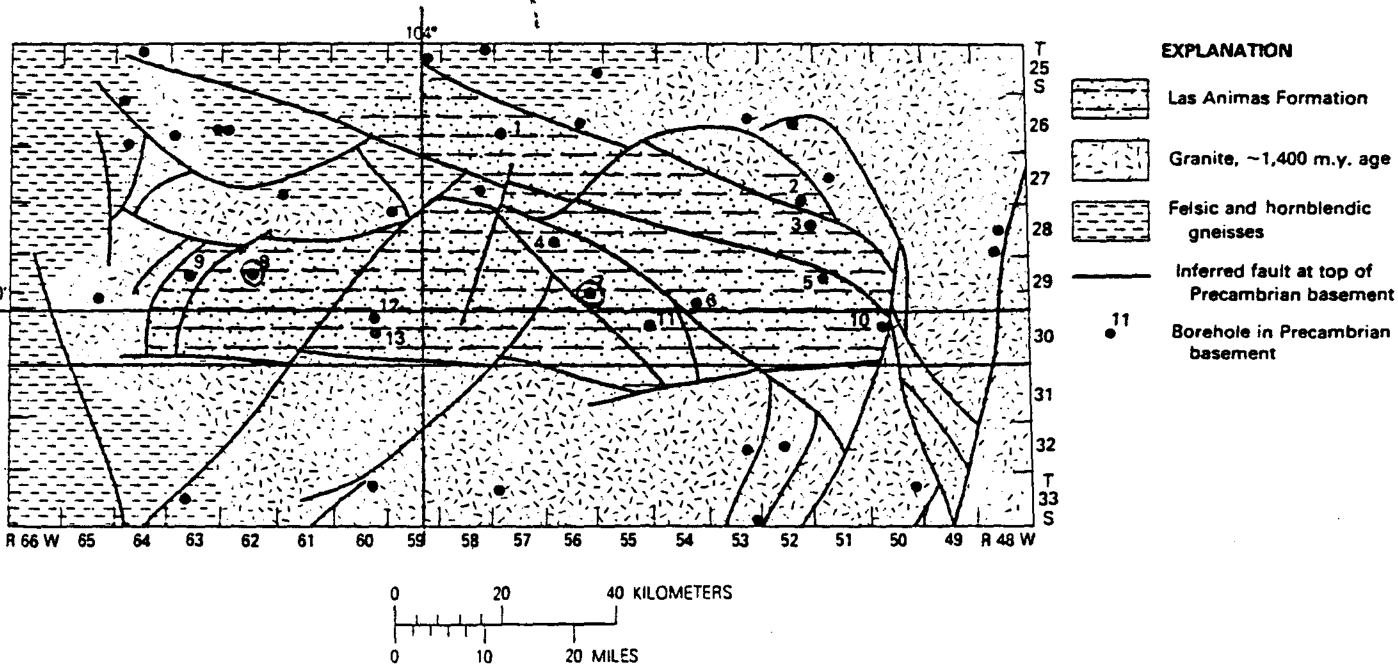
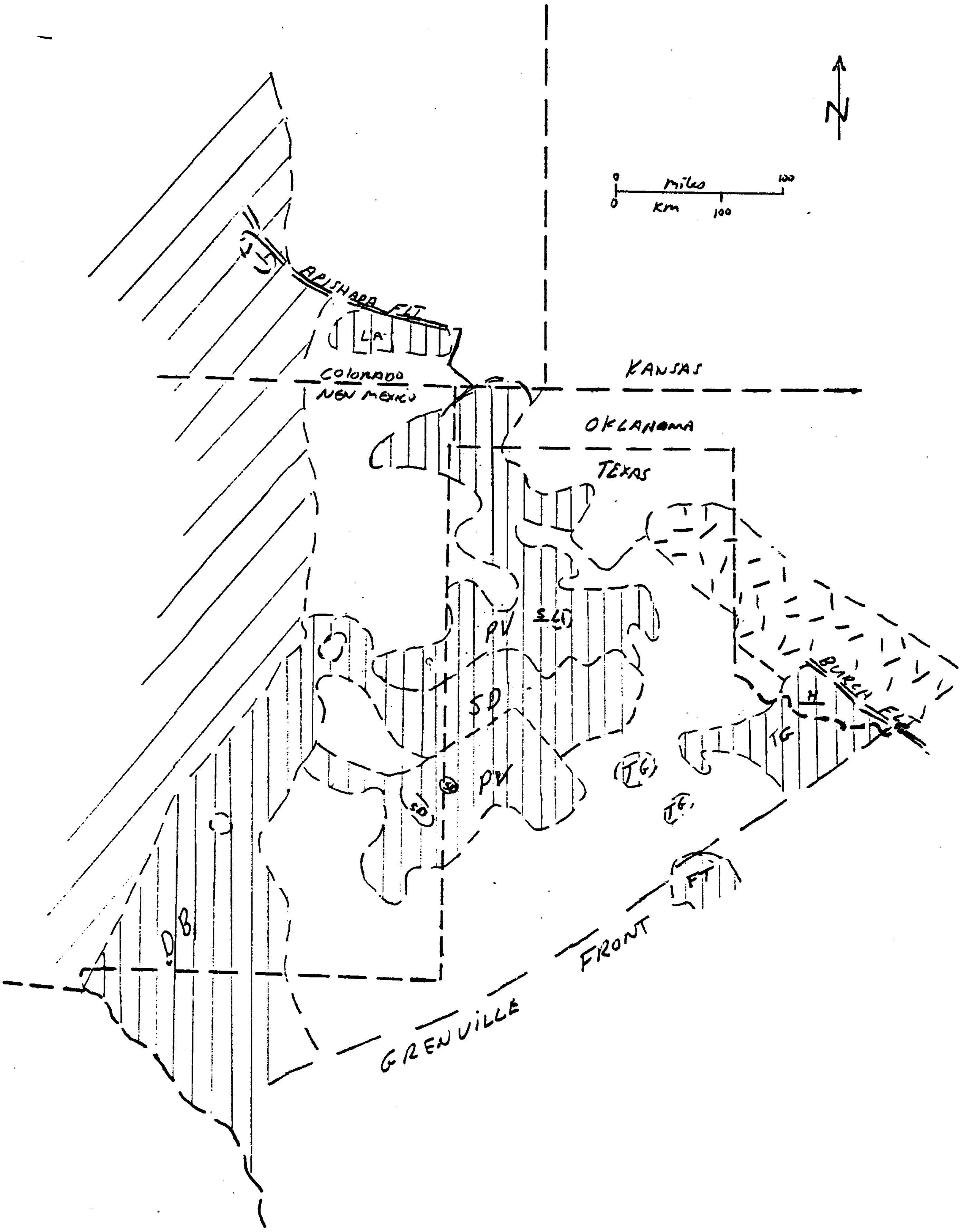
20 km



Index map of southeastern Colorado.




N
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COLORADO
NEW MEXICO
KANSAS
OKLAHOMA
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BURCH FLT
FT
DB
GRENVILLE FRONT

Figure 8

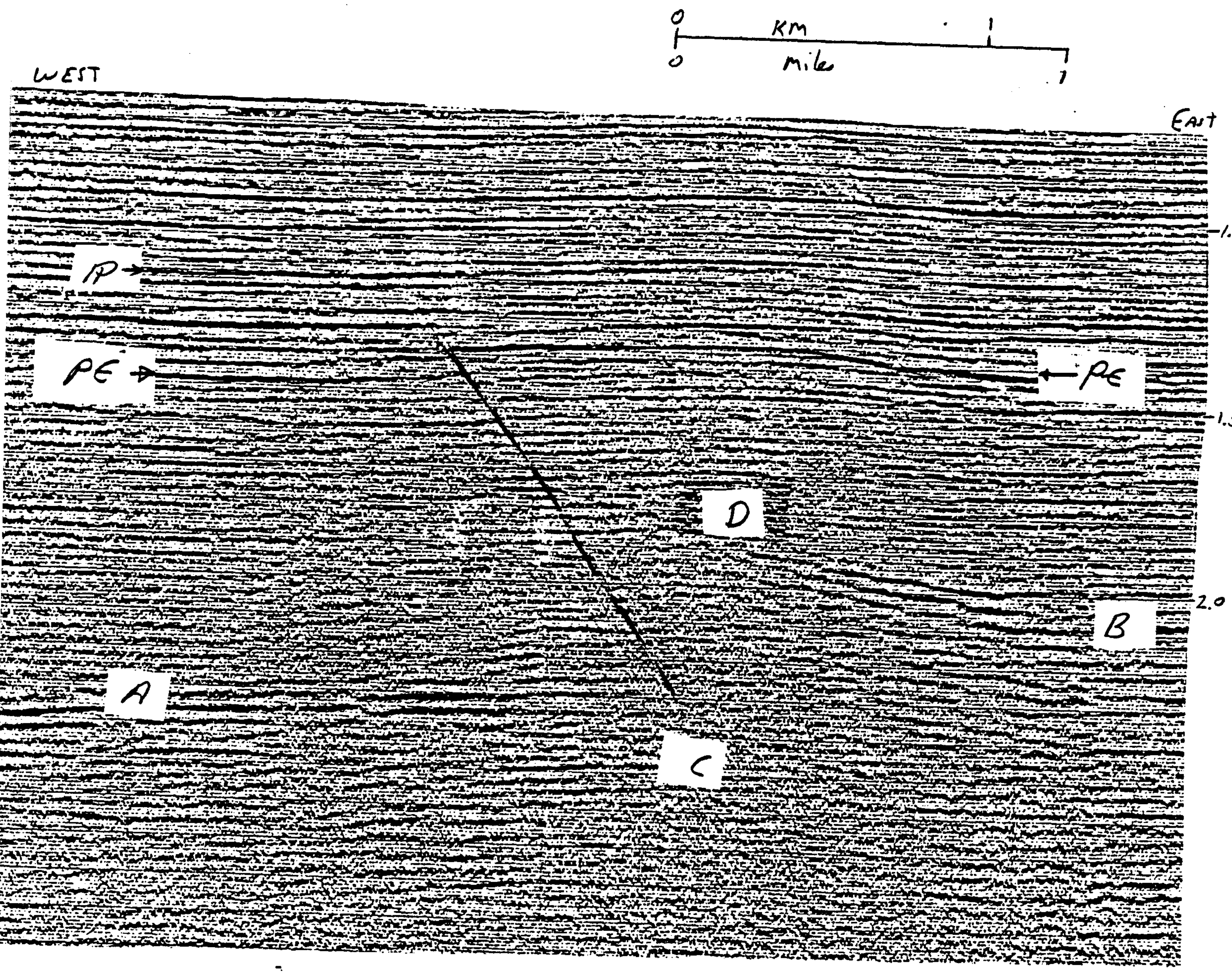
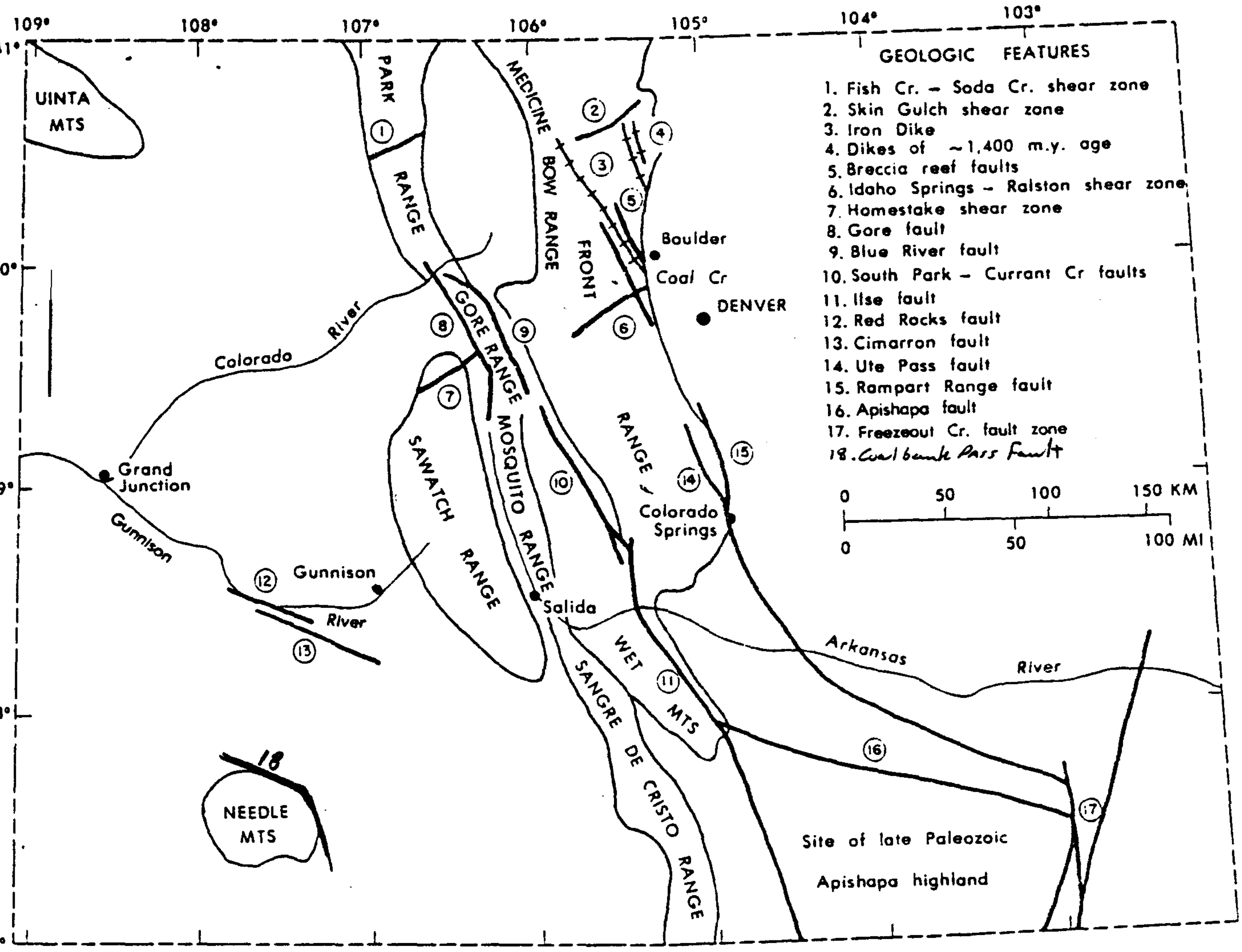
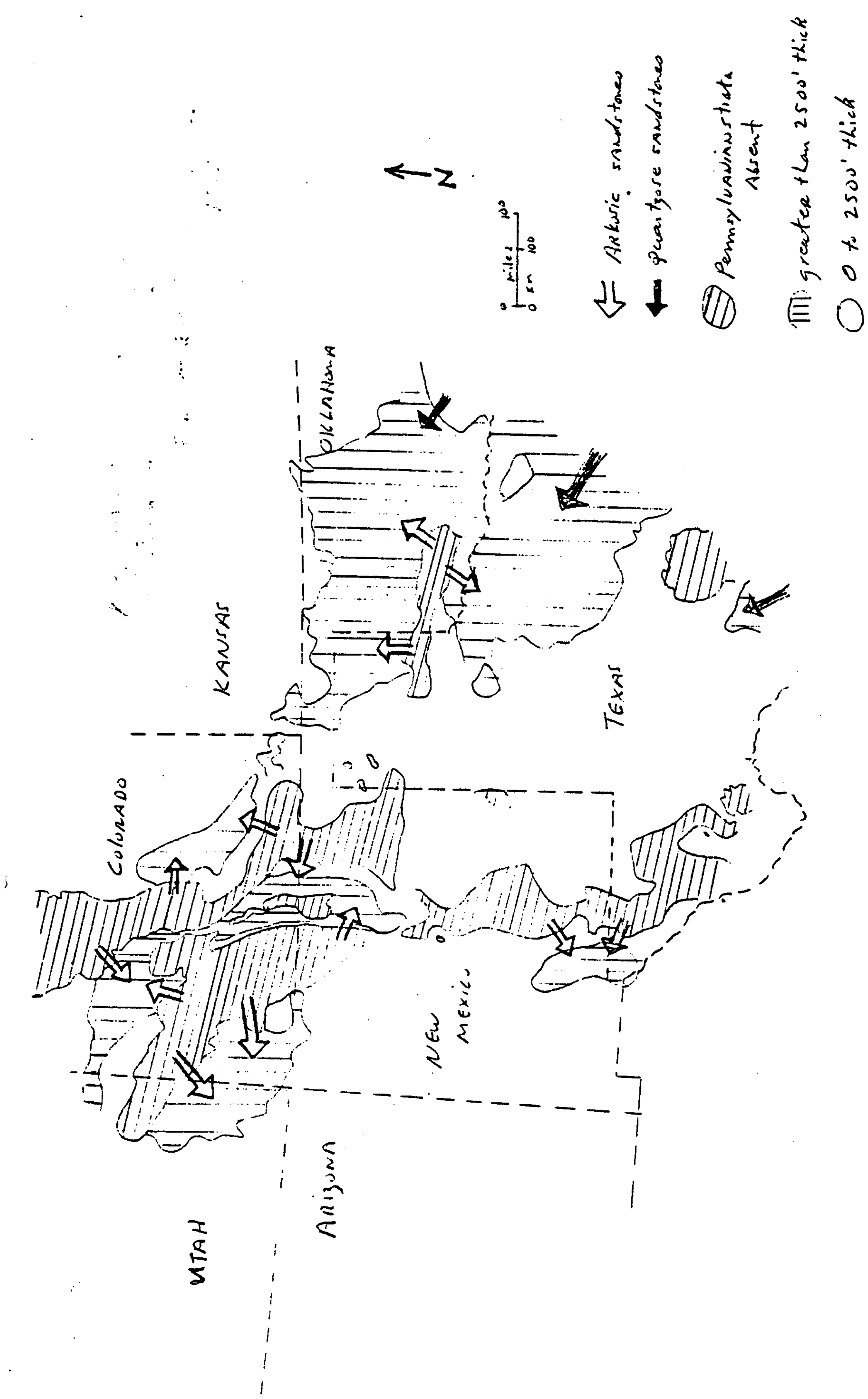


Figure 9



109°
108°
107°
106°
105°
104°
103°
41°
40°
39°
38°
37°
GEOLOGIC FEATURES
1. Fish Cr. – Soda Cr. shear zone
2. Skin Gulch shear zone
3. Iron Dike
4. Dikes of ~1,400 m.y. age
5. Breccia reef faults
6. Idaho Springs – Ralston shear zone
7. Homestake shear zone
8. Gore fault
9. Blue River fault
10. South Park – Currant Cr faults
11. Ilse fault
12. Red Rocks fault
13. Cimarron fault
14. Ute Pass fault
15. Rampart Range fault
16. Apishapa fault
17. Freezeout Cr. fault zone
18. Coal bank Pass Fault
0 50 100 150 KM
0 50 100 MI
UINTA MTS
PARK RANGE
MEDICINE BOW RANGE
FRONT RANGE
GORE RANGE
MOSQUITO RANGE
SAWATCH RANGE
WET MTS
SANGRE DE CRISTO RANGE
NEEDLE MTS
Boulder
Coal Cr
DENVER
Colorado River
Grand Junction
Gunnison River
Gunnison
Salida
Colorado Springs
Arkansas River
Site of late Paleozoic
Apishapa highland

Figure 10


N
miles 100
0 km 100
Arkosic sandstones
Quartzose sandstones
Pennsylvanian strata Absent
greater than 2500' thick
0 to 2500' thick
UTAH
COLORADO
KANSAS
OKLAHOMA
ARIZONA
NEW MEXICO
TEXAS

