The Permian Basin: Proving Ground for Tomorrow's Technologies

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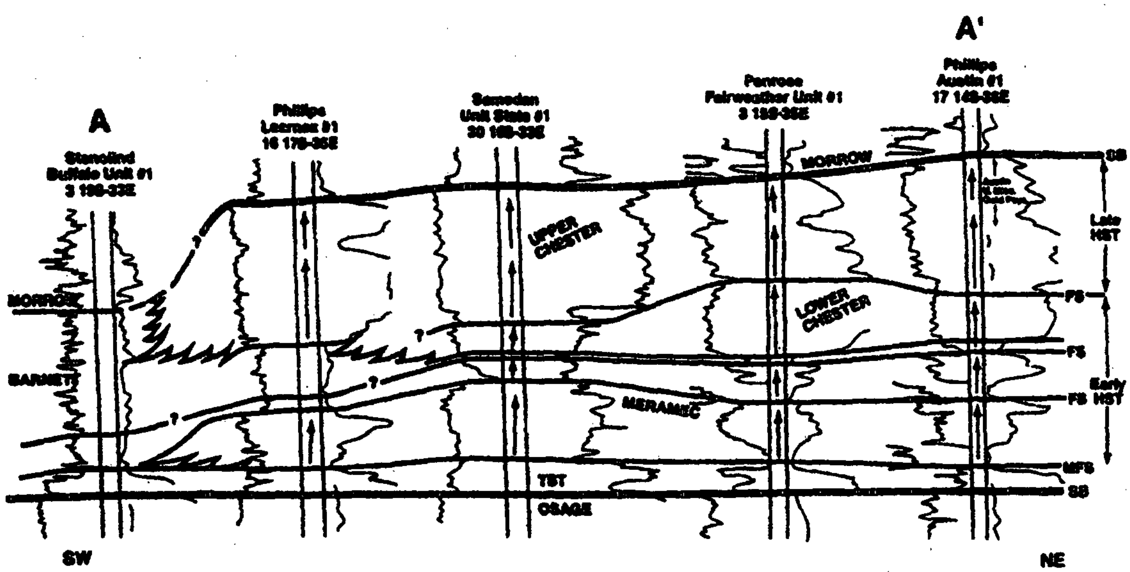

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Tectonic Model for Late Paleozoic Deformation of the Central Basin Platform, Permian Basin Region, West Texas

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ABSTRACT

The Central Basin Platform (CBP) is an important tectonic element in the subsurface of the Permian Basin region. It is a major intraforeland uplift that trends at high angle to the Marathon fold-and-thrust belt. This study examined structural features across the southwestern Midland Basin and eastern CBP along with a compilation of published information from the eastern Delaware Basin and other parts of the CBP in order to document the tectonic history of these areas.

Structural interpretation from seismic data, structure contour maps, and structural cross sections show that the southwestern Midland Basin, interior CBP, and eastern Delaware Basin are characterized by NW-SE trending en echelon folds. These folds are typically asymmetric in cross-section with the steeper limb of the fold being cut by steeply dipping reverse faults that trend sub-parallel to fold axes. The folds are arranged in a right-stepping en echelon pattern with low obliquity to the boundary fault zones of the CBP. At a larger scale, the CBP consists of two main crustal blocks that also are arranged in en echelon pattern with steeply dipping reverse and thrust faults, asymmetrical flower structures, and a few normal faults at boundaries. The western margin of the CBP has greater structural relief, vertical separation, and basement shortening than the eastern margin. The dominance of contractional structures and en echelon arrangement of these structures in map view indicate that the CBP and adjacent areas formed in a right-lateral convergent strike-slip (transpressional) tectonic setting.

A simple geometric method was applied to evaluate the slip motions along the boundary faults of the CBP. Geometric analysis shows that the NNW-NW trending boundary faults were subjected to right-lateral convergence-dominated oblique-slip deformation, whereas the ENE-WSW trending boundary faults were subjected to left-lateral strike-slip dominated oblique-slip deformation. The derived slip motions along the boundaries of the CBP explain the wide variety of structural features observed and also agree with previously proposed models that involve clockwise rotation of crustal blocks within the CBP.

The structural patterns associated with the eastern Delaware Basin, CBP, and western Midland Basin can be explained by considering these areas together as a transpressional deformation zone. Three stages of deformation can be recognized based on significant changes in the style of the deformation and by the area of active deformation through time. An initial NE-SW directed compressive stress caused minor en echelon folding across parts of the eastern Delaware Basin, CBP region, and western Midland Basin during late Mississippian-middle Pennsylvanian time. After a middle Pennsylvanian phase of relative tectonic quiescence, renewed and amplified compressive stress in late middle Pennsylvanian time generated right-lateral convergent shearing across the transpression zone and was responsible for the formation of regionally distributed en echelon faulted anticlines. During late Pennsylvanian-Wolfcampian time, strain partitioning occurred within the transpression zone. En echelon folding within the sub-basins ceased, but continued right-lateral oblique slip across the transpression zone was accommodated along the boundaries of the CBP, where pre-existing basement weaknesses were reactivated as high-angle faults. Major uplift of the CBP occurred during this last phase of late Pennsylvanian-Wolfcampian deformation.

The tectonic relationships between the subtle structures within the sub-basins and the CBP are an example of the sequential development of structures that can develop during progressive transpressional deformation across a foreland basin. Our study of the CBP and adjacent areas may provide insight into the origins of similar intraforeland basement uplifts that developed elsewhere across the interior of the North America during late Paleozoic time.

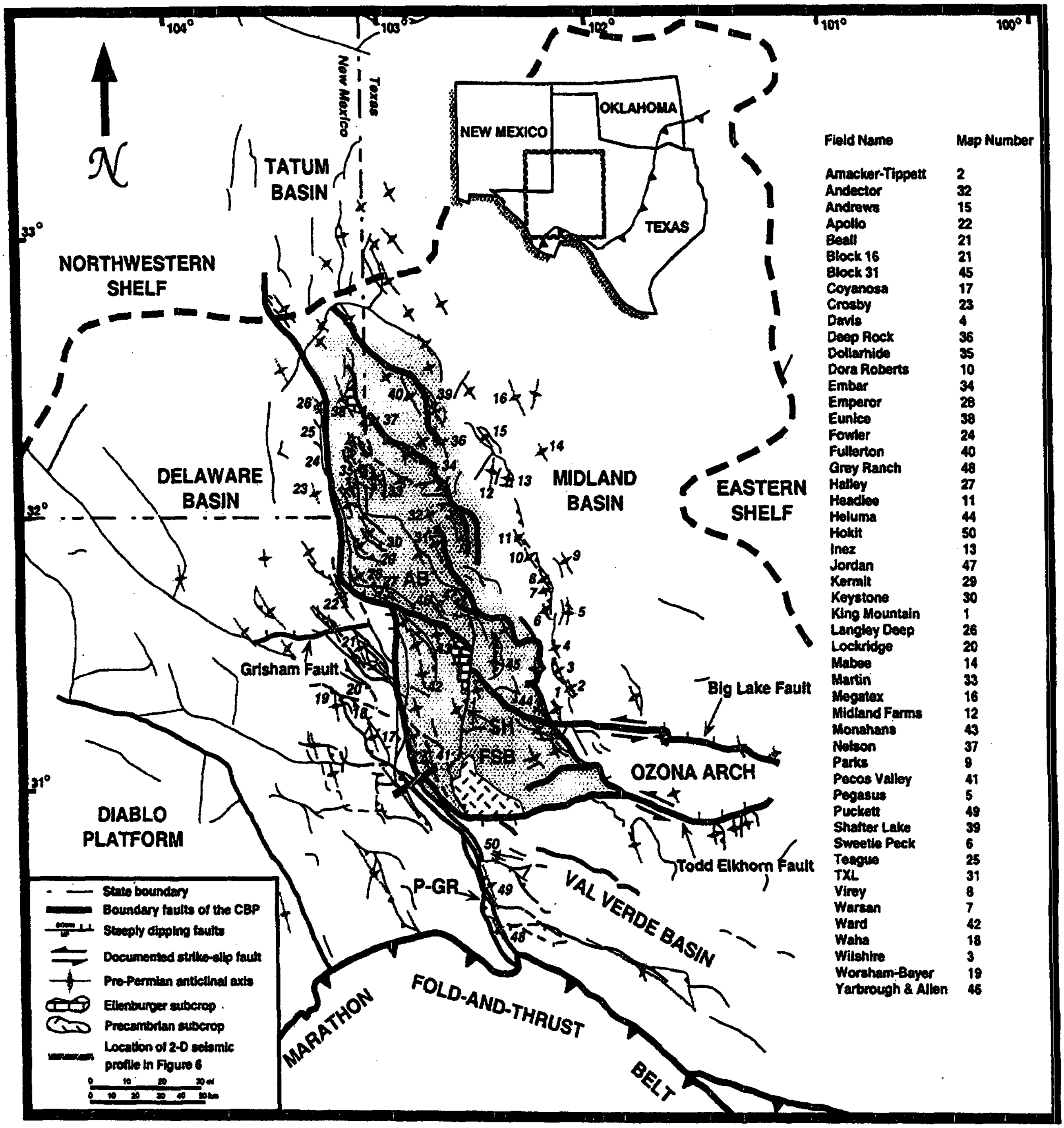


Figure 1. Generalized tectonic map for the Permian Basin, showing the Central Basin Platform, Delaware Basin, and Midland Basin. Modified from GEOPMAP (1983), Ewing (1990), Gardiner (1990a), Comer (1991), Shumaker (1992), and Yang and Dorobek (1995a). The oil-gas fields mentioned in this study are labeled by number. Orientations of the pre-Permian fold axes associated with selected oil-gas fields were compiled from Stipp et al. (1956), Herald (1957), Harrington (1963), Hills (1970), Galloway et al. (1983), GEOMAP (1983), Henderson et al. (1984), and Kosters et al. (1988). The shaded area represents the general outline of the Central Basin Platform. AB = Andector Block; FSB = Fort Stockton Block; SH = Sand Hills Fault; P-GR = Puckett-Grey Ranch Fault Zone.

INTRODUCTION

The CBP (CBP) is a positive tectonic feature of the Permian Basin in the subsurface of West Texas and southeastern New Mexico (Figure 1). It is a NNW-SSE trending basement uplift that is bounded by complex, high-angle fault zones. The CBP trends at high angle to the Marathon fold-and-thrust belt to the south and separates the Delaware Basin to the west and the Midland Basin to the east (Figure 1). The CBP started to form inboard of and at about the same time as crustal shortening in the Marathon-Ouachita fold-and-thrust belt to the south and east during late Mississippian time (Hills, 1970; Wuellner et al., 1986; Ewing, 1991; Yang and Dorobek, 1995a). Uplift of the CBP peaked in late Pennsylvanian-late Wolfcampian time and was largely over by early Leonardian time (Ewing, 1991; Yang and Dorobek, 1995a). Since Late Permian time, the CBP has not been subjected to significant deformation, and its present structural configurations are basically the same as those that existed during late Paleozoic time (Frenzel et al., 1988).

The complex structural features, together with their associated pre-, syn-, and post-orogenic stratigraphic relationships, provide many important hydrocarbon traps across the CBP. In the past few decades of hydrocarbon exploration and production, however, most previous studies have focused on individual oil and gas fields across the CBP. Few studies have attempted to summarize these data and address the relationships between local structures and regional, basin-scale tectonic features.