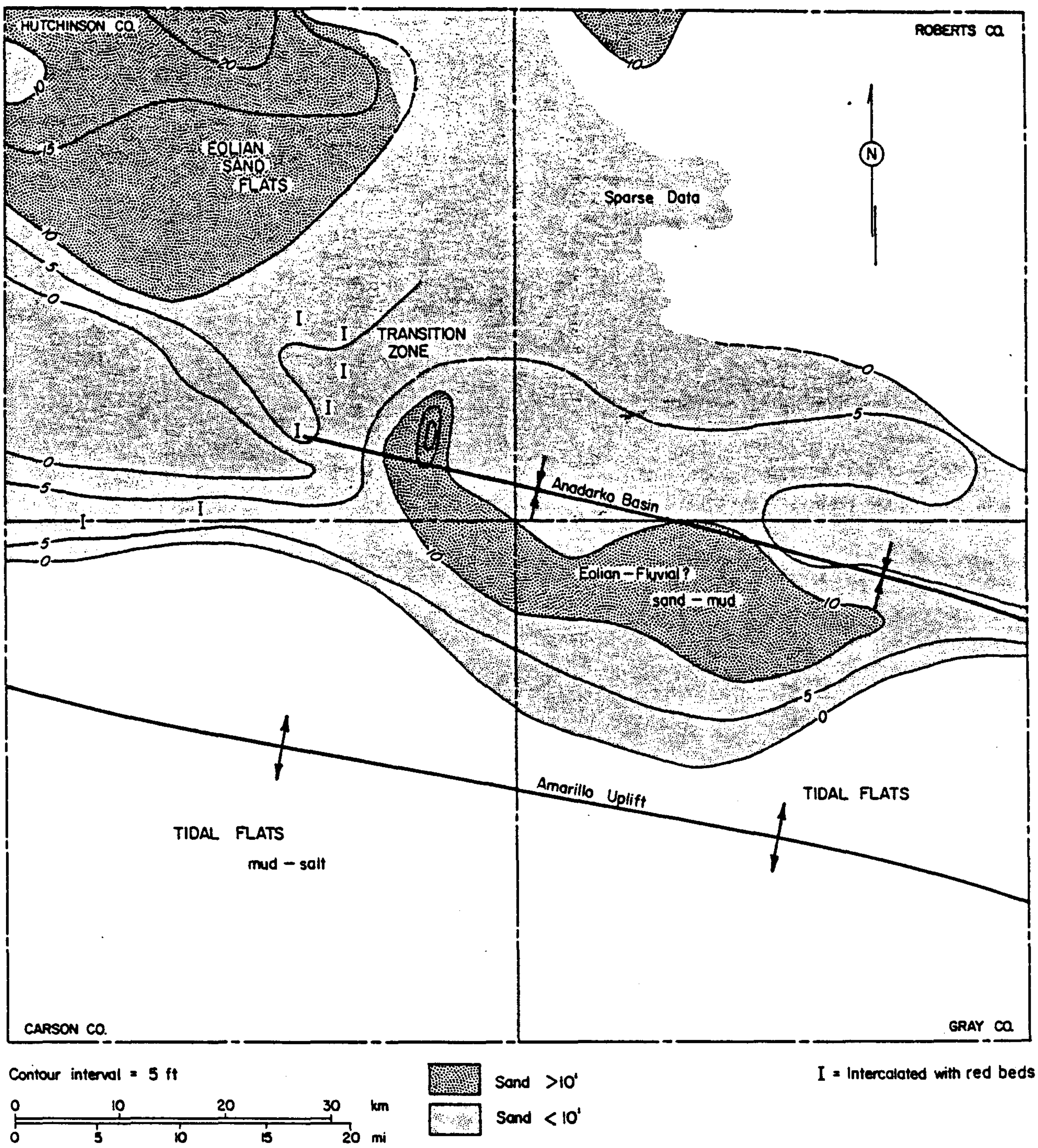
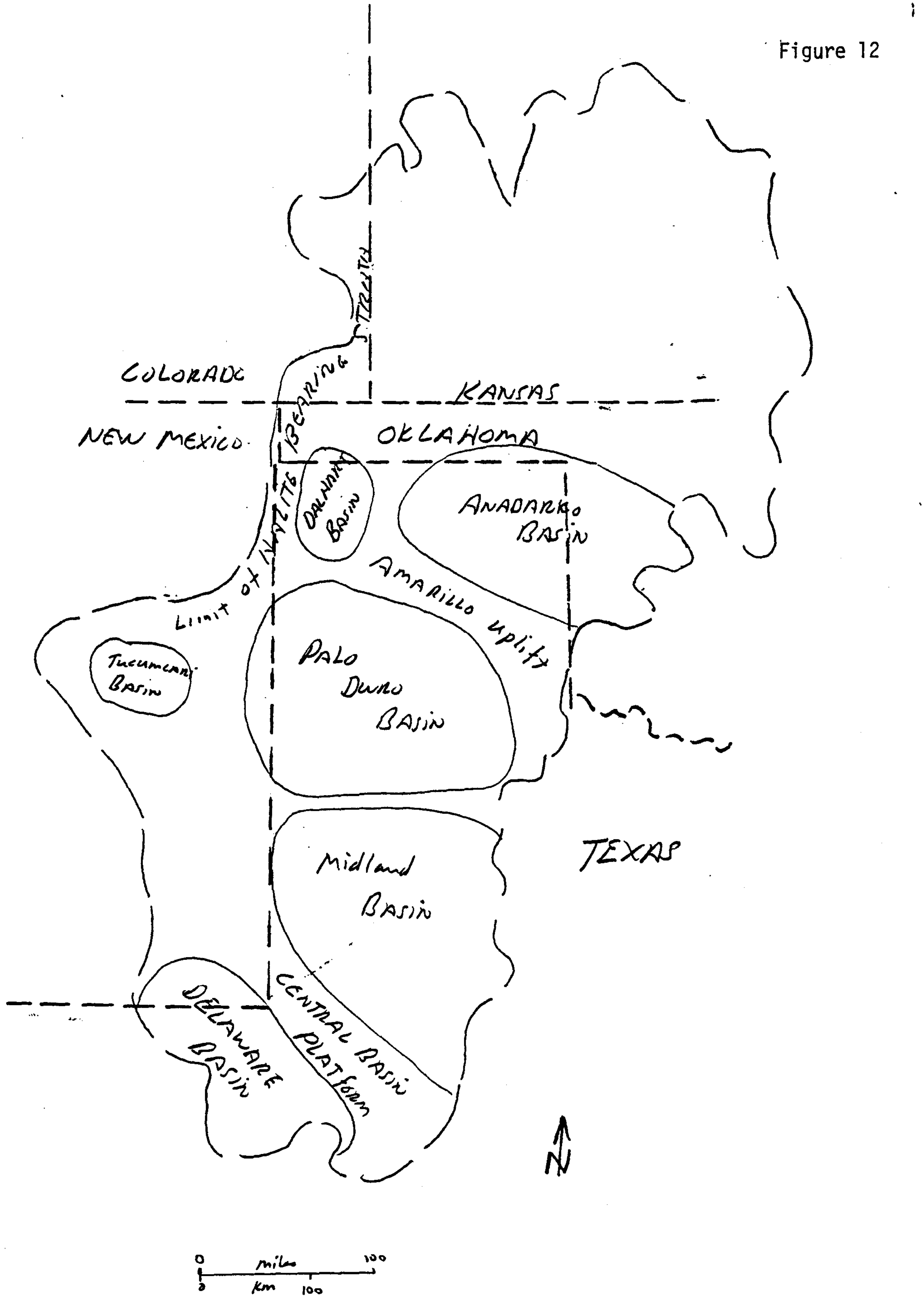

HUTCHINSON CO.
ROBERTS CO.
CARSON CO.
GRAY CO.
EOLIAN SAND FLATS
Sparse Data
N
TRANSITION ZONE
Anadarko Basin
Eolian-Fluvial? sand - mud
Amarillo Uplift
TIDAL FLATS
TIDAL FLATS mud - salt
Contour interval = 5 ft
0 10 20 30 km
0 5 10 15 20 mi
Sand >10'
Sand <10'
I = Intercalated with red beds

Figure 12



COLORADO
KANSAS
NEW MEXICO
OKLAHOMA
Limit of Nazite Bearing Strata
Dalhart Basin
Anadarko Basin
Amarillo uplift
Tucumcari Basin
Palo Duro Basin
TEXAS
Midland Basin
Delaware Basin
Central Basin Platform
N
0 miles 100
0 km 100

Figure 13

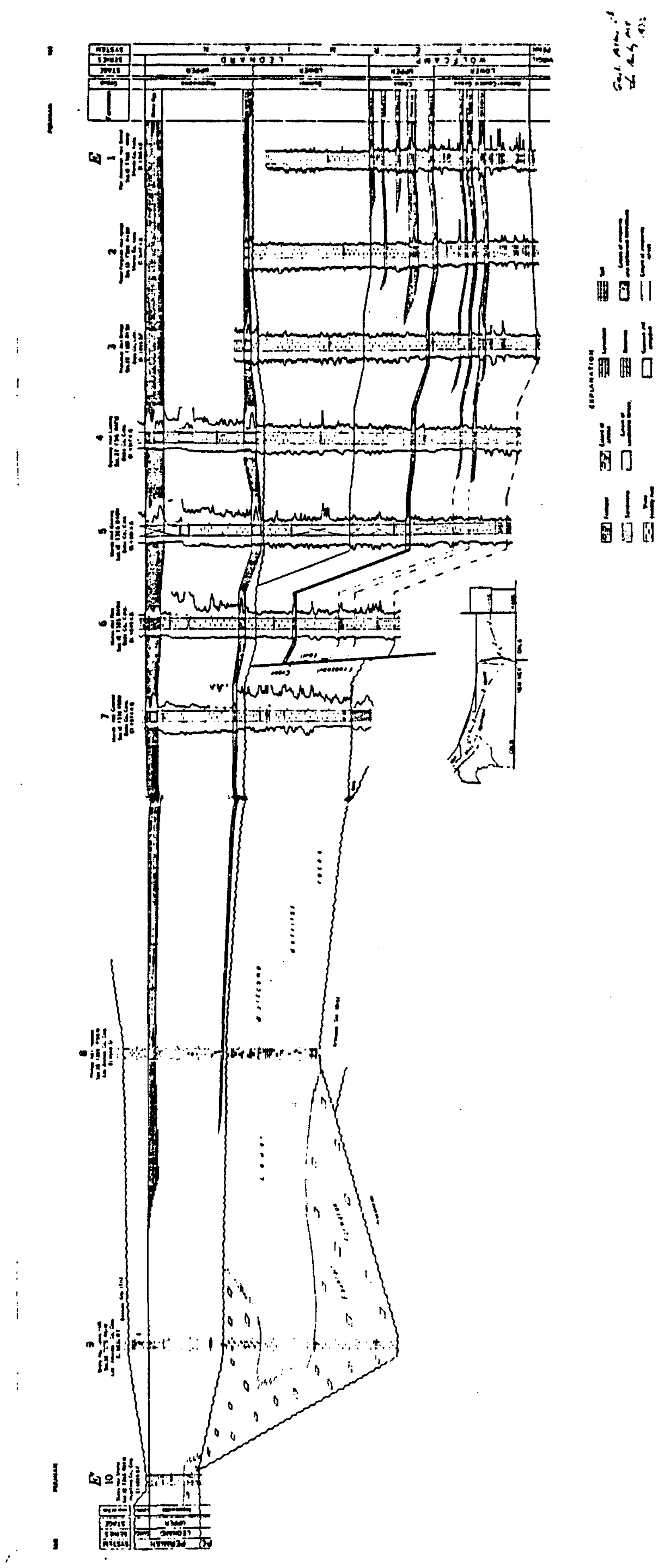
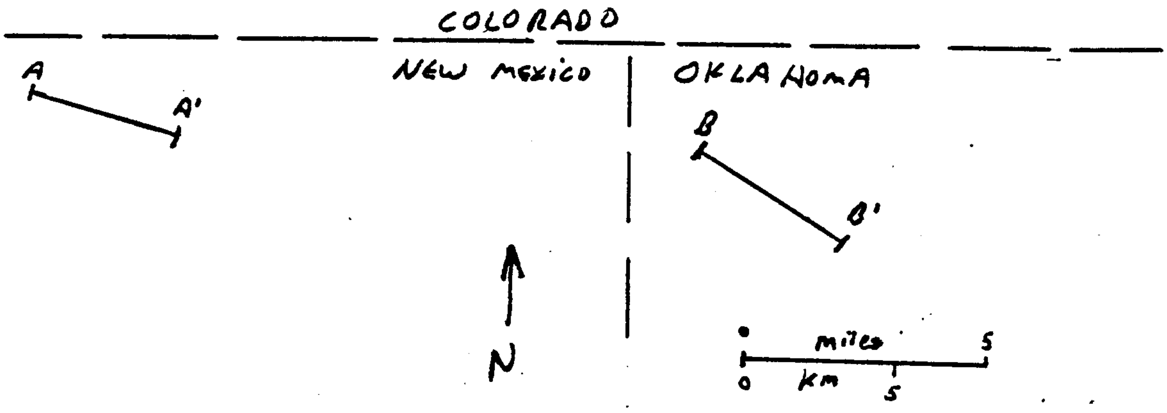
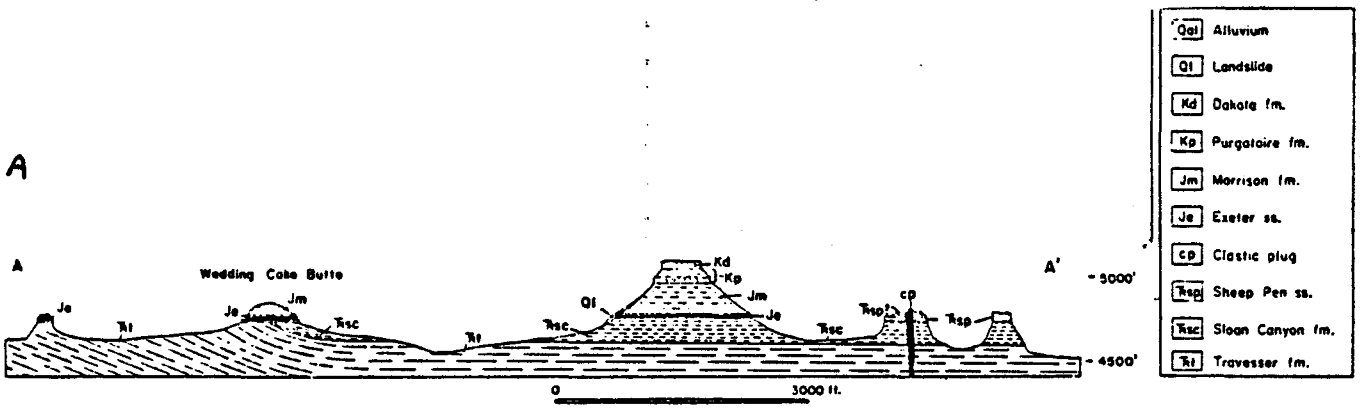


Figure 14a&b



A



B

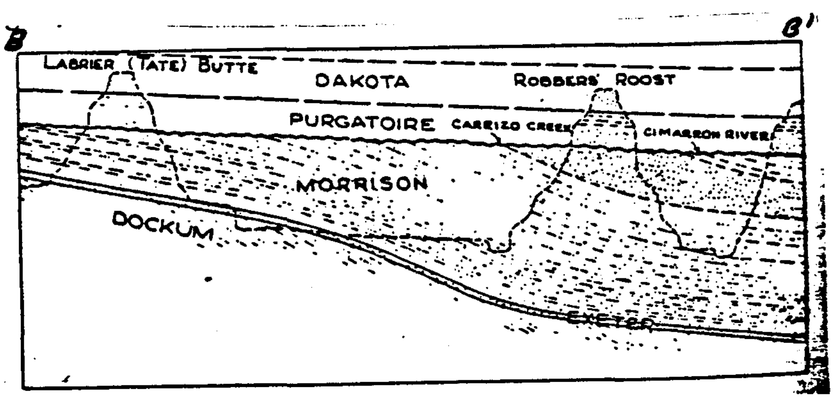


Figure 15

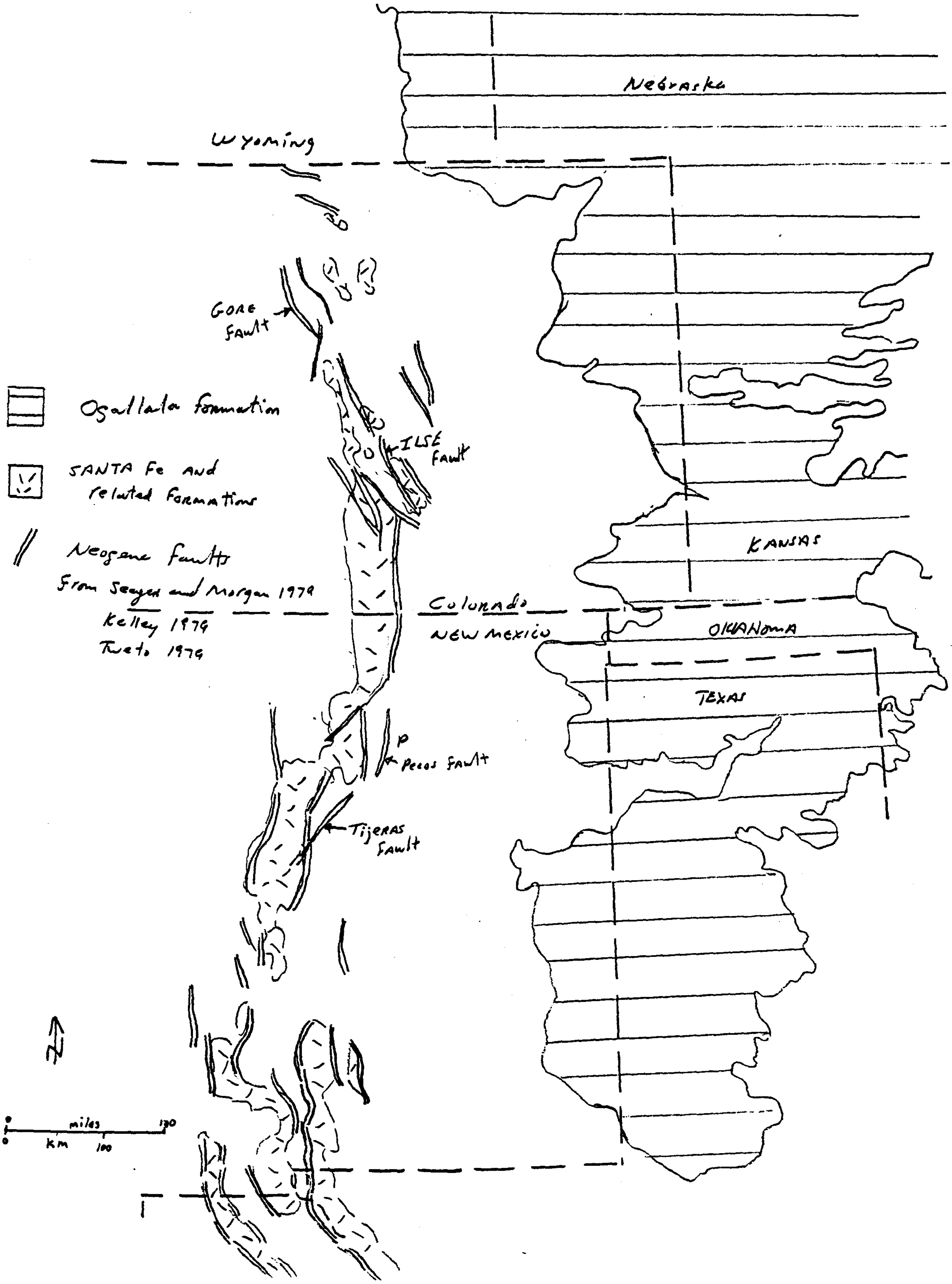
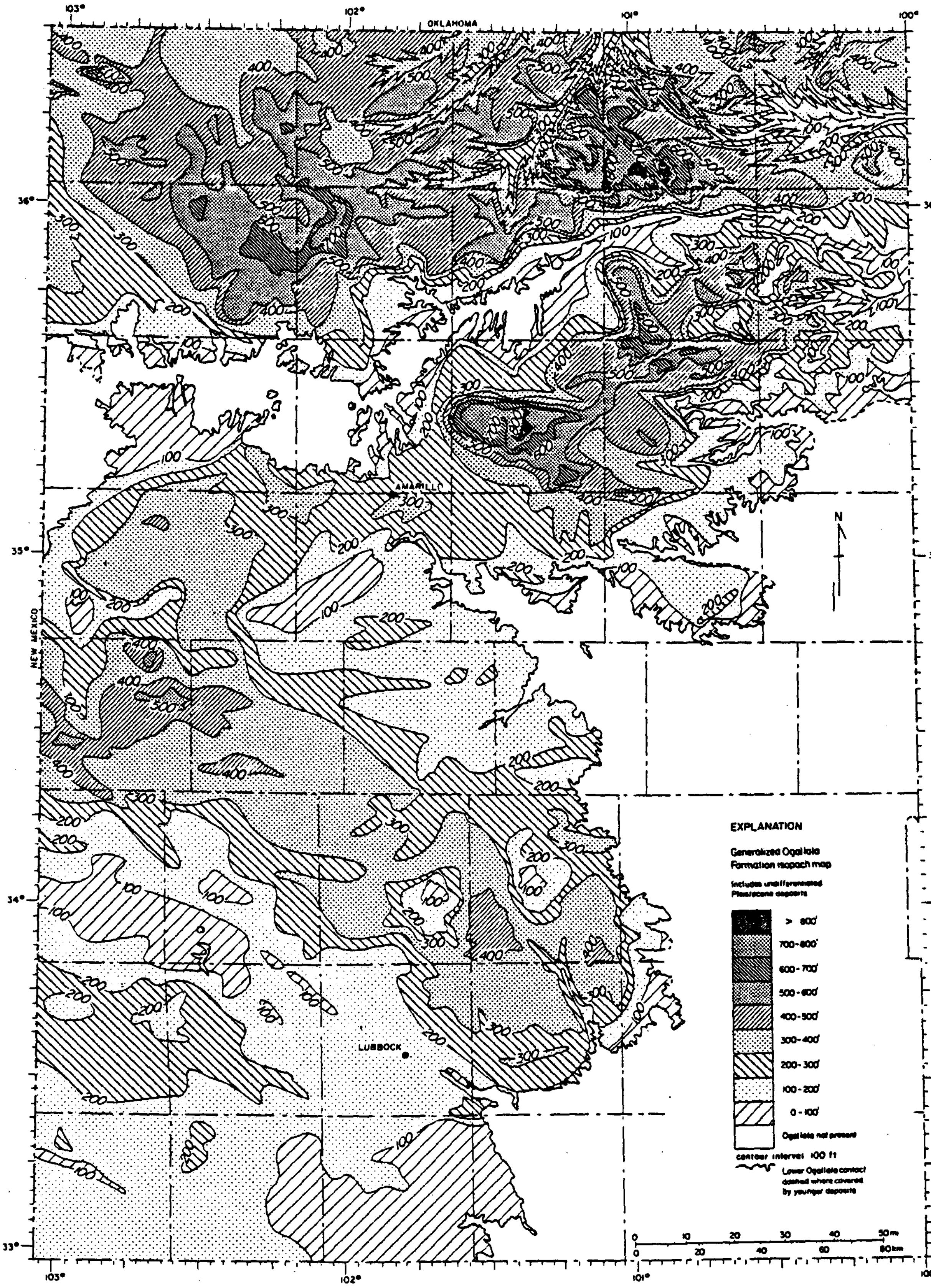
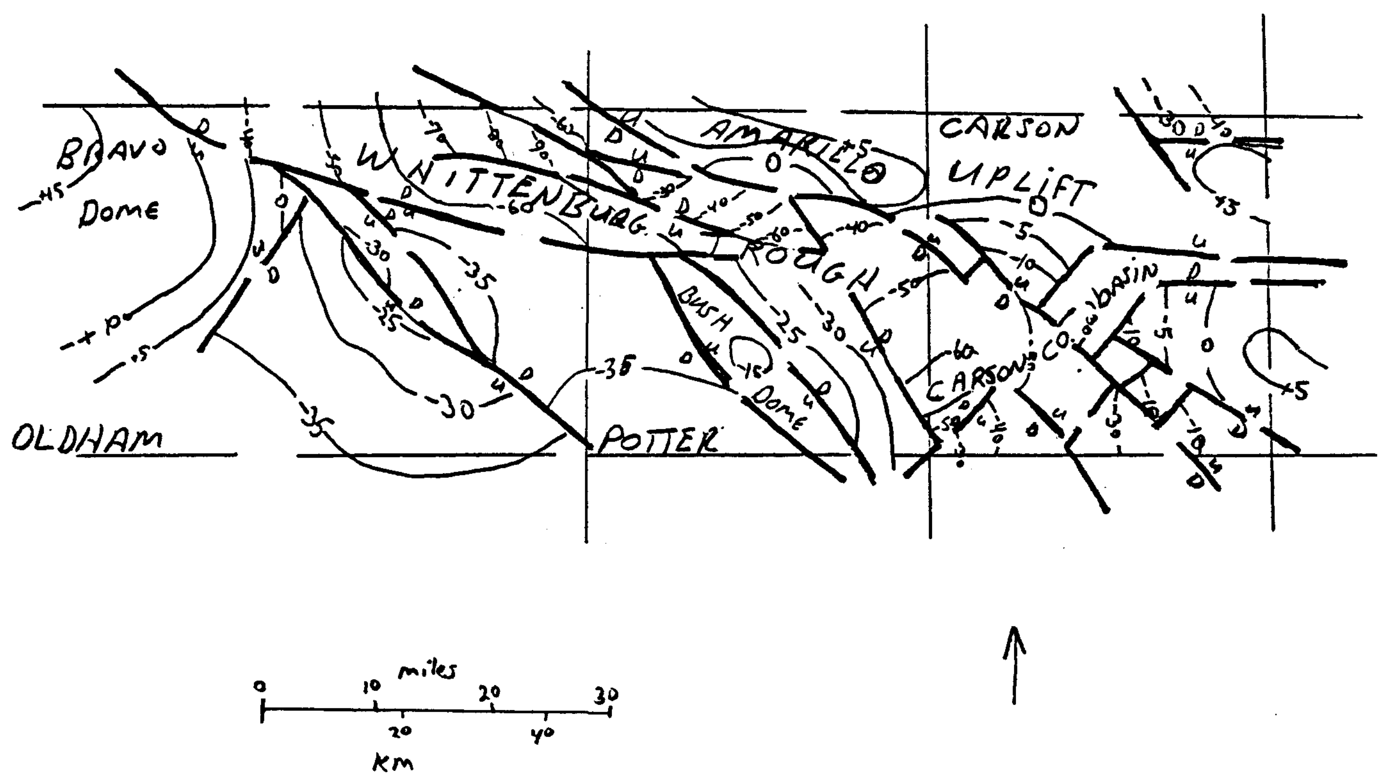

Nebraska
Wyoming
Gore Fault
Ilse fault
Ogallala formation
Santa Fe and related formations
Neogene faults
From Seager and Morgan 1979
Kelley 1979
Tweto 1979
Colorado
New Mexico
Kansas
Oklahoma
Texas
P
Pecos fault
Tijeras fault
miles
130
km
100
0

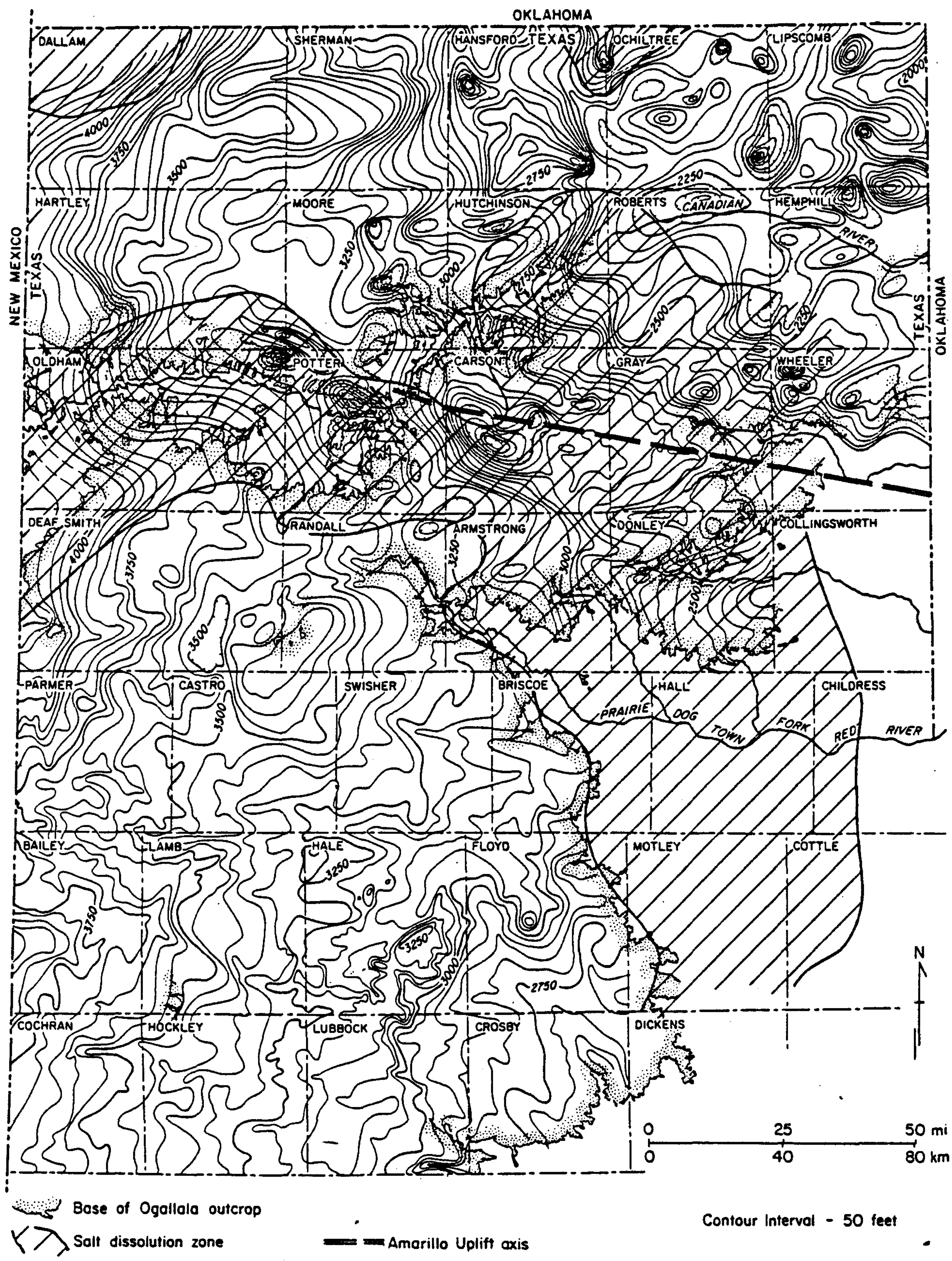
Figure 16



Isopach map, Ogallala Formation. Ogallala thickness is defined as net thickness of all deposits above base of the Ogallala Formation. Undifferentiated Pleistocene deposits (normally less than 7 m [20 ft] thick) may be included in this total.

Figure 17


BRAVO
DOME
WHITTENBURG
AMARILLO
CARSON
UPLIFT
TROUGH
BUSH
DOME
CARSON CO. BASIN
OLDHAM
POTTER
miles
KM



Structure-contour map on the base of the Ogallala Formation (in part from Cronin, 1961). Map also indicates the active salt dissolution zone for the Salado, Seven Rivers, San Andres, and Glorieta Formations.

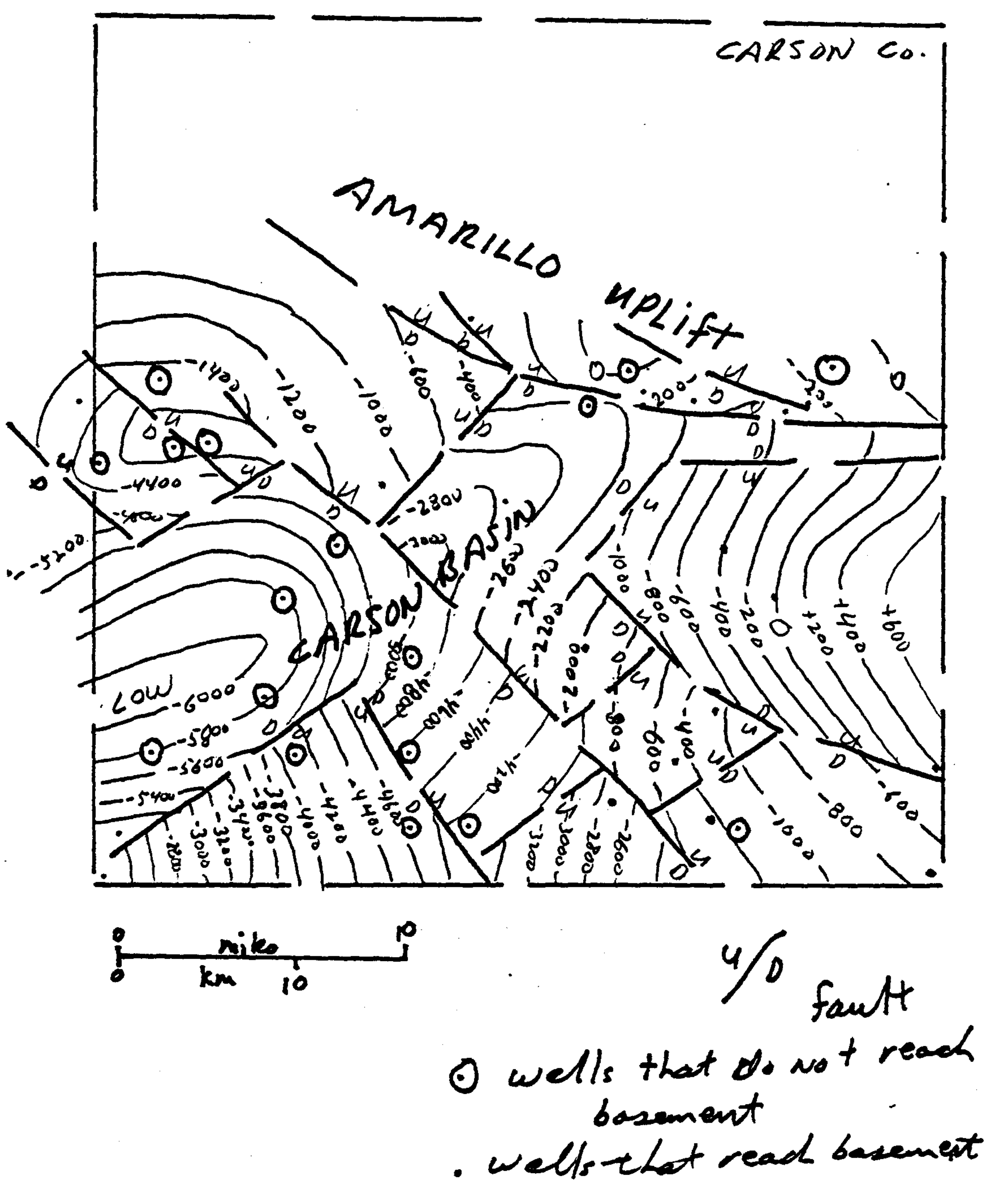

CARSON Co.
AMARILLO UPLIFT
CARSON BASIN
LOW
miles
km
U/D fault
⊙ wells that do not reach basement
. wells that reach basement

Figure 19b

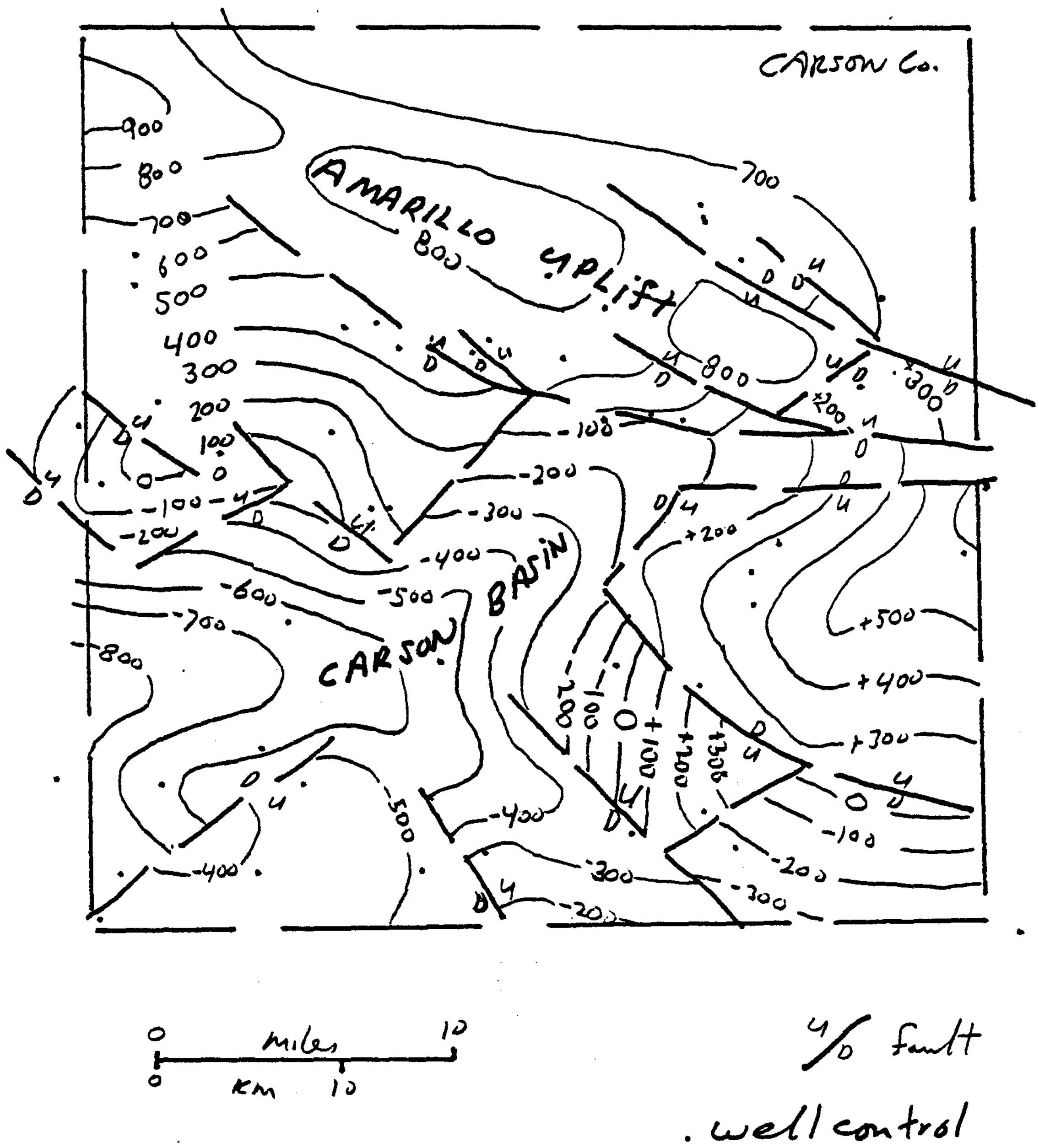
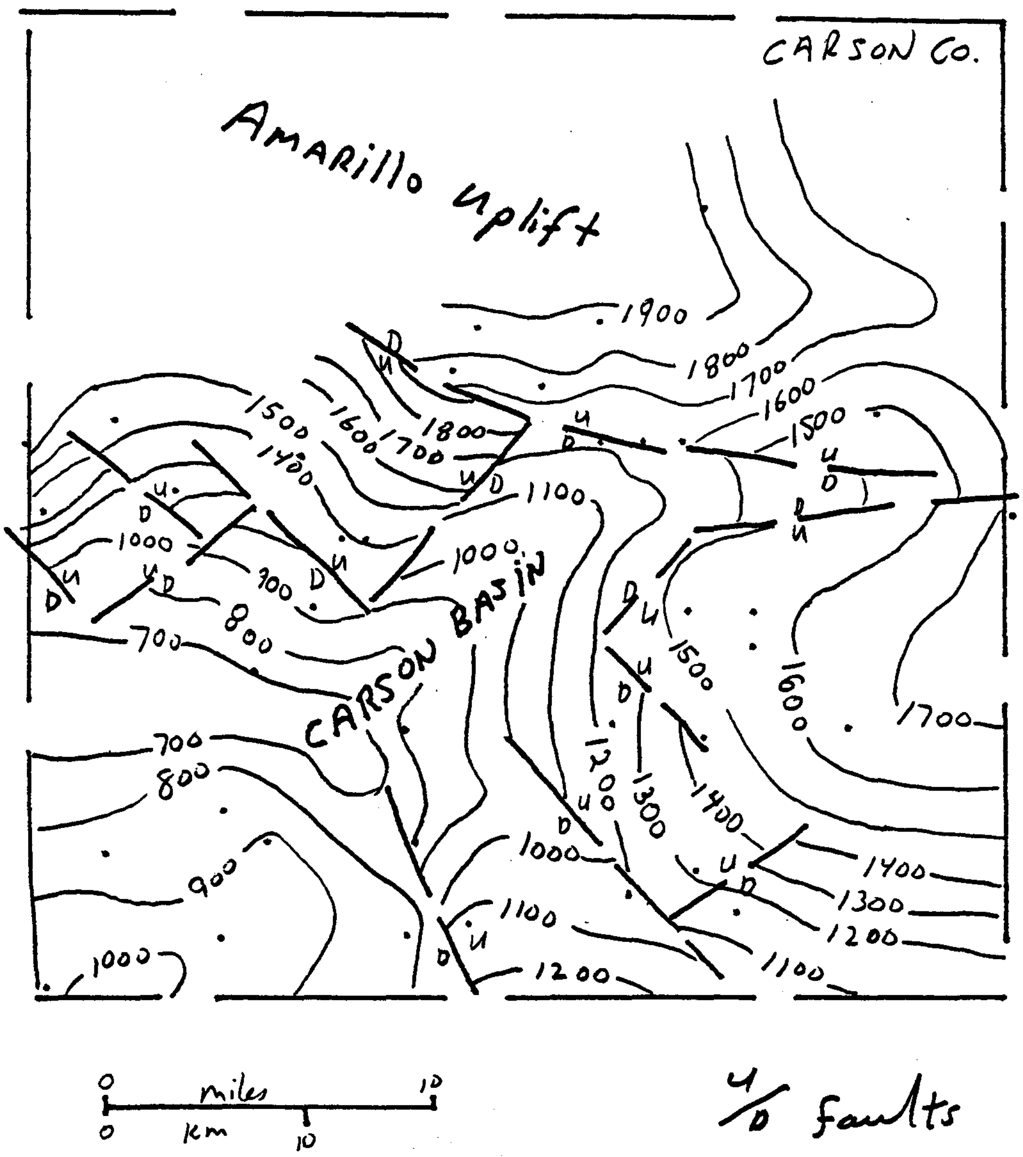