One long-standing question regarding the CBP is the tectonic model responsible for its origin. Various tectonic models, involving either regional extension (Elam, 1984), compression (Galley, 1958; Ye et al., 1996), or strike-slip deformation (Harrington, 1963; Hills, 1970; Walper, 1977; Goetz and Dickerson, 1985; Gardiner, 1990a, Ewing, 1991; Shumaker, 1992; Yang and Dorobek, 1995a), have been proposed to explain the deformation that produced the CBP, the structural features associated with the CBP, the stress fields responsible for its formation, and the significance of the CBP to regional deformation across the Marathon-Ouachita foreland (Kluth and Coney, 1981; Ye et al., 1996).

Despite debates on the tectonic origin of the CBP, right-lateral strike-slip deformation due to SW-NE directed compressive stress appears to best explain most of the structural features along the margins of the CBP (Harrington, 1963; Hills, 1970; Ewing, 1991; Yang and Dorobek, 1995a). There are many observed structural features, however, that cannot be explained by right-lateral strike-slip deformation. For example, clockwise rotation of crustal blocks resulting from right-lateral shear couple (cf. Yang and Dorobek, 1995a) does not adequately explain either regional uplift of the CBP or the broader pattern of en echelon folding that developed across the eastern Delaware Basin, CBP, and western Midland Basin prior to major deformation and uplift of the CBP.

Reasonably detailed descriptions of the boundary fault zones of the CBP are given by Shumaker (1992) and Yang and Dorobek (1995a). To date, however, no study has been conducted on the slip motion along the boundary faults of the CBP. The amount of lateral displacement along the CBP's boundary faults is difficult to estimate because of uncertainties in establishing piercing points across either the eastern or western boundary fault zones of the CBP (Shumaker, 1992). By largely focusing on the late Paleozoic structural features along the margins of the CBP, most previous studies (Hills, 1970; Gardiner, 1990a; Shumaker, 1992; Yang and Dorobek, 1995a; Ye et al., 1996) have generally overlooked the comparatively low-relief late Paleozoic structures within the sub-basins that are adjacent to the CBP (e.g., the Pegasus-Amacker structural trend in the southwestern Midland Basin; Figures 1, 2; Tai and Dorobek, 1999). Thus, the kinematic relationships between these subtle structures within the basins and the CBP have not been examined, even though they may provide important constraints on the tectonic evolution of the Permian Basin region (Tai and Dorobek, 1999).

A better understanding of the structural features of the CBP and adjacent areas is important for unraveling the complex tectonic history of the Permian Basin. In this study, we utilized a data set that was donated to Texas A&M University by Chevron USA. This data set, which covers the southwestern Midland Basin and eastern CBP regions, includes five 3-D seismic surveys (covering over 800 km^2), numerous 2-D seismic profiles, over 200 digital well-logs, and production data. We first examined the various structural features across the southwestern Midland Basin and eastern CBP using seismic data, structural contour maps, and well-log cross sections. The timing of deformation was inferred from variations in the thickness of stratigraphic units on cross sections and recognition of unconformities on seismic profiles and well-log cross sections. We also integrated our observations with previously published information from the eastern Delaware Basin and other parts of the CBP in order to put these structural features into a regional tectonic framework. Finally, we used a simple geometric method to determine the nature of slip motion and the displacement vector along the boundary faults of the CBP, which in turn, lead to a new tectonic model for the formation of the CBP and adjacent areas. A better understanding of the tectonic history of the CBP and adjacent sub-basins may provide an important analog for understanding other basement uplifts (e.g., Diablo Platform, Ozona Arch) that developed across distal parts of the Marathon-Ouachita foreland region during late Paleozoic time.

CHARACTERIZATION OF LATE PALEOZOIC STRUCTURAL STYLES

Our structural characterization was based on structural mapping (faults and folds) on 2-D seismic profiles and 3-D seismic surveys, construction of structural cross sections and structure contour maps, and integration with published information. Here we present brief descriptions of the temporal and spatial relationships between structural features across the study area.

Southwestern Midland Basin

Late Paleozoic structural features across the southwestern Midland Basin are characterized by a series of en echelon folds and basement-involved fault systems (Figure 2a). The Pegasus-Amacker structural trend, which is sub-parallel to the NNW-SSE trending CBP, is located eastward of the uplifted CBP within the southwestern part of the Midland Basin (Figure 2a; Becher and von der Hoya, 1990). Each field along this structural trend (e.g., Amacker-Tippett, Wilshire, Davis, and Pegasus fields) is characterized by a doubly plunging, asymmetrical anticline with a steeply dipping reverse fault that cuts the steeper fold limb (Tai and Dorobek, 1999). North of this structural trend, Sweetie Peck, Warsan, Virey, Dora Roberts, and Headlee fields also display similar structural styles (i.e., faulted asymmetrical anticlines), but with different fault dips and throws (Figure 2a).