CARSON Co.
AMARILLO UPLIFT
CARSON BASIN
miles
KM
u/D fault
. well control

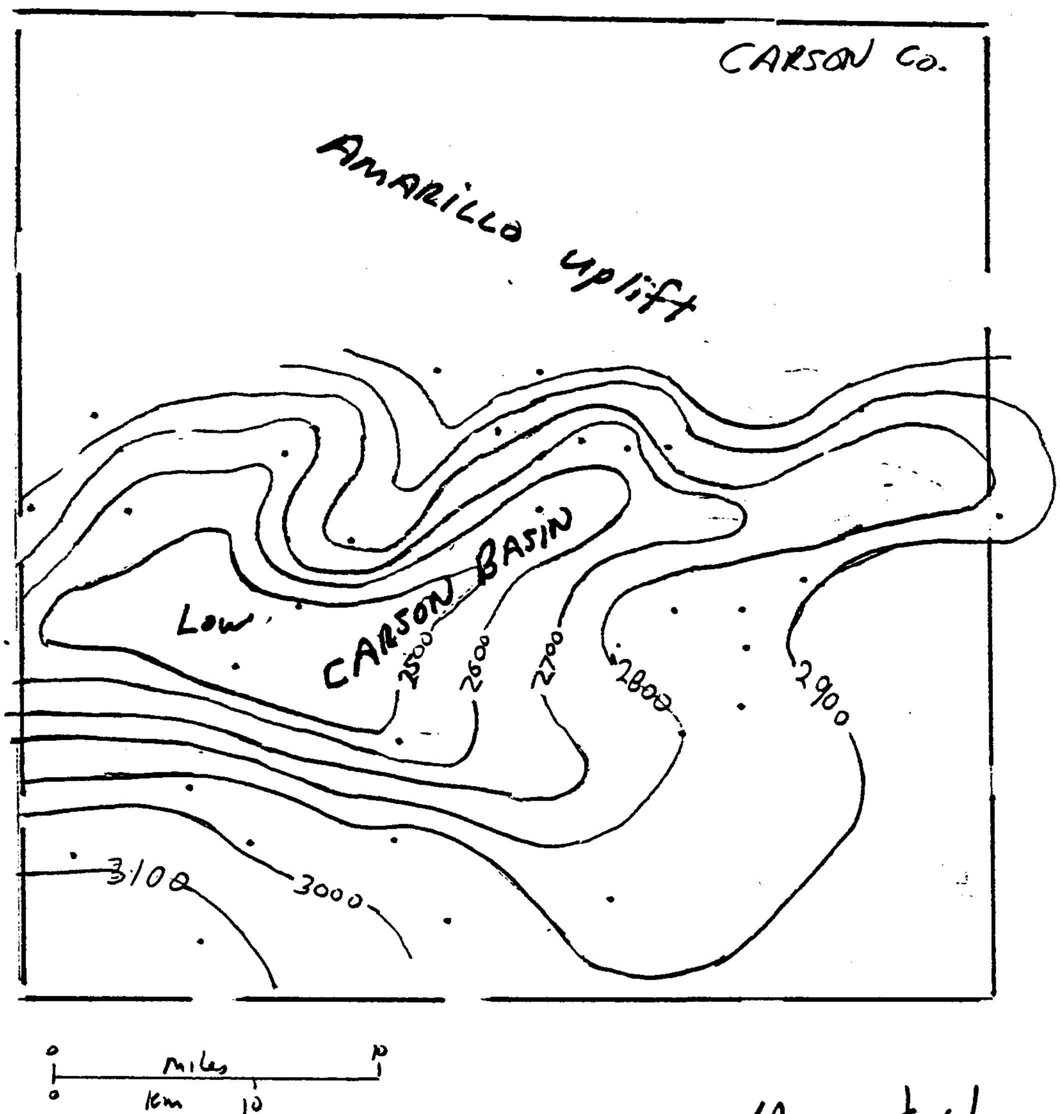
Figure 19c



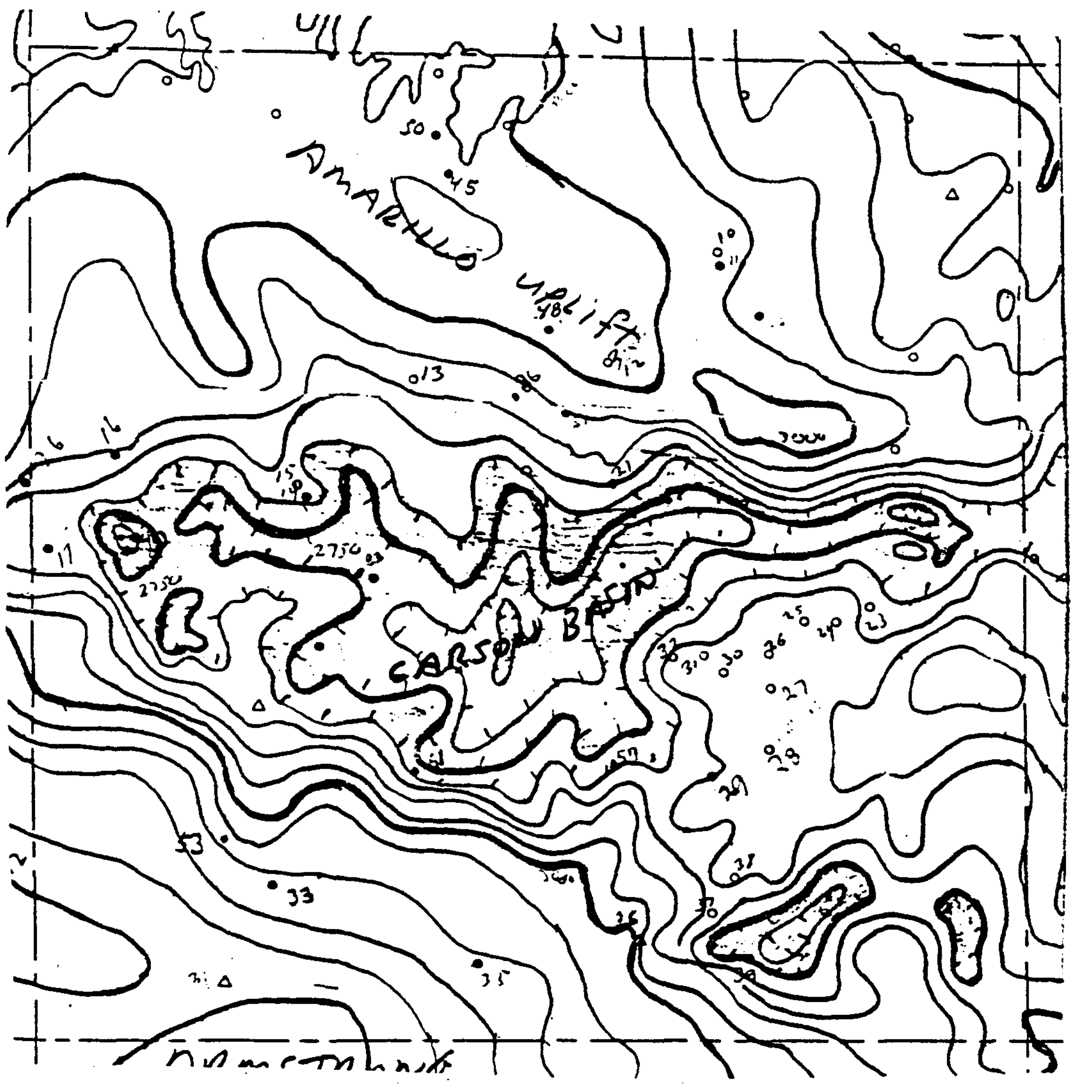
U/D faults

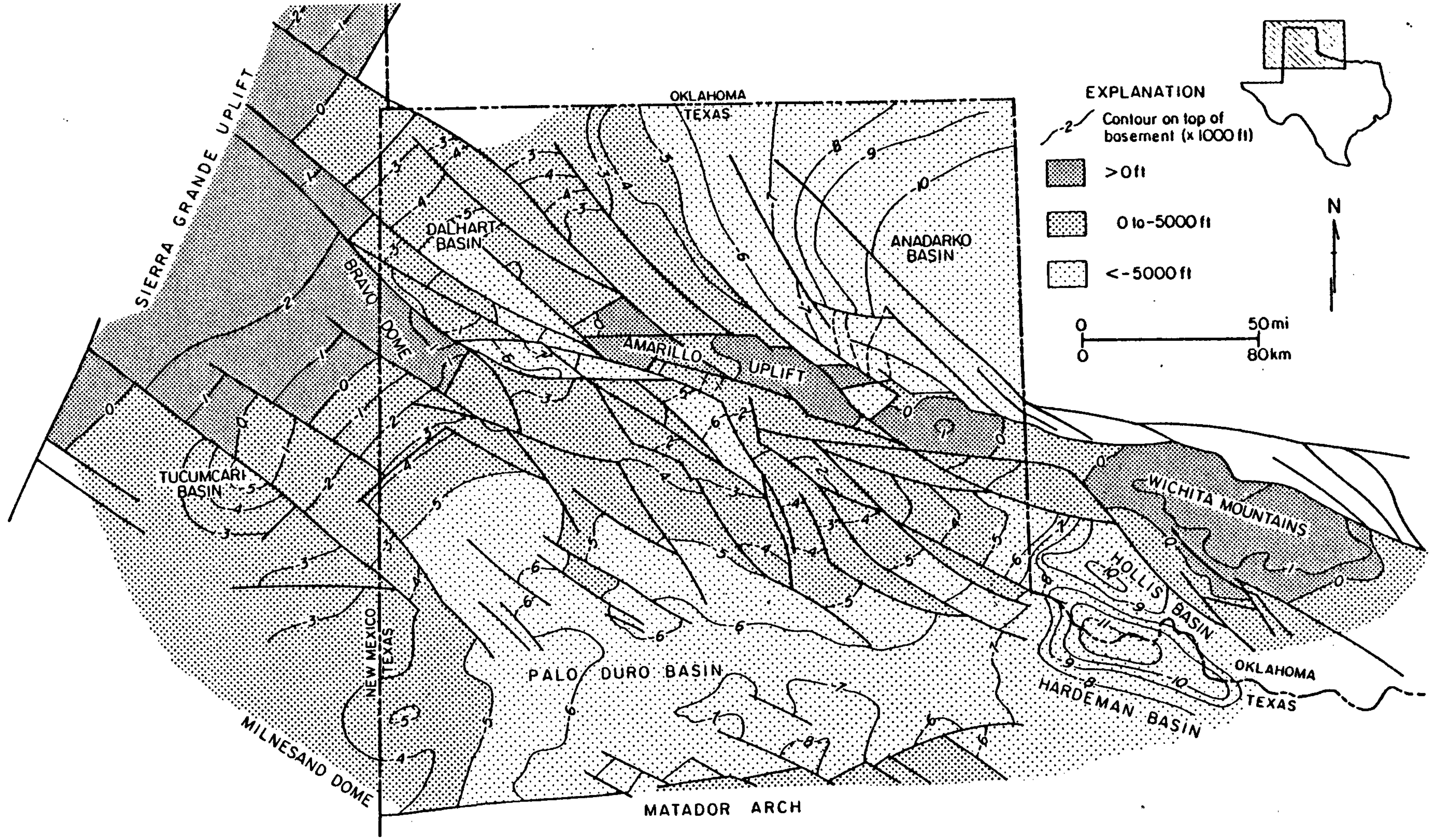
. well control

Tubb



. well control


AMARILLO UPLIFT
CARSON BASIN

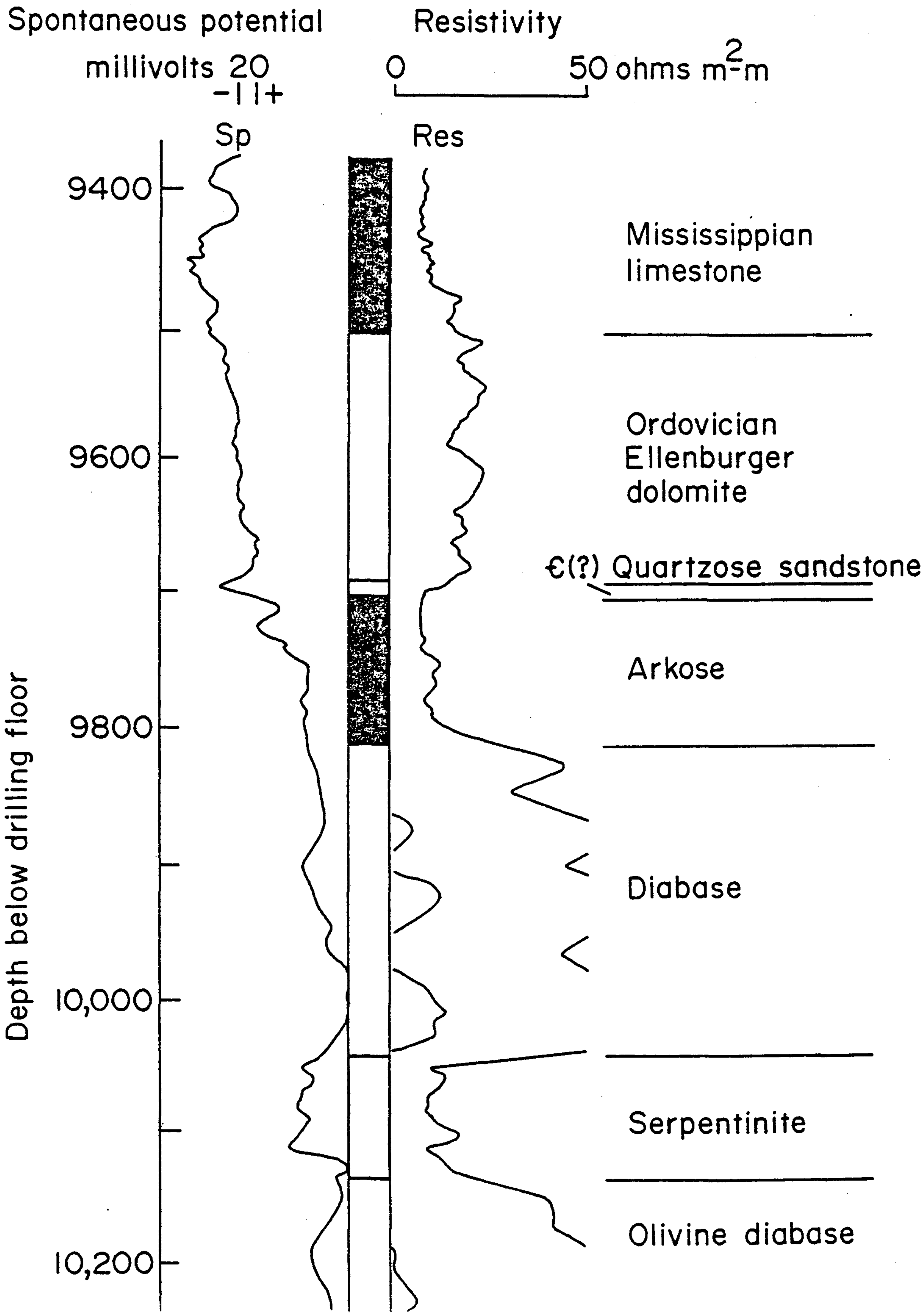


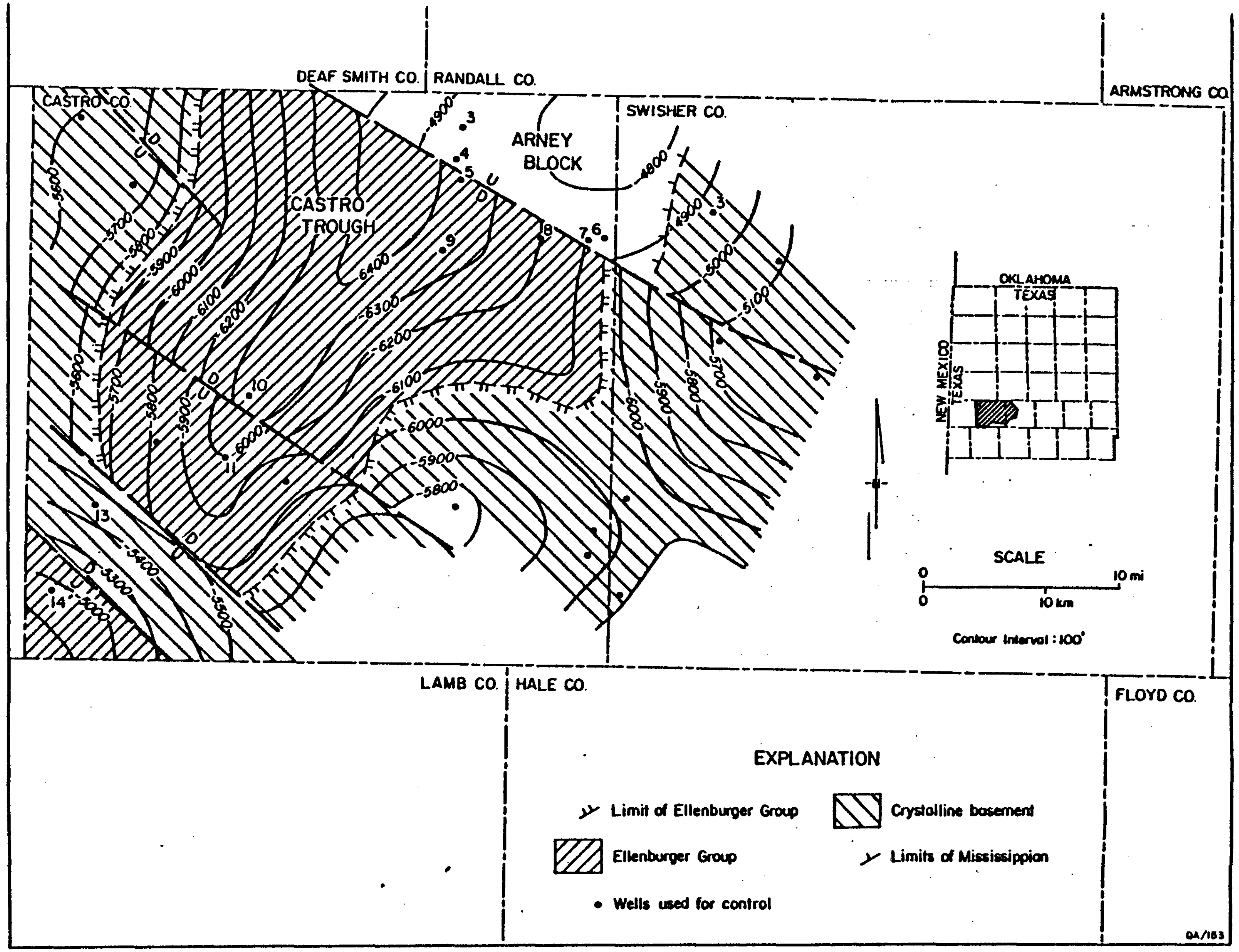
Structure-contour map on the top of Precambrian basement.

Figure 20

Figure 21

SUN OIL COMPANY #1 *Herring*, Castro Co

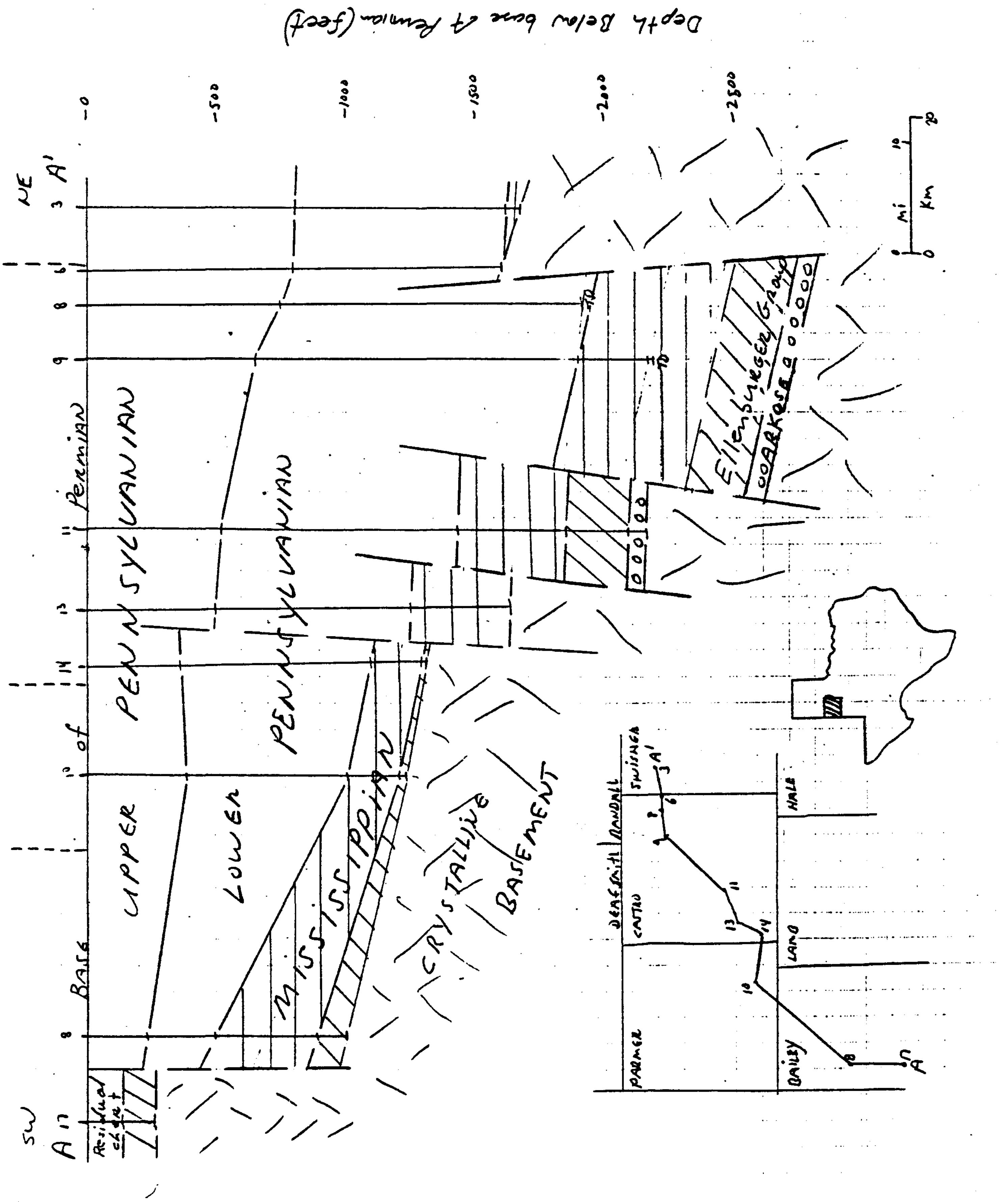




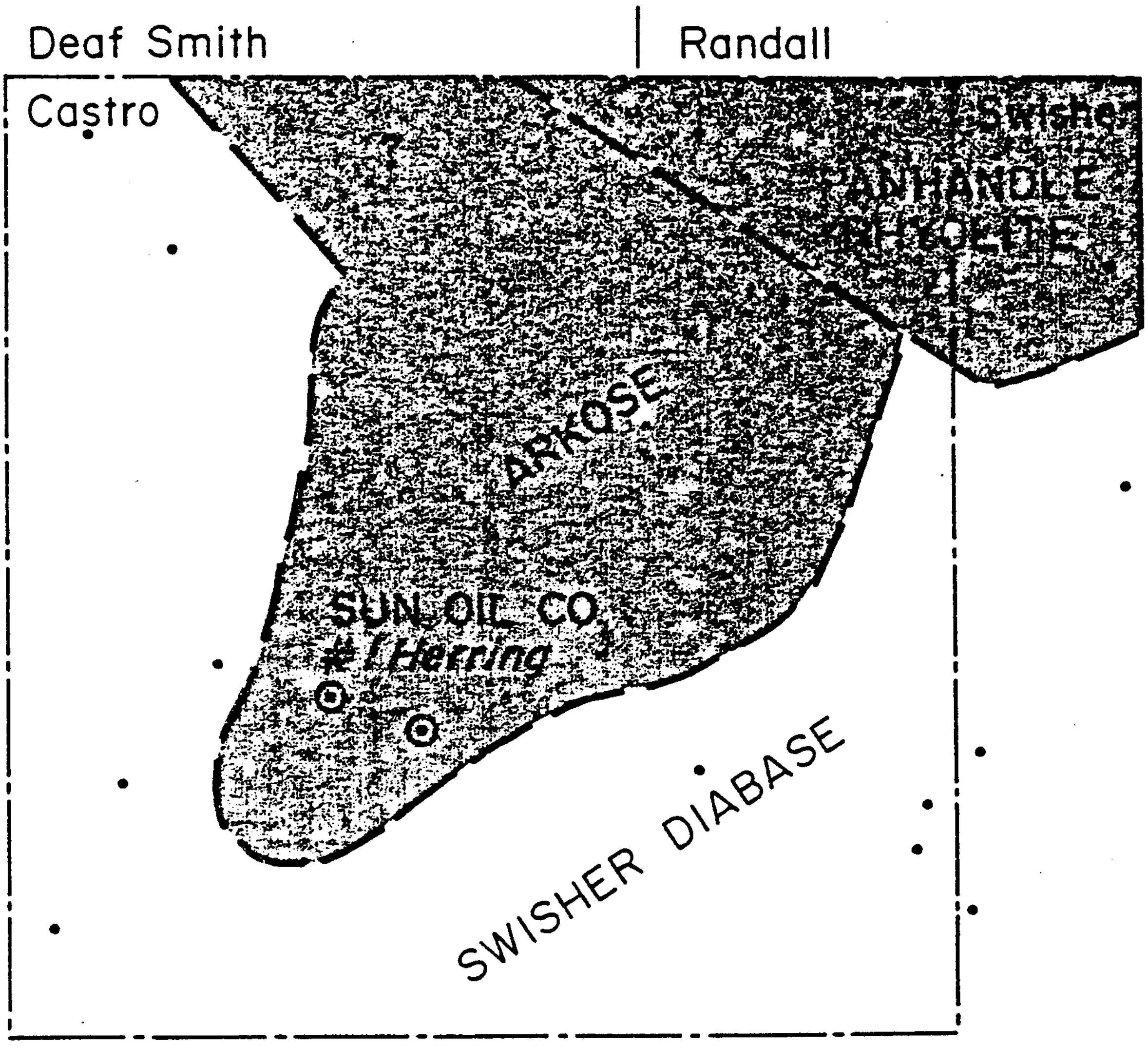
DEAF SMITH CO.
RANDALL CO.
ARMSTRONG CO.
CASTRO CO.
SWISHER CO.
ARNEY BLOCK
CASTRO TROUGH
LAMB CO.
HALE CO.
FLOYD CO.
OKLAHOMA
TEXAS
NEW MEXICO
TEXAS
SCALE
0
10 mi
0
10 km
Contour Interval : 100'
EXPLANATION
Limit of Ellenburger Group
Crystalline basement
Ellenburger Group
Limits of Mississippian
Wells used for control
QA/153

Figure 22

Figure 23



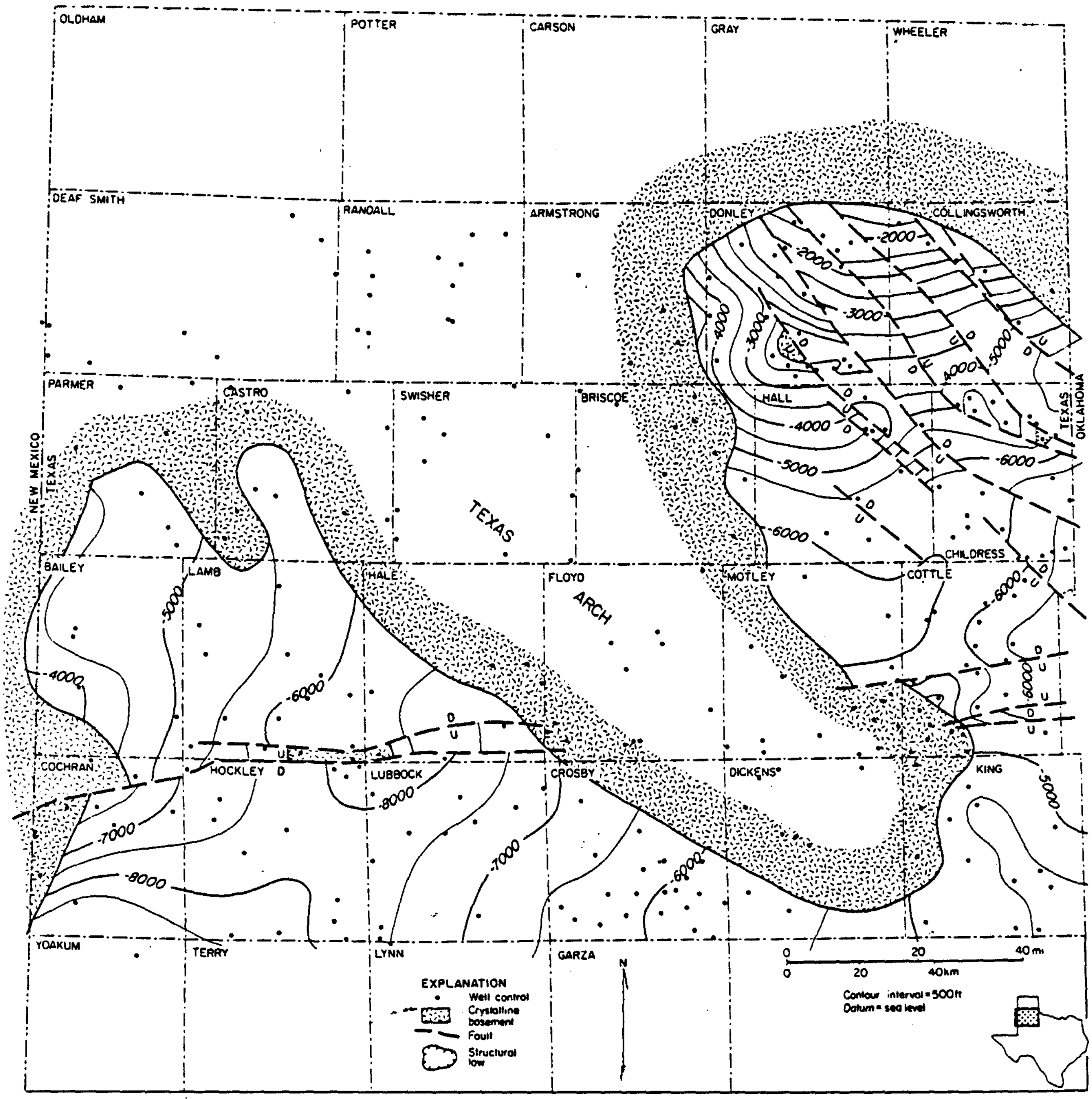
Depth Below base of Permian (feet)
0
-500
-1000
-1500
-2000
-2500
SW
A
NE
A'
BASE of Permian
UPPER
PENNSYLVANIAN
LOWER
PENNSYLVANIAN
MISSISSIPPIAN
CRYSTALLINE
BASEMENT
Ellenburger Group
ARKOSE
Residual chert
mi
Km
PARMER
DEAF SMITH
CASTRO
RANDALL
SWISHER
BAILEY
LAMB
HALE



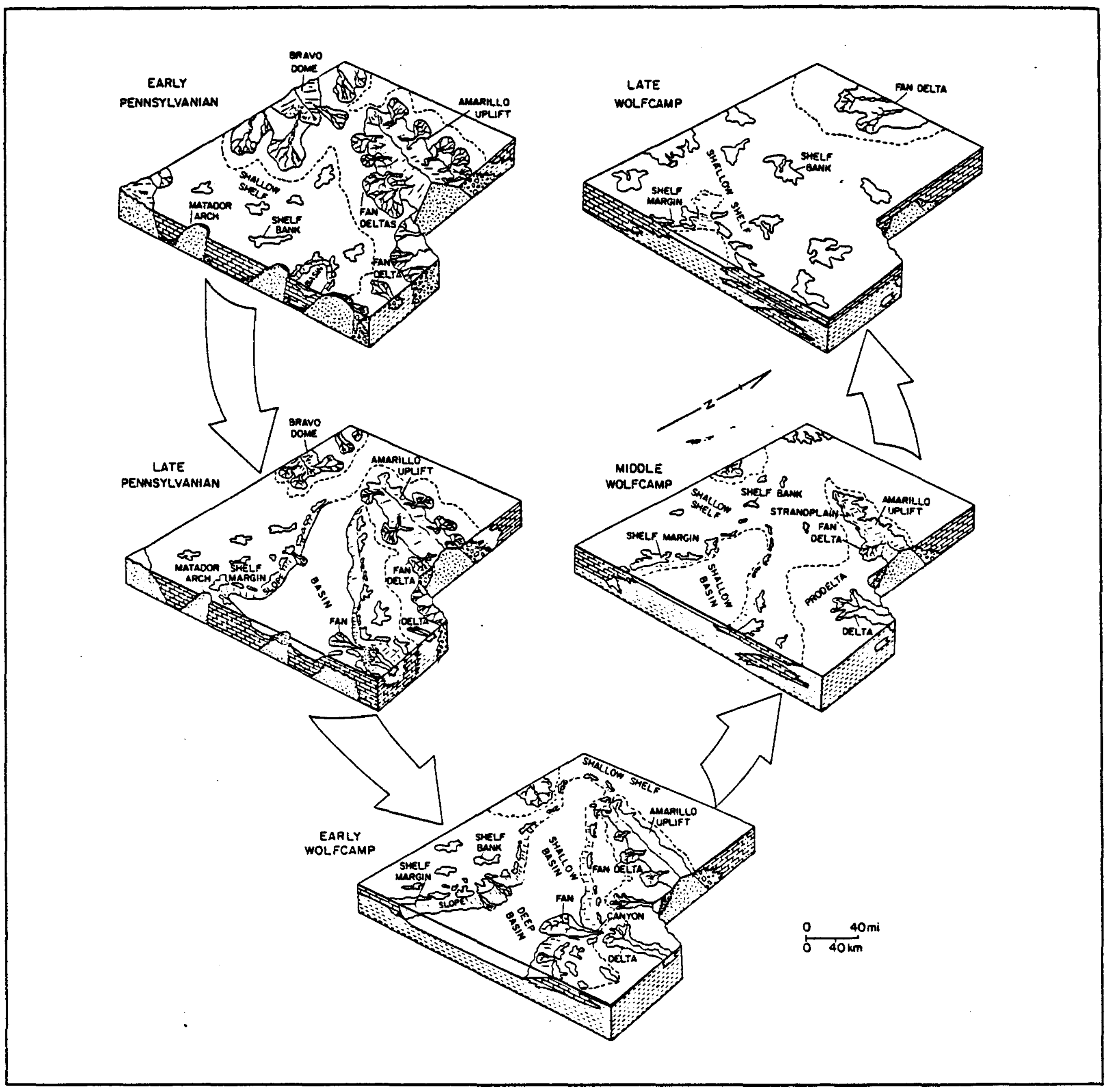
Distribution of pre-Ellenburger Group arkose in Castro Trough

- Well control
- ⊙ Wells penetrating pre-Ellenburger arkose

0 10 mi
0 10 km

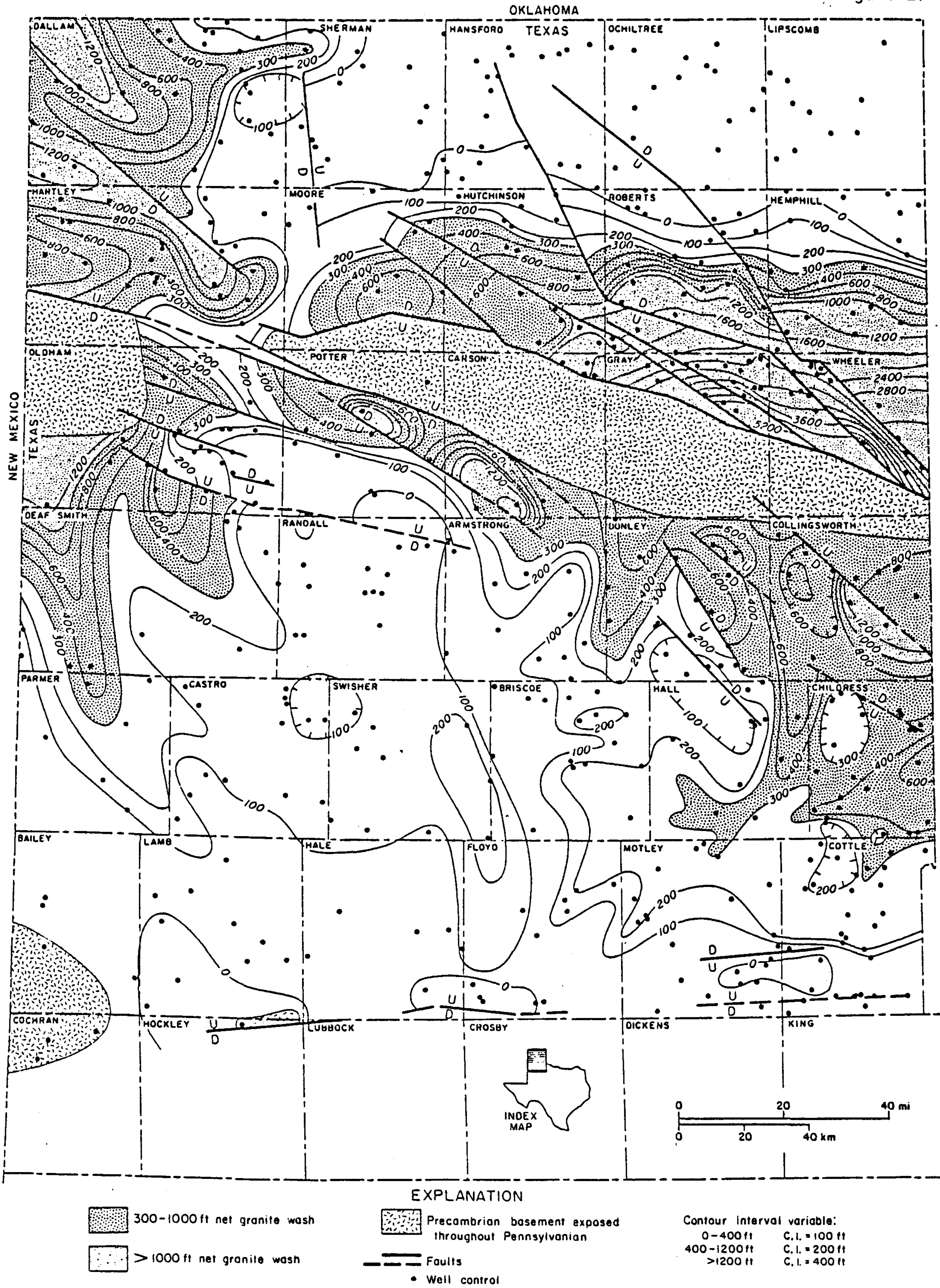


Structure contour map of top of Ordovician Ellenburger Group, Palo Duro Basin.