In map view, most anticlinal axes within the southwestern Midland Basin trend NW-SE, although fold axes at Sweetie Peck, Warsan, and Pegasus fields trend N-NNE. Overall, these faulted anticlines are arranged in an en echelon right-stepping pattern (Figure 2a). The average orientation of fold axes is N26°W, which is 10° from the average N16°W strike of faults along the eastern boundary of the CBP (Figure 2b). Similar deeply buried, en echelon anticlinal structures also can be found in other parts of Permian Basin, including the northwestern Midland Basin (e.g., Means, Midland Farms, Magutex, Inez, Mabee, and Andrews fields) and the eastern Delaware Basin (e.g., Beall, Block 16, Waha, Worsham-Bayers, and Langley Deep fields) (Figure 1). Fold axes from these faulted anticlines also generally trend NW-SE and are arranged in a right-stepping en echelon pattern (Stipp et al., 1956; Monley and Mercuri, 1976; Henderson

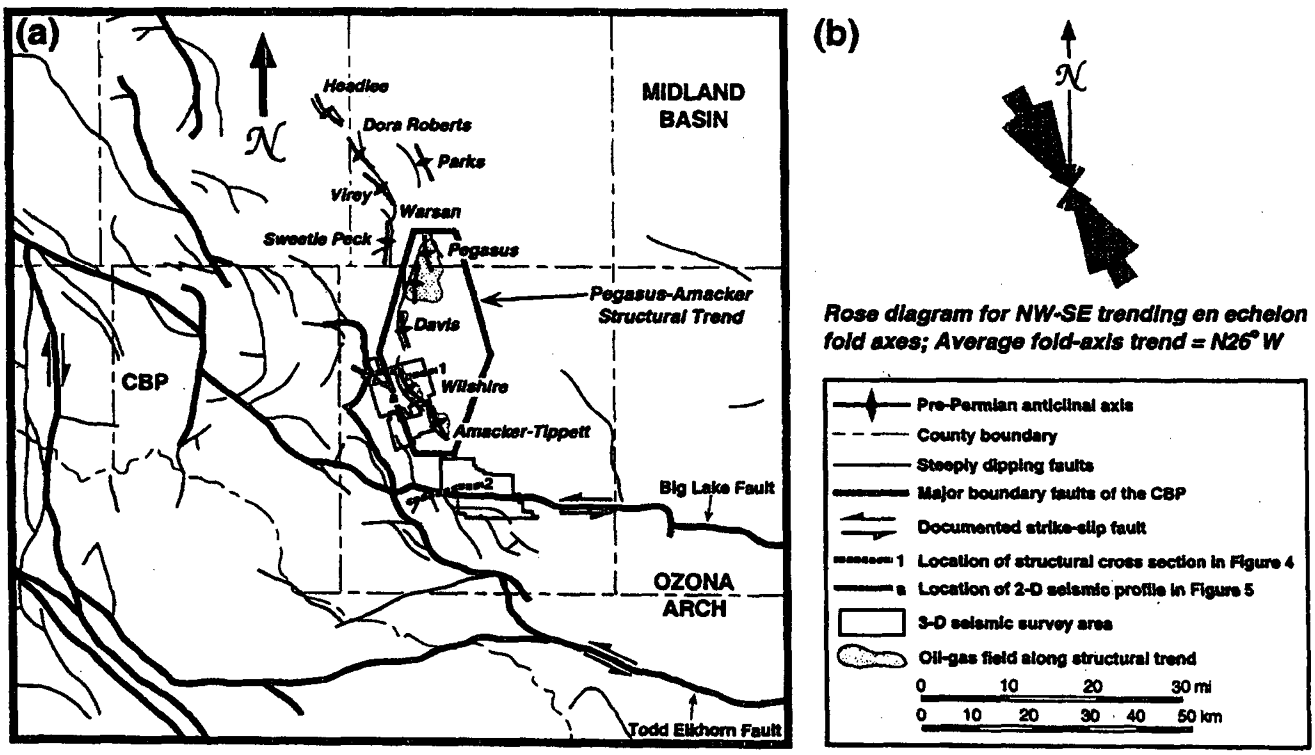


Figure 2. (a) Fault map for the southwestern Midland Basin, Ozona Arch, southern part of the Central Basin Platform, and locations of oil-gas fields along the Pegasus-Amacker structural trend. (b) Rose diagram of NW-SE trending fold axes derived from oil-gas fields along the Pegasus-Amacker structural trend. The average orientation is N26°W, which is 10° from the strike of the fault zone that defines the eastern boundary of the Central Basin Platform. This kind of right-stepping en echelon fold pattern is characteristic of the right-lateral strike-slip deformation zones.

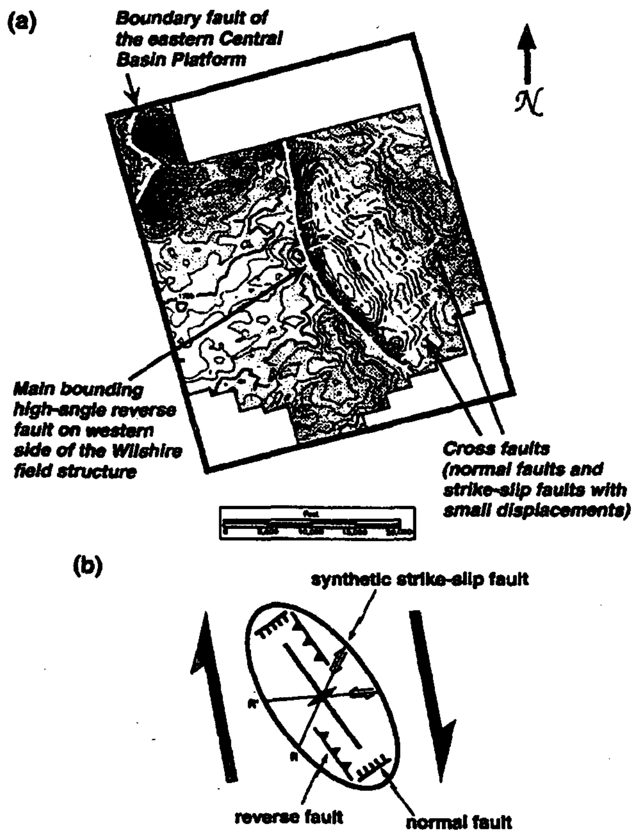


Figure 3. Comparison between the Devonian time-structure map of Wilshire field and the horizontal strain ellipse. Contour interval is 10 ms. The Wilshire field anticlinal structure is shown on the eastern part of 3-D survey. Note the close match between the structures documented in 3-D seismic data from Wilshire field and structures predicted by the horizontal strain ellipse.

et al., 1984; Hardage et al., 1999).