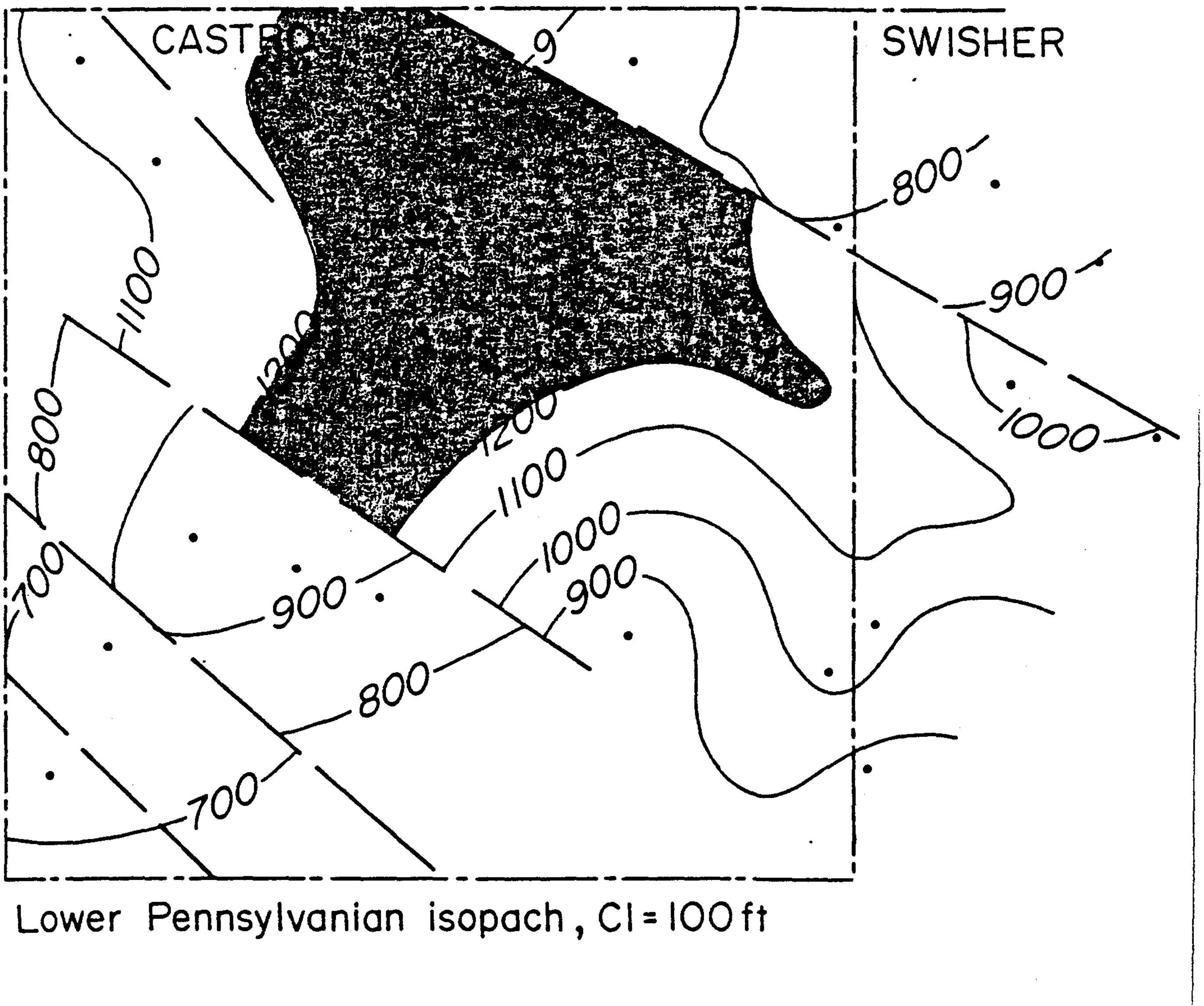


Block diagrams of paleogeographic evolution of Palo Duro Basin during Pennsylvanian and Wolfcampian time (from Handford and Dutton, 1980).

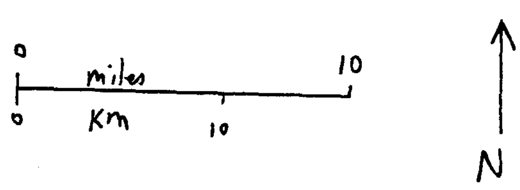
Figure 27

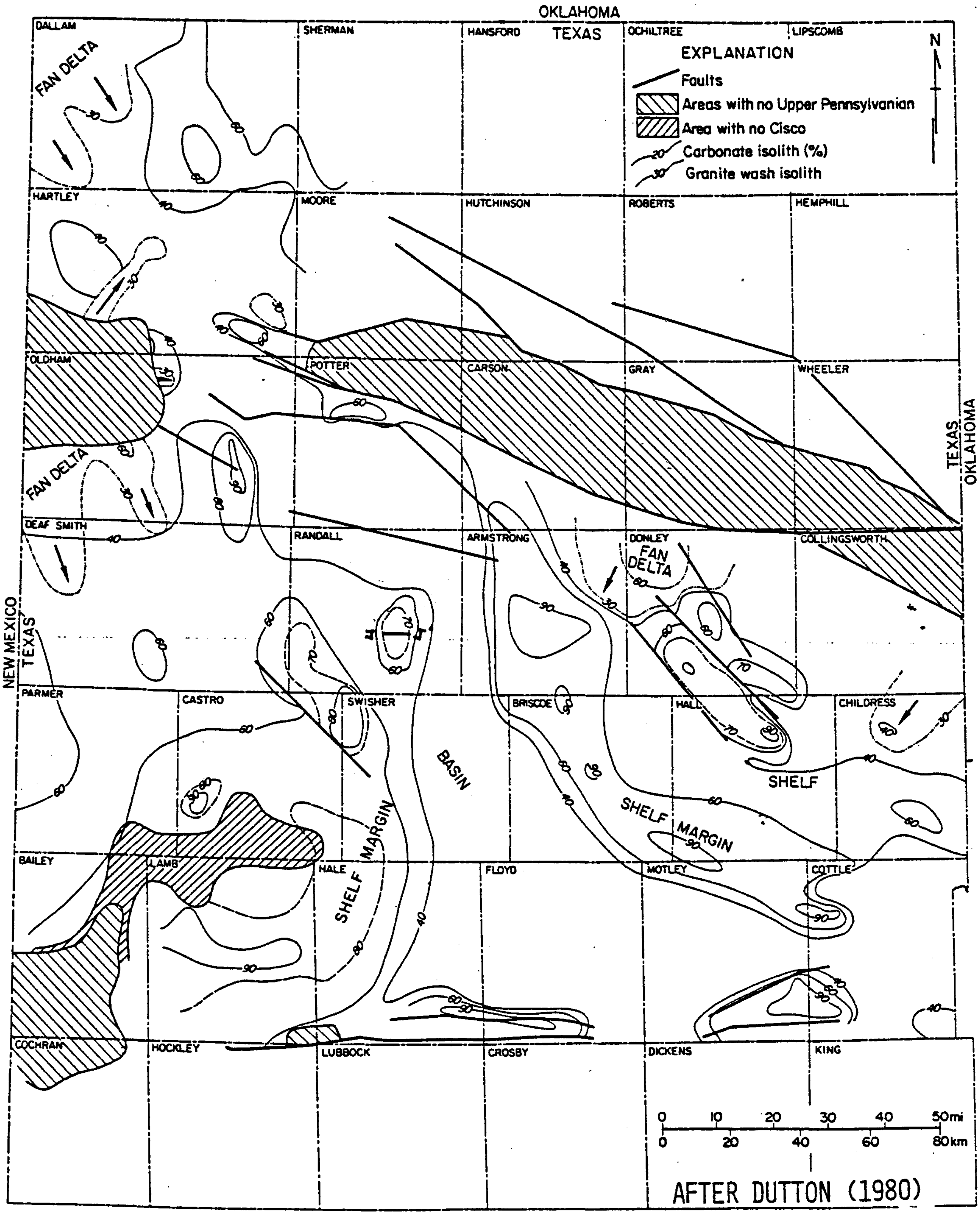


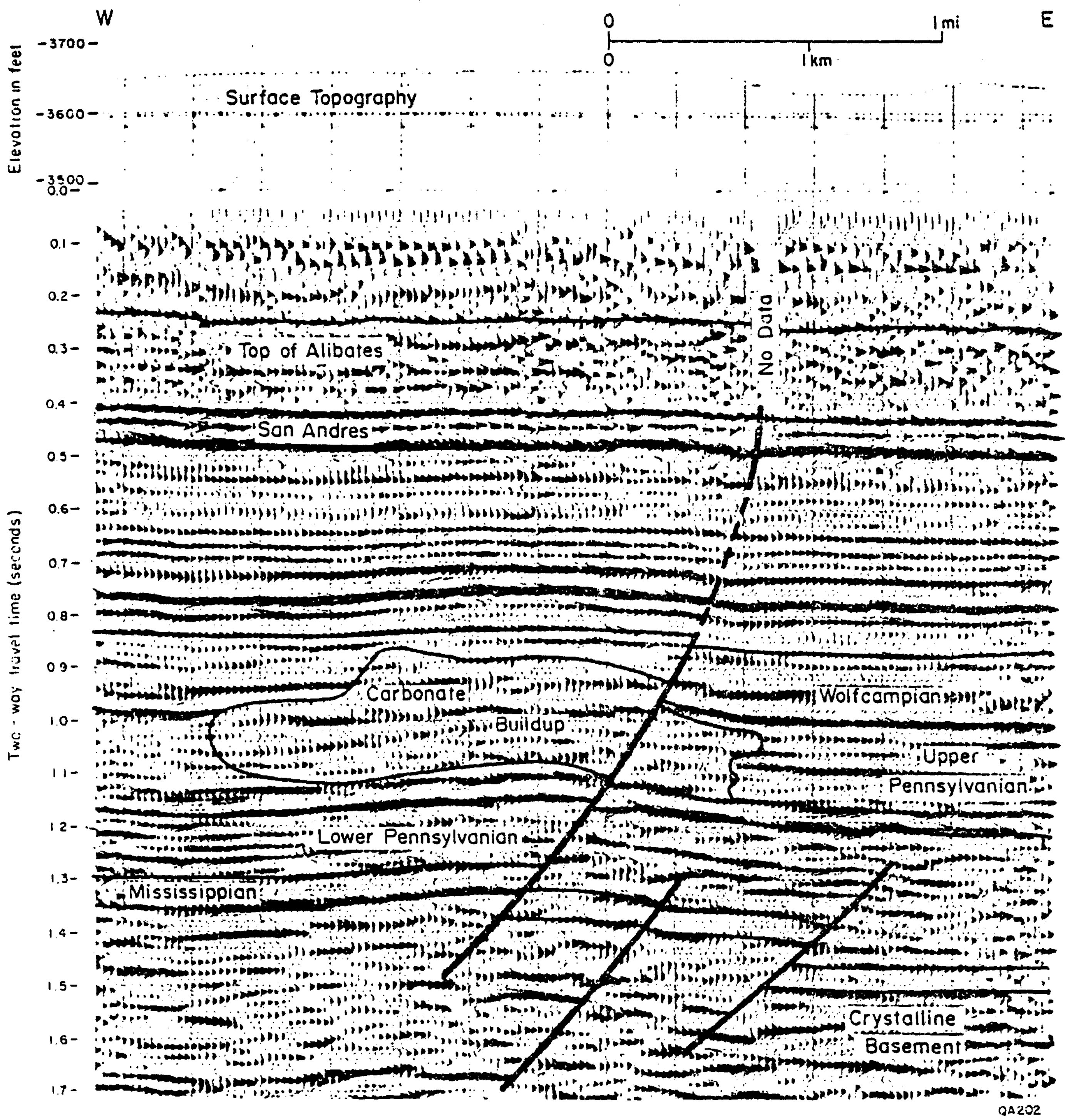
OKLAHOMA
TEXAS
NEW MEXICO
TEXAS
DALLAM
SHERMAN
HANSFORD
OCHILTREE
LIPSCOMB
HARTLEY
MOORE
HUTCHINSON
ROBERTS
HEMPHILL
OLDHAM
POTTER
CARSON
GRAY
WHEELER
DEAF SMITH
RANDALL
ARMSTRONG
DONLEY
COLLINGSWORTH
PARMER
CASTRO
SWISHER
BRISCOE
HALL
CHILDRESS
BAILEY
LAMB
HALE
FLOYD
MOTLEY
COTTLE
COCHRAN
HOCKLEY
LUBBOCK
CROSBY
DICKENS
KING
INDEX MAP
0 20 40 mi
0 20 40 km
EXPLANATION
300-1000 ft net granite wash
>1000 ft net granite wash
Precambrian basement exposed throughout Pennsylvanian
Faults
Well control
Contour interval variable:
0-400 ft C.I. = 100 ft
400-1200 ft C.I. = 200 ft
>1200 ft C.I. = 400 ft



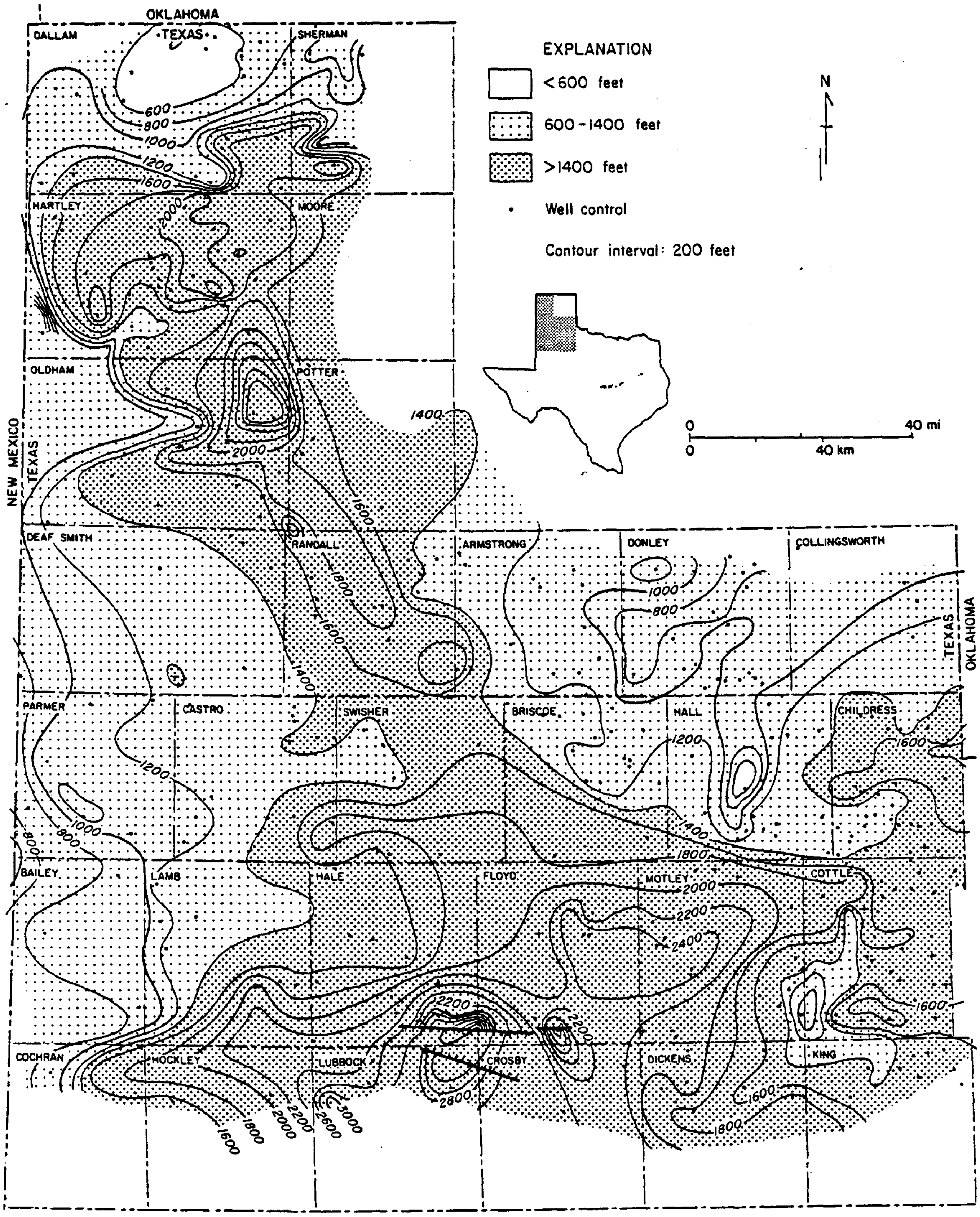
Lower Pennsylvanian isopach, CI = 100 ft




OKLAHOMA
TEXAS
EXPLANATION
Faults
Areas with no Upper Pennsylvanian
Area with no Cisco
Carbonate isolith (%)
Granite wash isolith
N
DALLAM
SHERMAN
HANSFORD
OCHILTREE
LIPSCOMB
HARTLEY
MOORE
HUTCHINSON
ROBERTS
HEMPHILL
OLDHAM
POTTER
CARSON
GRAY
WHEELER
DEAF SMITH
RANDALL
ARMSTRONG
DONLEY
COLLINGSWORTH
PARMER
CASTRO
SWISHER
BRISCOE
HALL
CHILDRESS
BAILEY
LAMB
HALE
FLOYD
MOTLEY
COTTLE
COCHRAN
HOCKLEY
LUBBOCK
CROSBY
DICKENS
KING
FAN DELTA
FAN DELTA
FAN DELTA
NEW MEXICO
TEXAS
TEXAS
OKLAHOMA
BASIN
SHELF MARGIN
SHELF MARGIN
SHELF
0 10 20 30 40 50mi
0 20 40 60 80km
AFTER DUTTON (1980)



W
E
0
1 mi
0
1 km
Elevation in feet
-3700
-3600
-3500
Surface Topography
Two-way travel time (seconds)
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.1
1.2
1.3
1.4
1.5
1.6
1.7
No Data
Top of Alibates
San Andres
Carbonate
Buildup
Wolfcampian
Upper
Pennsylvanian
Lower Pennsylvanian
Mississippian
Crystalline
Basement
QA202



Isopach map of Wolfcampian Series, Palo Duro Basin (Handford, unpublished data).

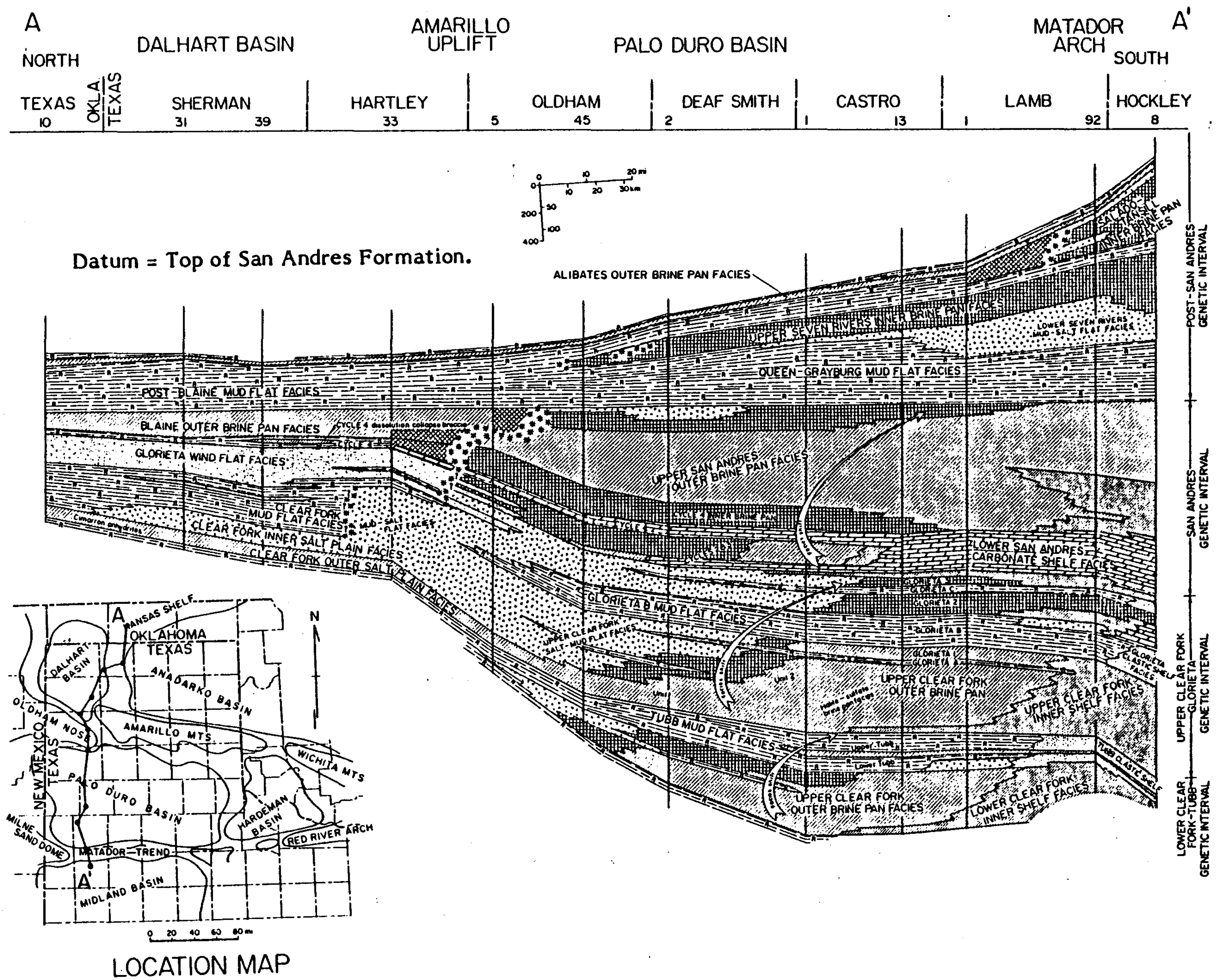
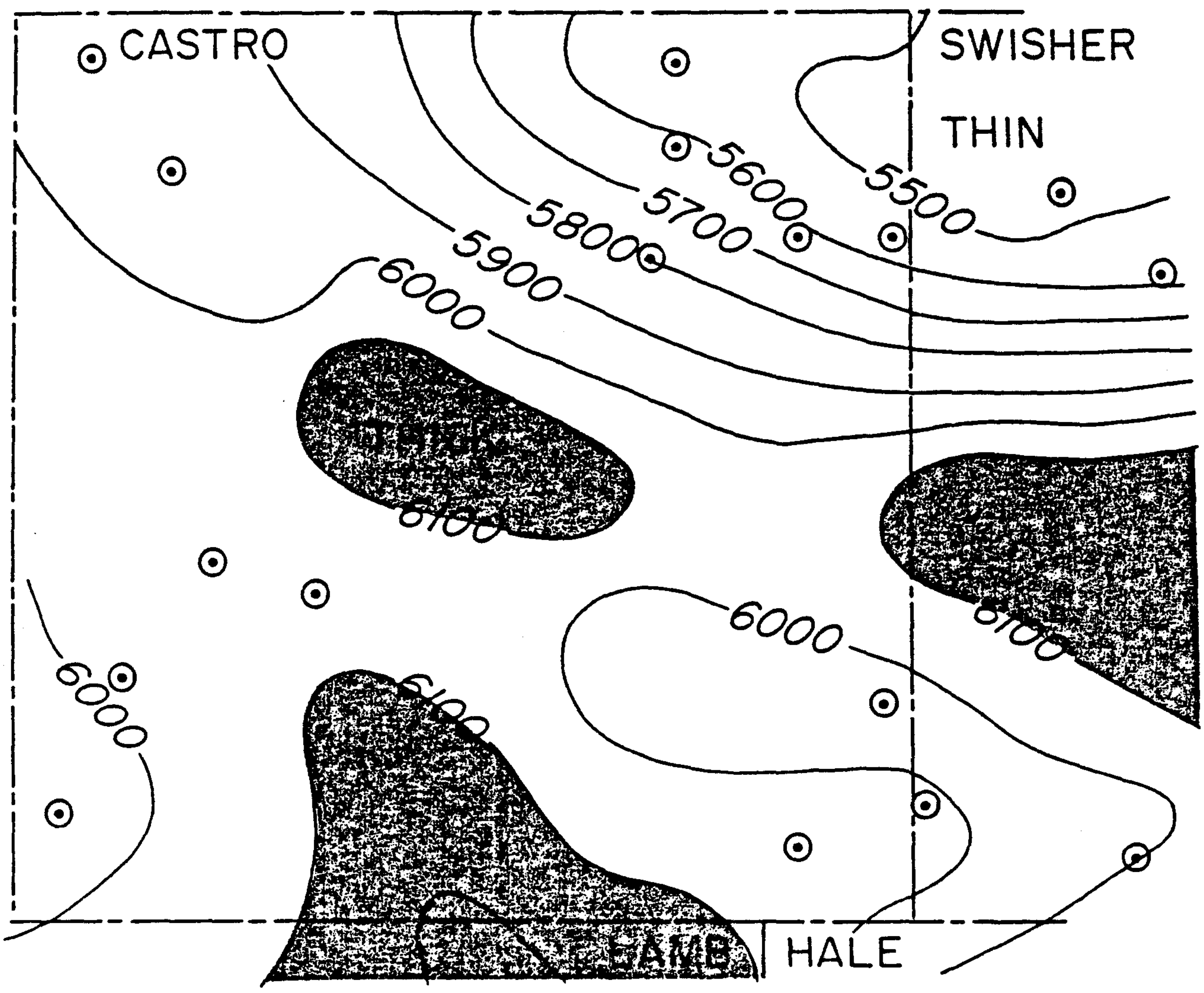
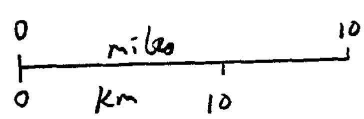
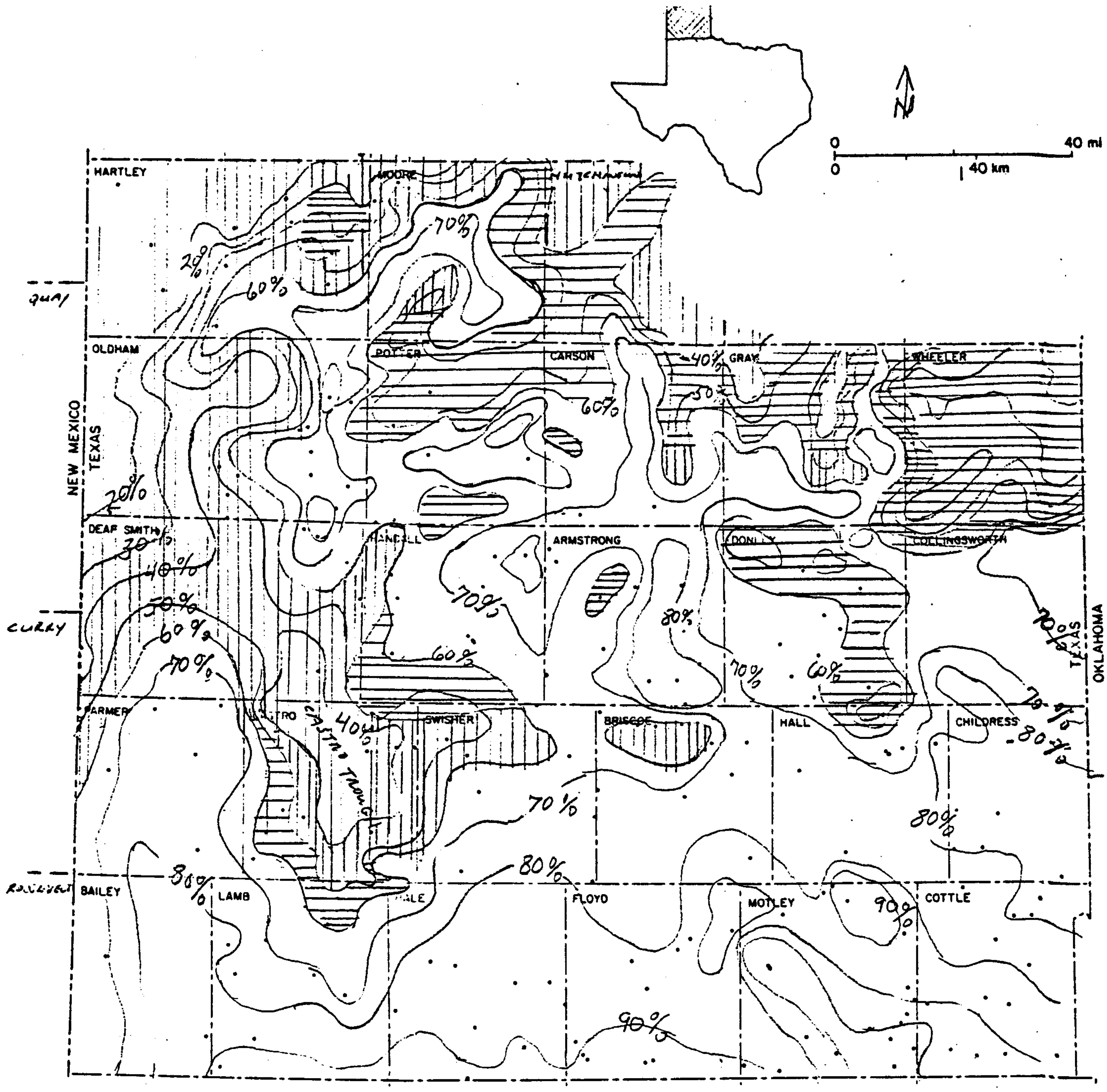

A
NORTH
DALHART BASIN
AMARILLO UPLIFT
PALO DURO BASIN
MATADOR ARCH
A'
SOUTH
TEXAS
OKLA
TEXAS
SHERMAN
HARTLEY
OLDHAM
DEAF SMITH
CASTRO
LAMB
HOCKLEY
Datum = Top of San Andres Formation.
ALIBATES OUTER BRINE PAN FACIES
UPPER SEVEN RIVERS INNER BRINE PAN FACIES
LOWER SEVEN RIVERS MUD-SALT FLAT FACIES
QUEEN-GRAYBURG MUD FLAT FACIES
POST-BLAINE MUD FLAT FACIES
BLAINE OUTER BRINE PAN FACIES
GLORIETA WIND FLAT FACIES
UPPER SAN ANDRES OUTER BRINE PAN FACIES
CLEAR FORK MUD FLAT FACIES
CLEAR FORK INNER SALT PLAIN FACIES
CLEAR FORK OUTER SALT PLAIN FACIES
LOWER SAN ANDRES CARBONATE SHELF FACIES
GLORIETA B MUD FLAT FACIES
UPPER CLEAR FORK OUTER BRINE PAN
UPPER CLEAR FORK INNER SHELF FACIES
TUBB MUD FLAT FACIES
UPPER CLEAR FORK OUTER BRINE PAN FACIES
LOWER CLEAR FORK INNER SHELF FACIES
POST-SAN ANDRES GENETIC INTERVAL
SAN ANDRES GENETIC INTERVAL
UPPER CLEAR FORK GLORIETA GENETIC INTERVAL
LOWER CLEAR FORK-TUBB GENETIC INTERVAL
OKLAHOMA
TEXAS
DALHART BASIN
ANADARKO BASIN
OLDHAM NOSE
AMARILLO MTS
WICHITA MTS
NEW MEXICO
PALO DURO BASIN
HARDEMAN BASIN
RED RIVER ARCH
MILNE SAND DOME
MATADOR TREND
MIDLAND BASIN
LOCATION MAP

Figure 32



Permian isopach, CI = 100 ft



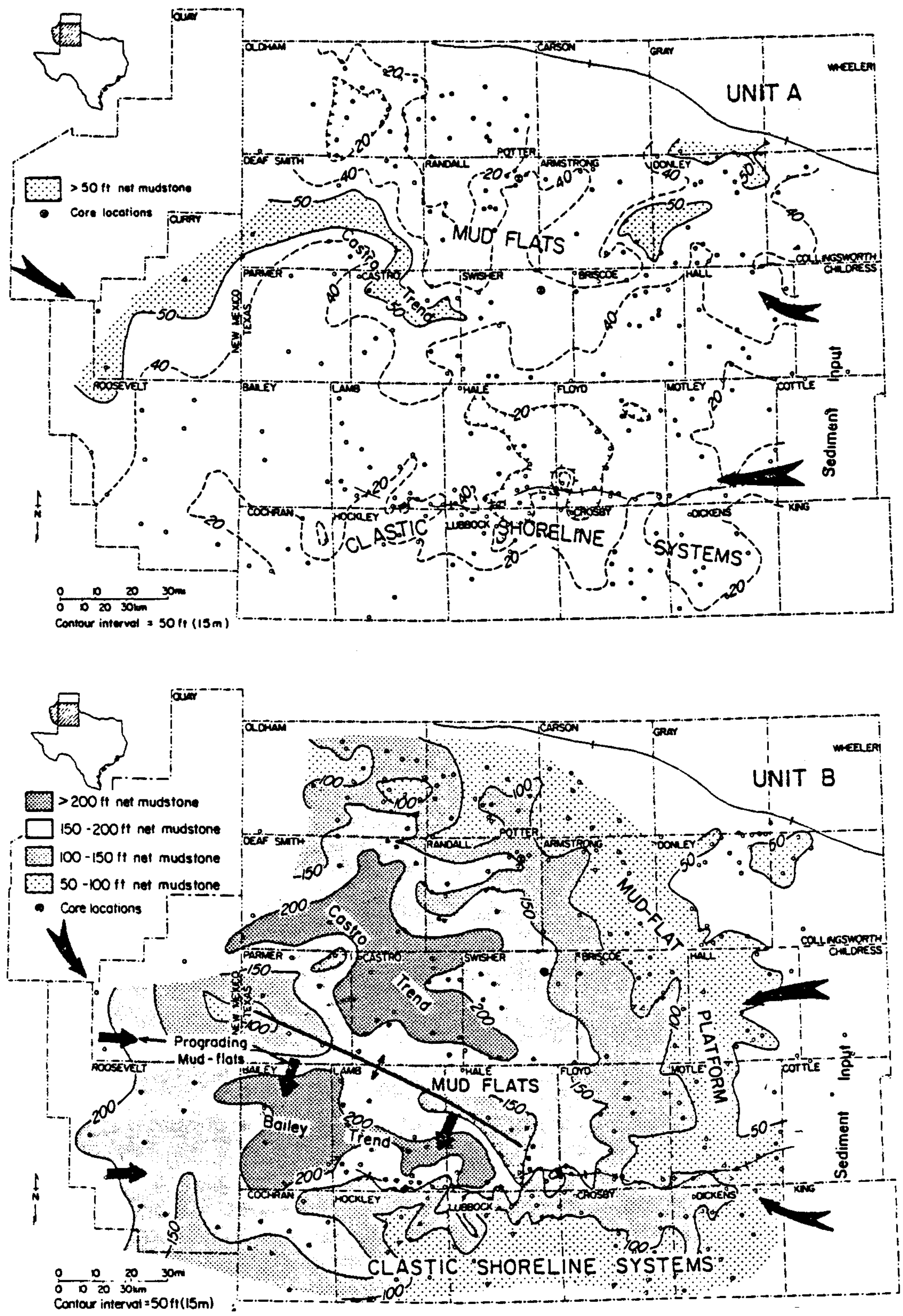


% CO_3 (DOLO) CONTOURED
C.I. - 10%

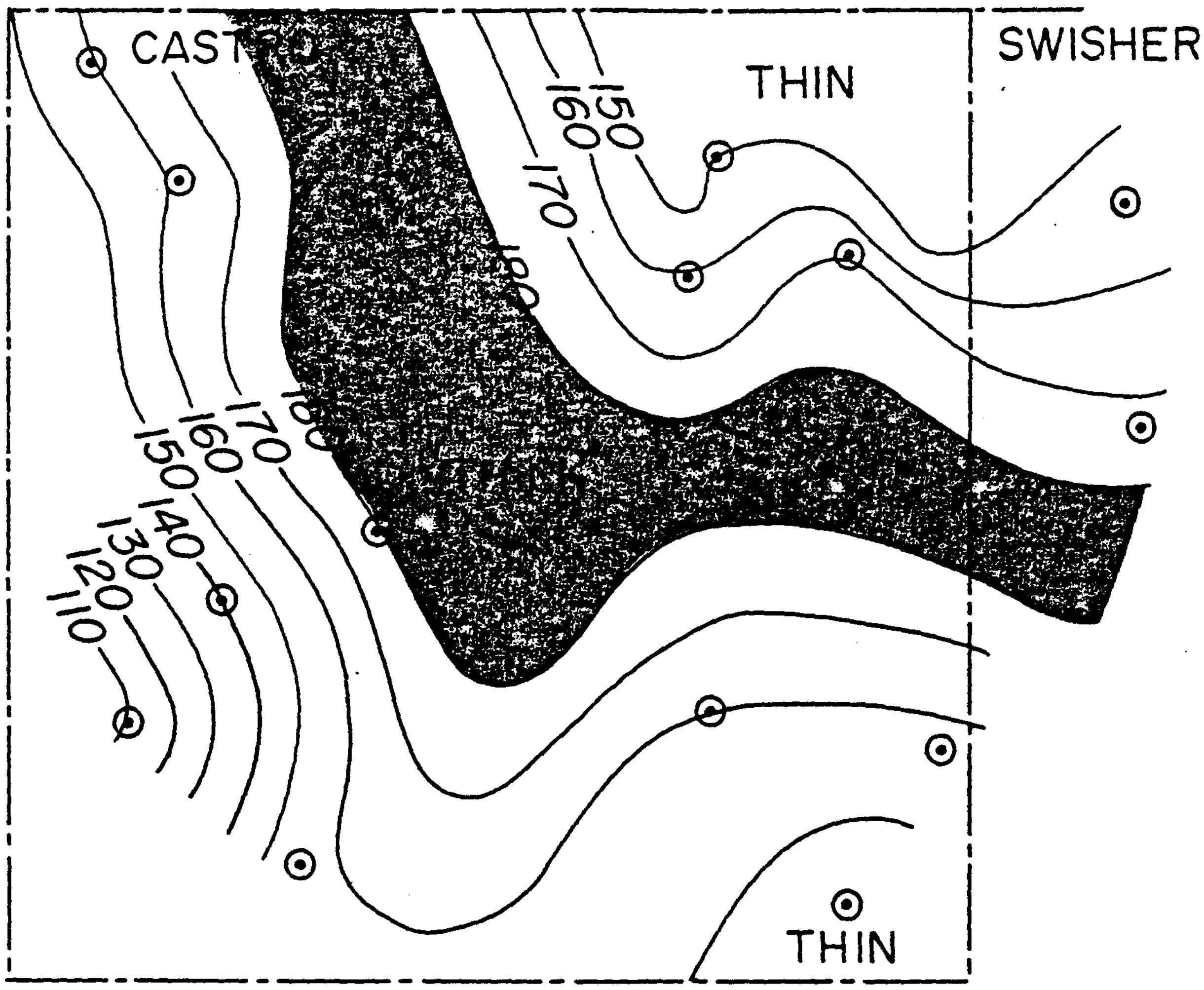
> 60% CO_3

40-60% CO_3 , ANHY > CLASTICS

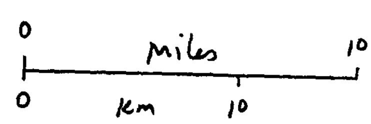
40-60% CO_3 , ANHY < CLASTICS



Facies distribution maps for Glorieta clastic units. Values for net mudstone calculated from gamma-ray data.