Estimated fold length within the Pegasus-Amacker Structural Trend is between 2 and 5 miles (3 to 8 km). The steep limb of each anticlinal structure is cut by a steeply dipping fault that is curved in map view (Figures 2a, 3a). These basement-involved faults dip eastward for Amacker-Tippett, Wilshire, and Davis fields, but they dip westward for Sweetie Peck, Warsan, Virey, Dora Roberts, and Headlee fields (Figure 2a). At Wilshire field, the main bounding fault is a single, steep dipping reverse fault at depth with several splay faults that branch from the main fault at shallower depths. Together the master and splay faults form a positive flower structure. Compared to the margin of the uplifted CBP to the west, these anticlines have low structural relief (Tai and Dorobek, 1999). The cross section across the Wilshire field structure and eastern margin of the CBP (Figure 4a) shows that most faults cut across the Devonian-Atokan interval and terminate at or below the top of the Strawn Formation. Post-Strawn uplift resulted in erosion of upper Strawn strata (Strawn Carbonate) and unconformity developed across much of the Wilshire field structure, whereas a thicker and more complete Strawn section is preserved in the structural low to the west of it. The amount of upper Strawn erosion across the Wilshire field structure is relatively small in comparison to that over the CBP, where only thin Strawn strata are locally preserved (Figure 4a; Tai and Dorobek, 1999). By late Pennsylvanian time (Canyon-Cisco), deformation at Wilshire field had essentially ceased. Similar low structural relief and post-Strawn unconformities are also reported across the folds that define oil and gas fields in the northwestern Midland Basin and eastern Delaware Basin (Stipp et al., 1956; Herald, 1957; Monley and Mercurio, 1976; Henderson et al., 1984).

At Wilshire field, vertical displacement of the Devonian-Atokan interval on either side of the master fault is largest in the central part of the structure, with an offset of ~800 feet; vertical offset progressively decreases away from the center of the master fault (Tai and Dorobek, 1999). The greatest fault offset is also coincident with higher structural relief and a narrower deformation zone, whereas decreasing offset toward the tips of the master fault is associated with lower structural relief and a broader deformation zone. Several NE-SW trending cross faults were observed on the eastern, gentler limb of the Wilshire field structure (Figure 3a). These faults terminate into the main reverse fault at a high angle and locally offset the Wilshire field structure with minor normal and strike-slip faulting displacements. Similar cross faults that trend at high angles to the main bounding fault of the anticline were identified in the Amacker-Tippett field structure, which is located south of Wilshire field (Figures 1, 2a; Ewing, 1990).

Central Basin Platform

Tectonic maps of the Permian Basin show that the CBP is composed of several fault-bounded structural domains (Gardiner, 1990a; Ewing, 1991; Shumaker, 1992; Yang and Dorobek, 1995a). In this study, we followed the convention of Yang and Dorobek (1995a) and separated the CBP into two dominant crustal blocks, the Andector and Fort Stockton blocks. This subdivision of the CBP is based on generally similar sense of vergence, structural relief, and orientations of structural features within each of these blocks. This simplification facilitates visualization of our interpretation for the large-scale, kinematic evolution of the CBP.

The CBP is internally folded and faulted, although fault displacements are much smaller in comparison to the boundary fault zones. NW-SE trending faulted asymmetrical anticlines are the dominant structural features in interior parts of the CBP (Figure 1). Like the en echelon folds within