San Andres Formation - net salt Cycle 4, CI = 10ft



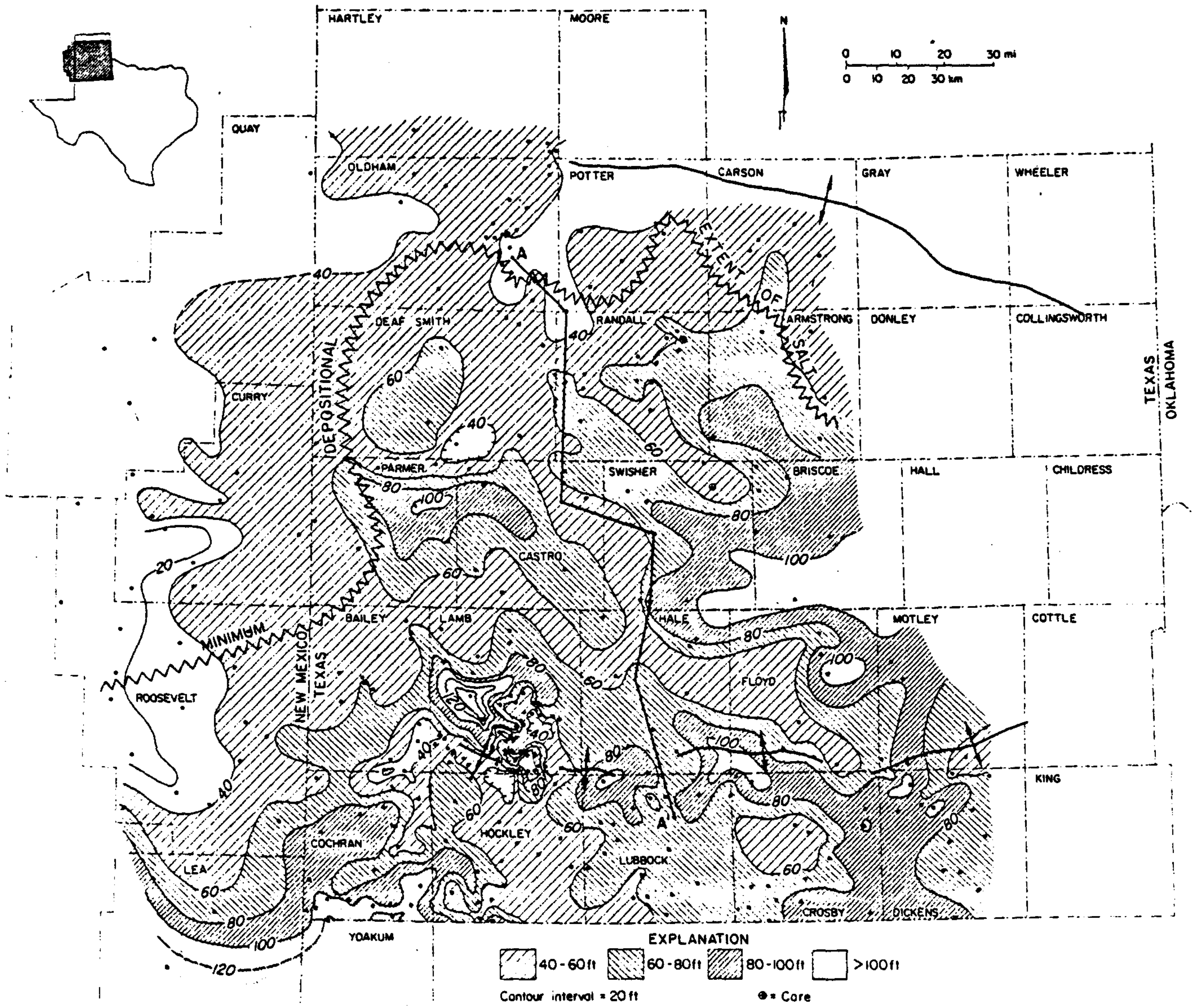
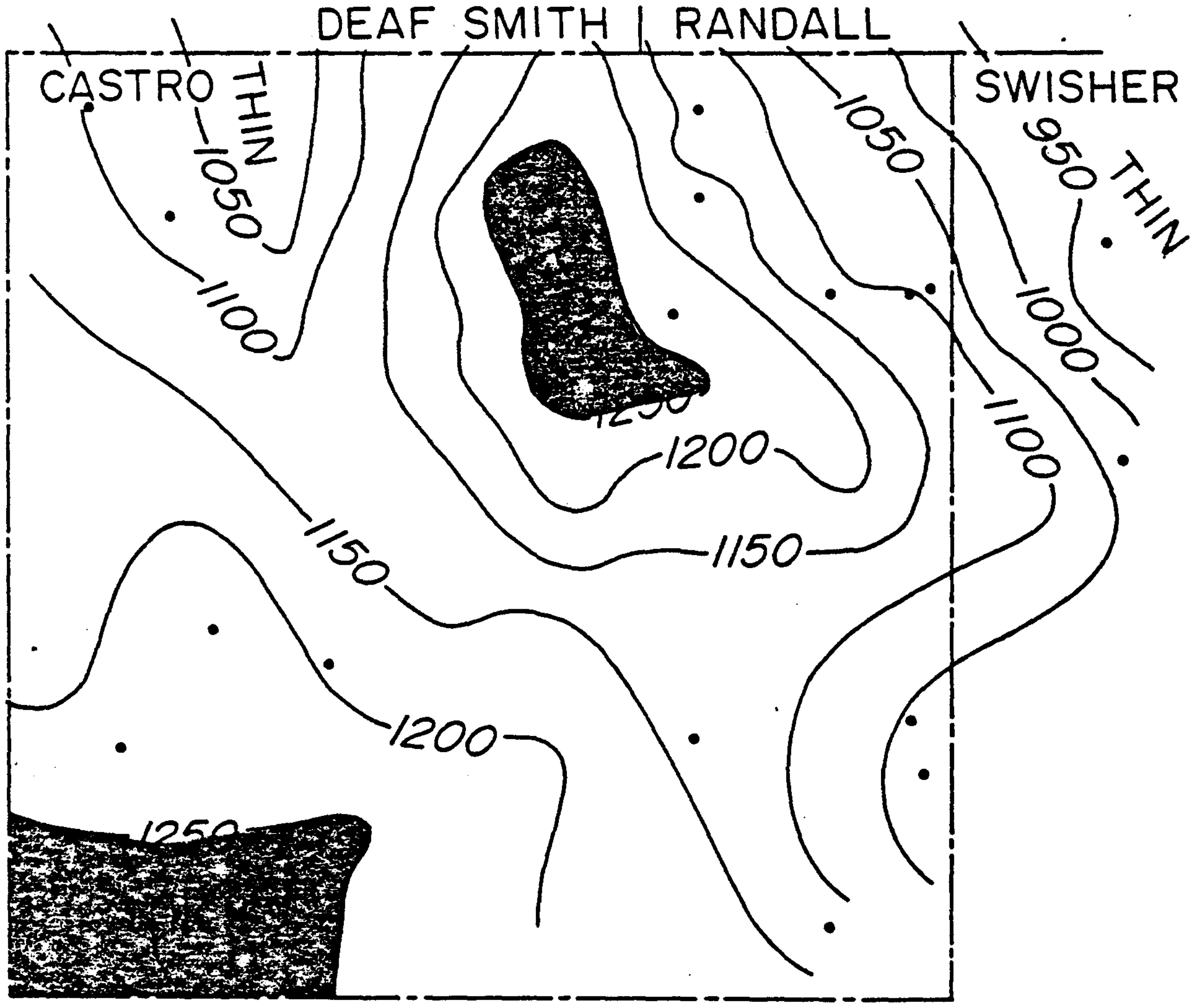

HARTLEY
MOORE
QUAY
OLDHAM
POTTER
CARSON
GRAY
WHEELER
DEAF SMITH
RANDALL
ARMSTRONG
DONLEY
COLLINGSWORTH
CURRY
PARMER
SWISHER
BRISCOE
HALL
CHILDRESS
CASTRO
BAILEY
LAMB
HALE
MOTLEY
COTTLE
ROOSEVELT
FLOYD
KING
COCHRAN
HOCKLEY
LUBBOCK
LEA
CROSBY
DICKENS
YOAKUM
DEPOSITIONAL MINIMUM
EXTENT OF SALT
NEW MEXICO
TEXAS
TEXAS
OKLAHOMA
A
A'
N
0 10 20 30 mi
0 10 20 30 km
EXPLANATION
40-60 ft
60-80 ft
80-100 ft
>100 ft
Contour interval = 20 ft
● = Core

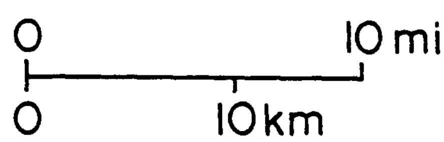
Figure 38

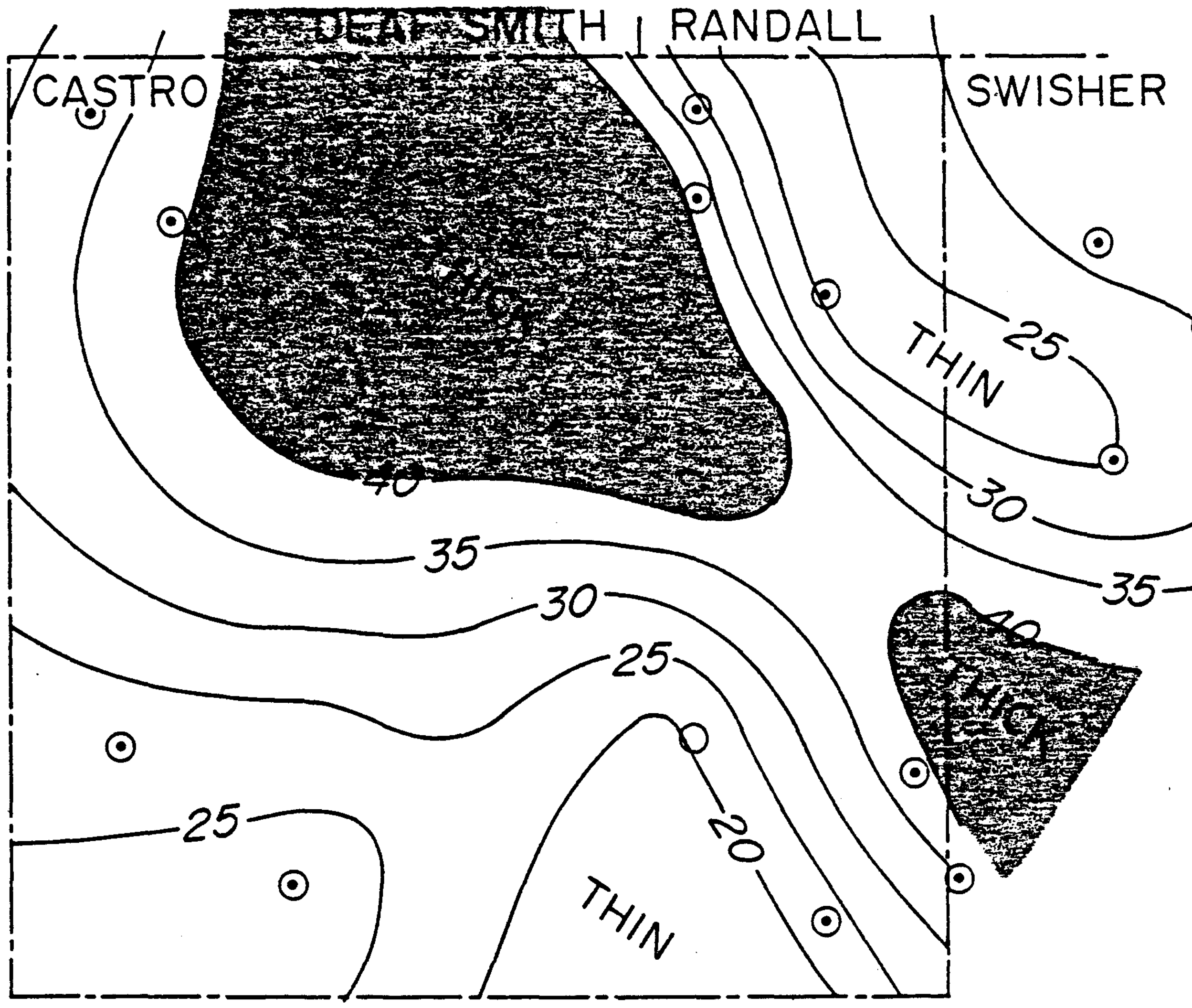
photograph

photograph



Isopach- Dockum Group and Dewey Lake Formation
CI = 50 ft



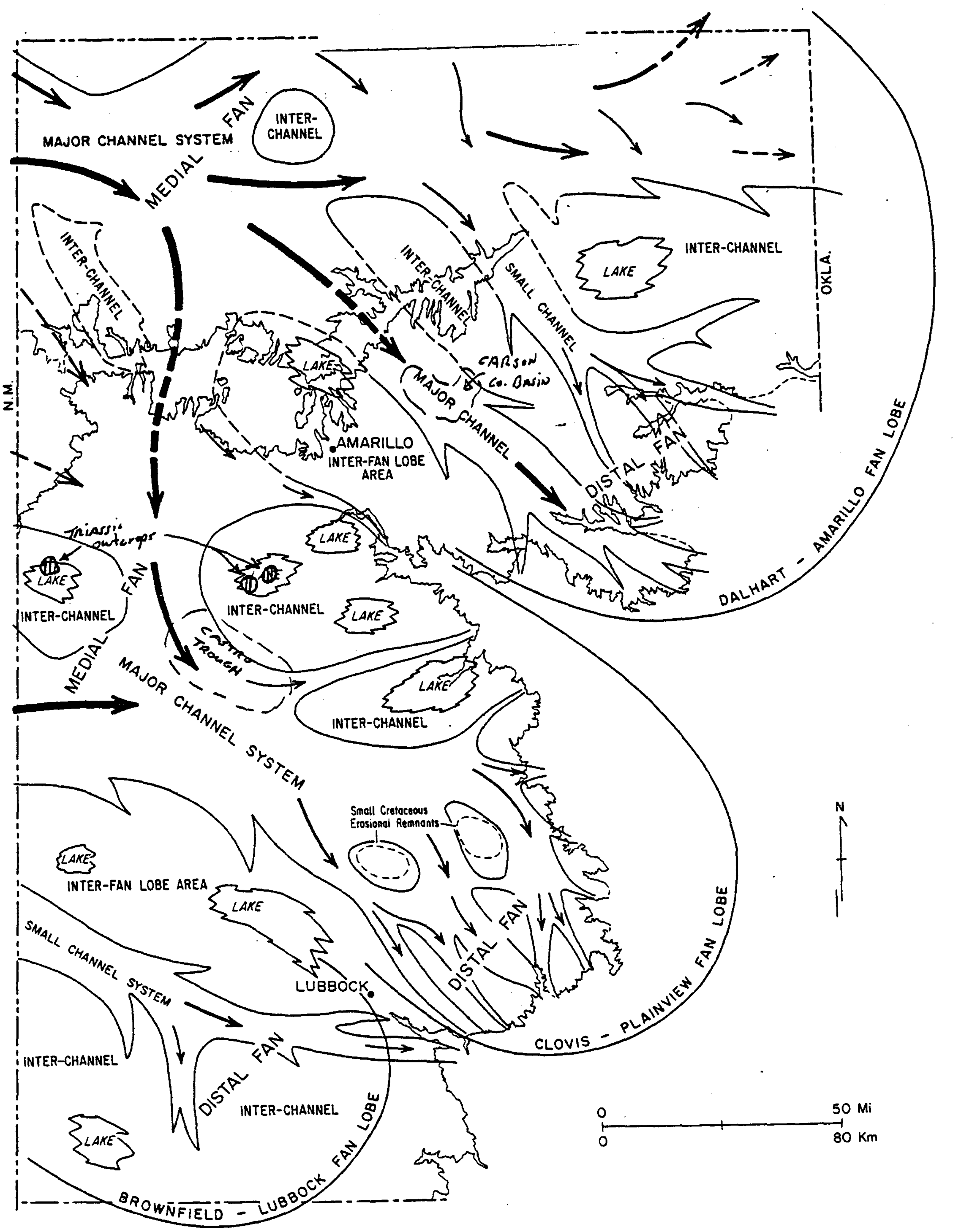


Percent sand - Triassic lower Dockum Group
CI = 5%

0 10 mi
0 10km

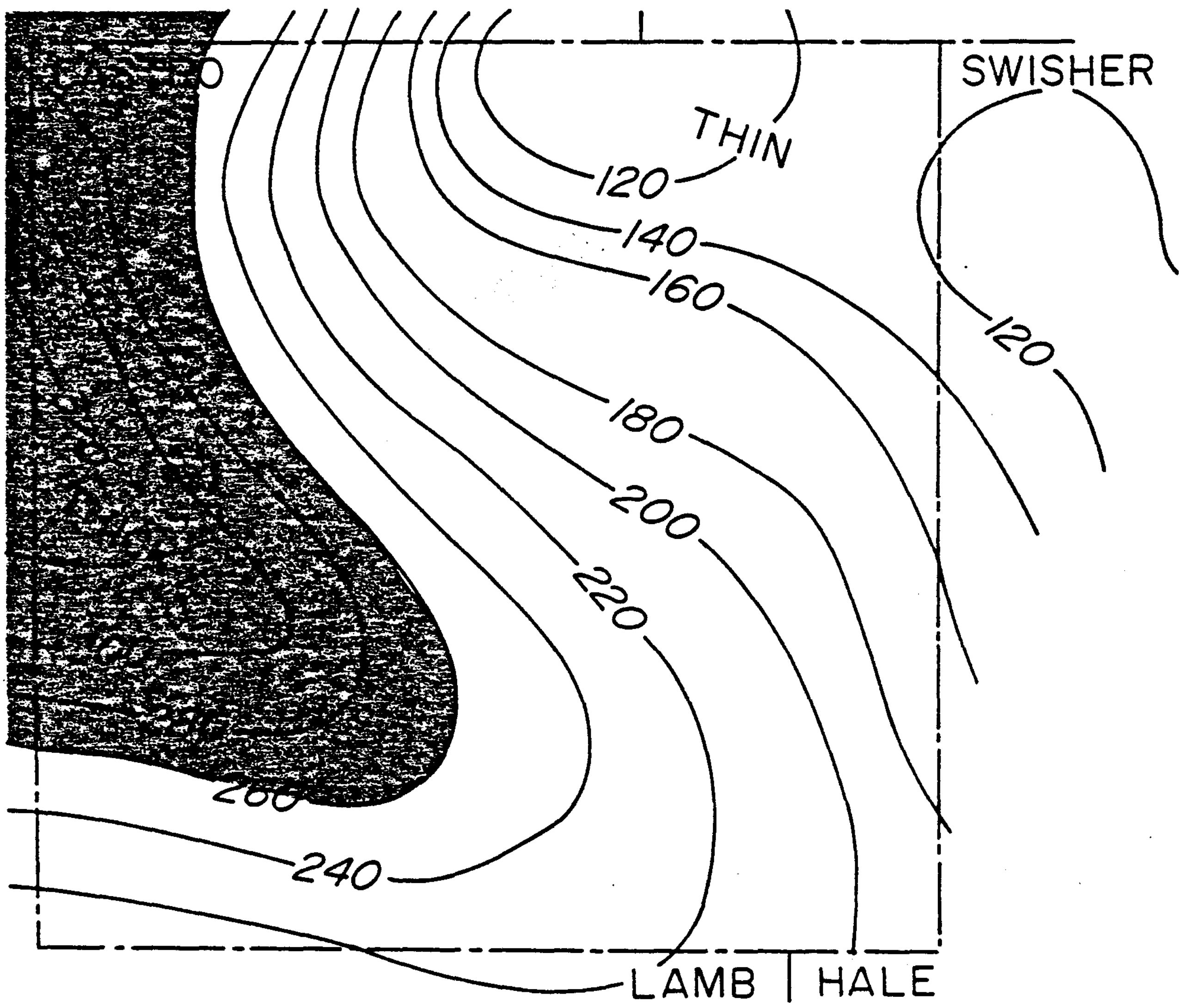
photograph

Figure 43



MAJOR CHANNEL SYSTEM
MEDIAL FAN
INTER-CHANNEL
INTER-CHANNEL
INTER-CHANNEL
SMALL CHANNEL
LAKE
INTER-CHANNEL
OKLA.
N.M.
LAKE
CARSON Co. BASIN
MAJOR CHANNEL
DISTAL FAN
AMARILLO
INTER-FAN LOBE AREA
DALHART - AMARILLO FAN LOBE
Triassic outcrops
LAKE
LAKE
INTER-CHANNEL
LAKE
INTER-CHANNEL
MEDIAL FAN
CASTRO TROUGH
LAKE
MAJOR CHANNEL SYSTEM
INTER-CHANNEL
Small Cretaceous Erosional Remnants
LAKE
INTER-FAN LOBE AREA
LAKE
DISTAL FAN
SMALL CHANNEL SYSTEM
LUBBOCK
CLOVIS - PLAINVIEW FAN LOBE
INTER-CHANNEL
DISTAL FAN
INTER-CHANNEL
LAKE
BROWNFIELD - LUBBOCK FAN LOBE
N
0
50 Mi
0
80 Km

Figure 44



Net sand – Tertiary Ogallala Formation, CI = 20 ft
Source: Texas Department of Water Resources (1982)