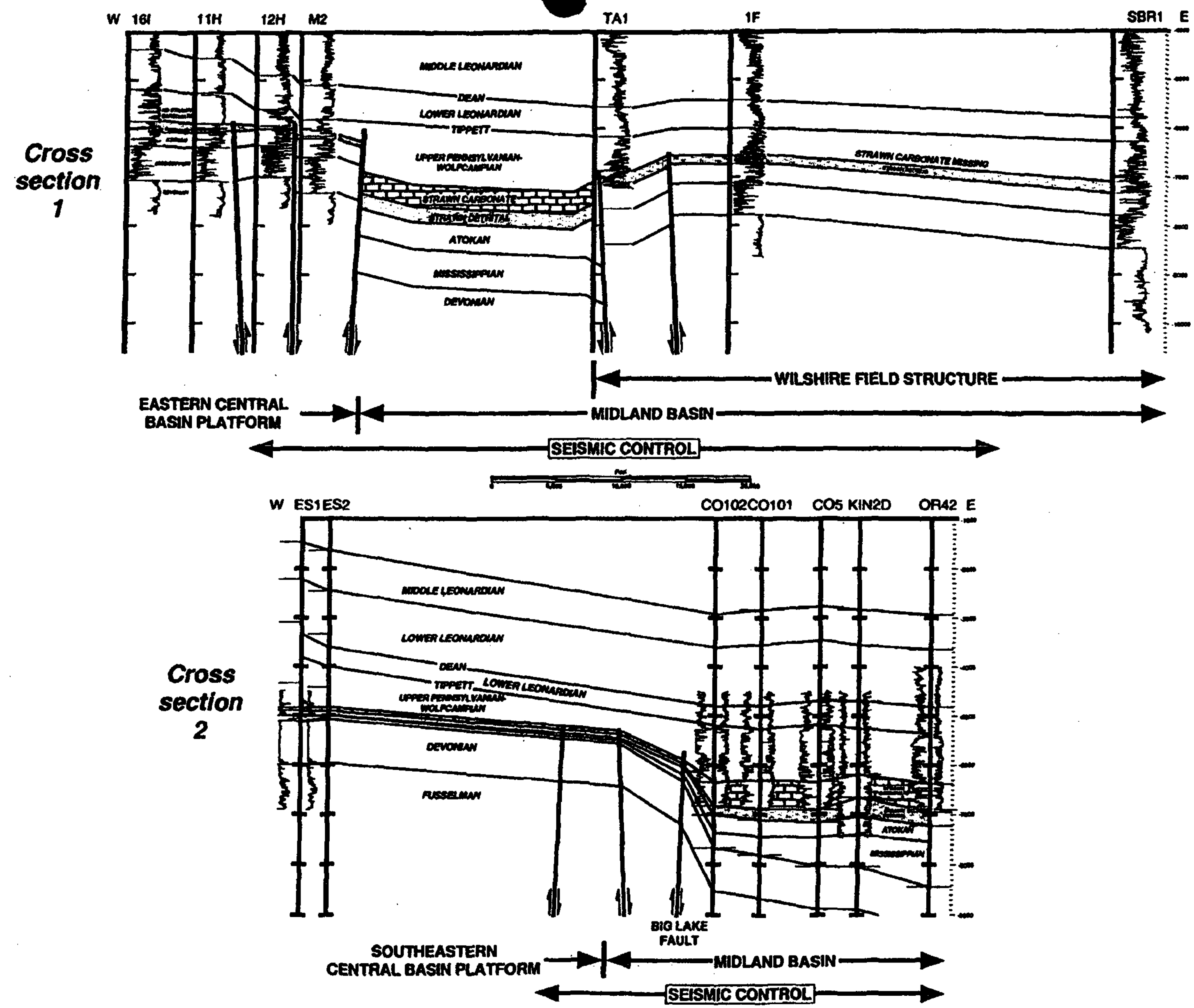


Figure 4. Cross sections from the eastern boundary of the Central Basin Platform (see Figure 2a for locations). Data used to constrain stratigraphic thicknesses include both well-logs and seismic profiles. Cross section 1 extends from the NE corner of the Fort Stockton Block to the Wilshire field structure in the Midland Basin. Note the broad anticlinal feature and the differential erosion of the upper Strawn Formation (Strawn Carbonate) over the eastern margin of the Central Basin Platform (wells 16I, 11H, 12H, and M2) and over the crest of the Wilshire field structure (wells TA1, 1F, and SBR1). Cross section 2 extends form the southeastern Central Basin Platform to the southwestern Midland Basin. Note the very thin Mississippian to Strawn section that is preserved over the Central Basin Platform (wells ES1 and ES2).

the southwestern Midland Basin, these anticlines are important petroleum traps and also display an en echelon pattern relative to the boundary fault zones of the CBP (Figure 1; Harrington, 1966; Hills, 1970; Frenzel et al., 1988). The average trend of fold axes is N30°W. Compared to the en echelon folds within the eastern Delaware and western Midland Basin, the crest of folds from interior parts of the CBP are more deeply eroded, with a major post-Pennsylvanian unconformity that generally separates Permian rocks from underlying lower Paleozoic rocks. Cross faults that cut the asymmetric anticlines and terminate into the main boundary fault have been reported in the Andector, Dollarhide, Eunice, Martin, Embar, Andector, Fullerton, Halley, and TXL fields, and they are right-lateral strike-slip faults or normal faults with small displacement (Gardiner, 1990a; Ewing, 1991; Algeo, 1992; Shumaker, 1992; Montgomery, 1998).

The Sand Hills Fault is an intra-block fault located within the Fort Stockton Block (Figure 1; Gardiner, 1990a). This fault has a sigmoidal trace in map view and has been described as a scissor fault with changing sense of throw along the fault's strike. At its northern end, the Sand Hills Fault dips westward and Wolfcampian strata lie unconformably on the Ordovician Ellenburger Formation, whereas at its southern end, the fault dips eastward and Wolfcampian strata directly overlie the Precambrian basement rocks (Figure 1; Gardiner, 1990a).

Steeply dipping fault zones characterize the boundaries of the CBP (Figures 1, 4, 5, and 6; Hills, 1970; Bebout and Meador, 1985; Yang and Dorobek, 1995a). The eastern margins of the CBP are characterized by NNW-SSE trending (N16°W) high-angle reverse faults that dip 50°-60° westward toward the interior of the CBP (Figures 2a, 4, and 5; Yang and Dorobek, 1995a). Deformed pre-Permian rocks along the boundary fault zone commonly display asymmetrical positive flower structures (Figures 4, 5; Gardiner, 1990a; Turmelle, 1992). In map view, the eastern boundary faults of the CBP are not as laterally continuous as the western boundary faults. Instead, the traces of individual fault segments tend to display a jagged pattern (Figures 1, 2a). The greatest amount of vertical displacement along the eastern side of the CBP is found at the NE corners of the Andector and Fort Stockton blocks (Yang and Dorobek, 1995a). Vertical displacement progressively decreases from north to south along the eastern margins of Andector and Fort Stockton blocks. Calculated amounts of basement shortening also decrease southward along the eastern boundary of the Andector and Fort Stockton blocks, away from their NE corners. Normal faults at the SE corner of the Andector Block dip eastward into the Midland Basin (Yang and Dorobek, 1995a).

The western boundary of the CBP is an approximately 10-mile wide fault zone that separates the uplifted CBP from the Delaware Basin to the west (Figure 1, Hills, 1970). In general, the western boundary of the CBP has greater structural relief, vertical separation, and basement shortening than its eastern boundary (Yang and Dorobek, 1995a). The western boundary fault zone consists of several closely spaced and steeply dipping faults that bound narrow, elongate slices of basement, which rapidly step down to the west (Figures 1, 6; Hills, 1970; Bebout and Meador, 1985). The SW corners and western margins of the Andector and Fort Stockton blocks are characterized by NW-SE trending (N10°W-N45°W) steeply-dipping, basement-involved reverse faults that dip 50°-60° eastward toward the interior of the CBP (Figure 1, 6; Yang and Dorobek, 1995a). The greatest amount of vertical displacement is found at the SW corners of the Andector and Fort Stockton blocks; vertical displacement progressively decreases from south to north along the western margins of the Andector and Fort Stockton blocks (Ewing, 1991; Yang and Dorobek, 1995a), with maximum vertical separation of 10,000 to 25,000 feet at the SW block corners (Hills, 1985; Shumaker, 1992). Calculated amounts of basement shortening also decreases northward along the western boundary of the Andector and Fort Stockton blocks, away from their SW corners (Yang and Dorobek, 1995a). Some steeply dipping faults at the SW corner of the Fort Stockton Block are traceable along the western margin to NW corner of the block, where they become high-angle normal faults that dip westward toward the Delaware Basin (Yang and Dorobek, 1995a).

The boundary between the Andector and the Fort Stockton blocks is an ENE-WSW cross fault zone (Figure 1). This fault zone is characterized by flower structures, pop-ups, and near vertical faults (Yang and Dorobek, 1995a).

Another important structural feature along the western boundary of the CBP is the Puckett-Grey Ranch fault zone, which extends southward from the CBP to the Marathon fold-and-thrust belt (Figure 1). This high relief, steeply dipping fault zone extends southward from the western boundary fault zone of the CBP and disappears southward beneath the Marathon thrust sheets (Ewing, 1991). The Puckett-Grey Ranch fault zone separates the Val Verde Basin to the east from the southern Delaware Basin to the west (Figure 1). Several NW-SE trending faulted anticlines are distributed along this fault zone and are arranged in an en echelon pattern with the average fold axis trending at N34°W (e.g., Puckett, Grey Ranch, and Hokit fields; Figure 1).

INTERPRETATION OF STRUCTURAL FEATURES

In terms of the dominance of contractional structures (folds and reverse faults) across the study area and the en echelon arrangement of these structures in map view, we interpret the CBP and adjacent areas to have formed in a convergent strike-slip (transpressional) tectonic setting (cf. Harland, 1971; Sanderson and Marchini, 1984).

Southwestern Midland Basin

The en echelon pattern of the NW-SE trending faulted anticlines in the Pegasus-Amacker structural trend is comparable to the en echelon folds formed in clay models of strike-slip deformation (Tchalenko, 1970; Wilcox et al., 1973; Odonne and Vialon, 1983; Richard et al., 1991). The right-stepping pattern of fold axes is what would be expected if a major right-lateral strike-slip fault was located nearby or if there was a right-lateral strike-slip displacement in the basement beneath the folds (Harding, 1973; Sylvester, 1988; Harding, 1990). Within the Pegasus-Amacker structural tend, reverse faults that bound the Pegasus, Davis, Wilshire, and Amacker-Tippett field structures dip eastward (Figure 2a). North of Pegasus field, however, the anticlinal structures at Sweetie Peck, Warsan, Virey, Dora Roberts, and Headlee fields also display en echelon pattern, but are cut by reverse faults that dip westward (Figure 2a). The changes in fault-dip direction and in the apparent upthrown side along the structural trend suggest a strike-slip origin. Similar discrete zones of en echelon folds are also found across the northwestern Midland Basin, CBP, and eastern Delaware Basin (Figure 1; Henderson et al., 1984; Hardage et al., 1999). Available data suggest that right-lateral strike-slip displacements occurred along the deep-seated basement faults near margins of the CBP and in adjacent parts of the Midland and Delaware basins during late middle Pennsylvanian time. This broad regional strike-slip motion deformed pre-Permian rocks into a series of en echelon folds in the central part of the Permian Basin region (Figure 1).

In addition to the strike-slip deformation, the fault-bounded en echelon folds further suggest that significant crustal shortening occurred across the fold set (Harding and Tuminas, 1988). Additional evidence for regional shortening includes the low angle (10) between the average strike of the en echelon fold axes and the strike of the eastern CBP boundary (Figure 2b). In convergent strike-slip (transpressional) settings, en echelon folds should initiate with fold axes oriented less than 45° to the principal deformation zones (Sanderson and Marchini, 1984; Jamison, 1991). Low obliquity of the fold axes to the main deformation zone indicates a significant component of shortening occurred during the strike-slip deformation (Sanderson and Marchini, 1984). Similar low obliquity is also observed between en echelon faulted fold sets in the northwestern Midland Basin and along the eastern boundary of the CBP, and between en echelon faulted fold sets in the western Delaware Basin and along the western boundary of the CBP (Figure 1).

The characteristics of the Wilshire field anticline are comparable to styles of deformation that are predicted to form by right-lateral simple shear (Figure 3). The fold axis and the bounding reverse fault on the steep western limb of the Wilshire field structure are normal to the direction of maximum principal compressive stress. The right-lateral and normal faults with small displacements that cut the eastern, more gently dipping limb of the Wilshire field structure are similar to cross faults known to form at high angles to fold axes in strike-slip settings (Jamison, 1991). The right-lateral faults are comparable to synthetic strike-slip faults, whereas the normal faults probably accommodated a certain amount of extension parallel to the fold axis as the fold grow during strike-slip deformation (cf. Jamison, 1991; Tikoff and Peterson, 1998). The small vertical displacement along the normal faults indicates only minor amounts of extension parallel to the fold axis, which points to a convergence-dominated strike-slip origin for the Wilshire field structure (Figure 3; Jamison, 1991; Tikoff and Peterson, 1998).

Comparison between structure contour maps of different stratigraphic horizons shows that there was almost no fold axis rotation during growth of the Wilshire field structure (Figure 3a). This suggests there was no prolonged period of strike-slip deformation that could have caused rotation of the fold axis.

Nearly all faults in the Wilshire field structure terminate below the top of the Strawn Formation (Figure 4a; Tai and Dorobek, 1999). A major post-Strawn unconformity also developed over the Wilshire field structure and suggests erosion across the structure prior to deposition of upper Pennsylvanian-Wolfcampian strata. These relationships indicate that deformation took place during or just after late middle Pennsylvanian time, but only persisted for a very short period of time (less than five million years) before the Wilshire filed structure was covered by upper Pennsylvanian-Wolfcampian deep-water facies (Tai and Dorobek, 1999).

Central Basin Platform

Regional Structural Evidence for Strike-Slip Deformation: The general left-stepping, en echelon arrangement of crustal blocks and a regional en echelon fault–and–fold pattern suggest that the CBP formed by right-lateral strike-slip deformation (Yang and Dorobek, 1995a). Changing senses of fault throw and variable vertical displacement along fault planes are typical of many faults associated with the CBP and also indicate a strike-slip origin (Christie-Blick and Biddle, 1985; Naylor et al., 1986; Woodcock and Schubert, 1994). The boundary faults of the CBP are characterized by asymmetrical flower structures with large vertical offset and significant basement shortening (Figures

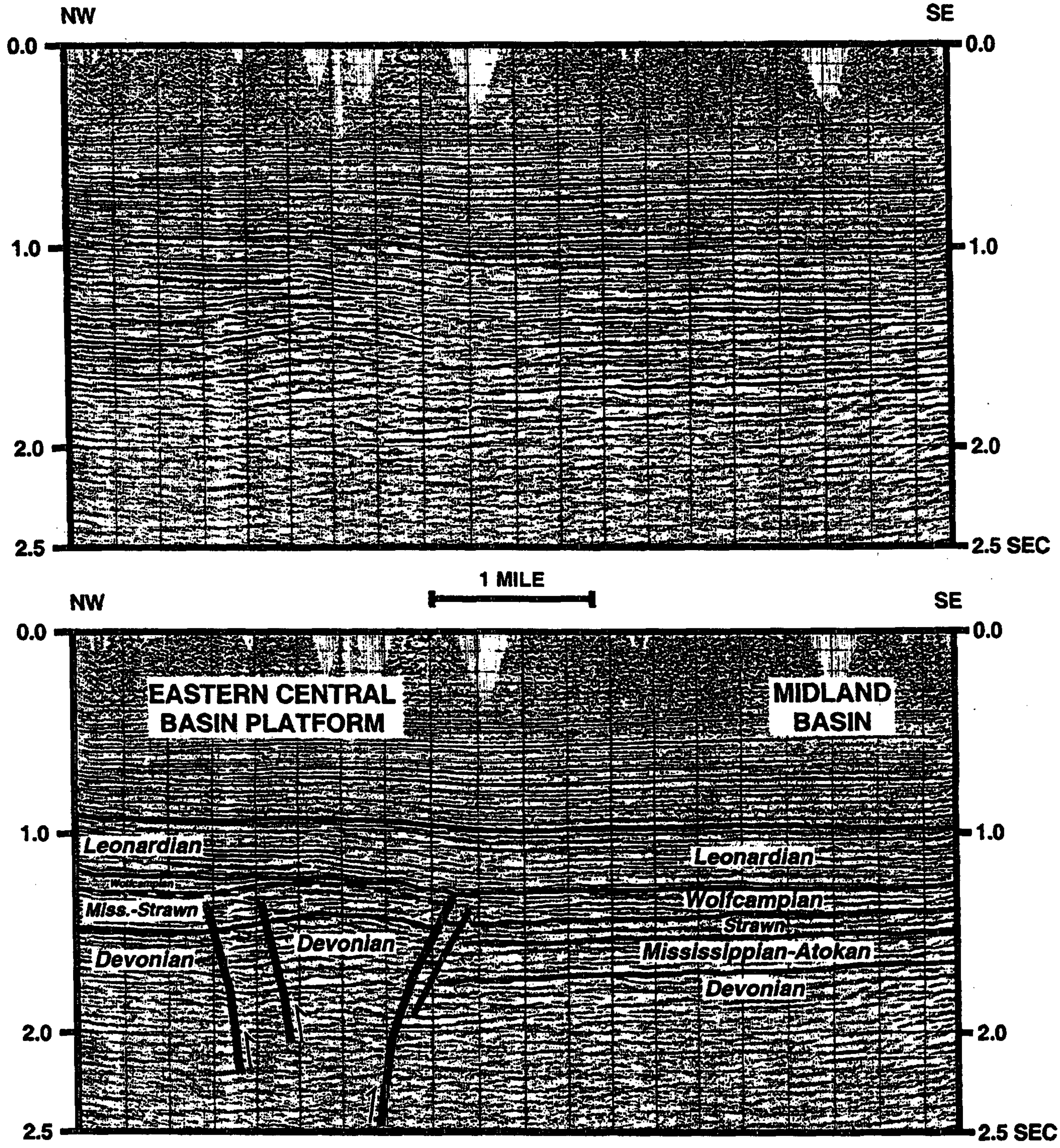


Figure 5. Migrated seismic line across the NE corner of the Fort Stockton Block and southwestern Midland Basin (see Figure 2a for location). Uninterpreted and interpreted profiles are shown. Note an asymmetrical flower structure characterizes the boundary fault zone along this part of the Fort Stockton Block. Compared to the western boundary of the Central Basin Platform (Figure 6), the eastern boundary has lesser structural relief and vertical separation. Dashed line represents the late middle to late Pennsylvanian unconformity that extends across much of the Central Basin Platform in this area.

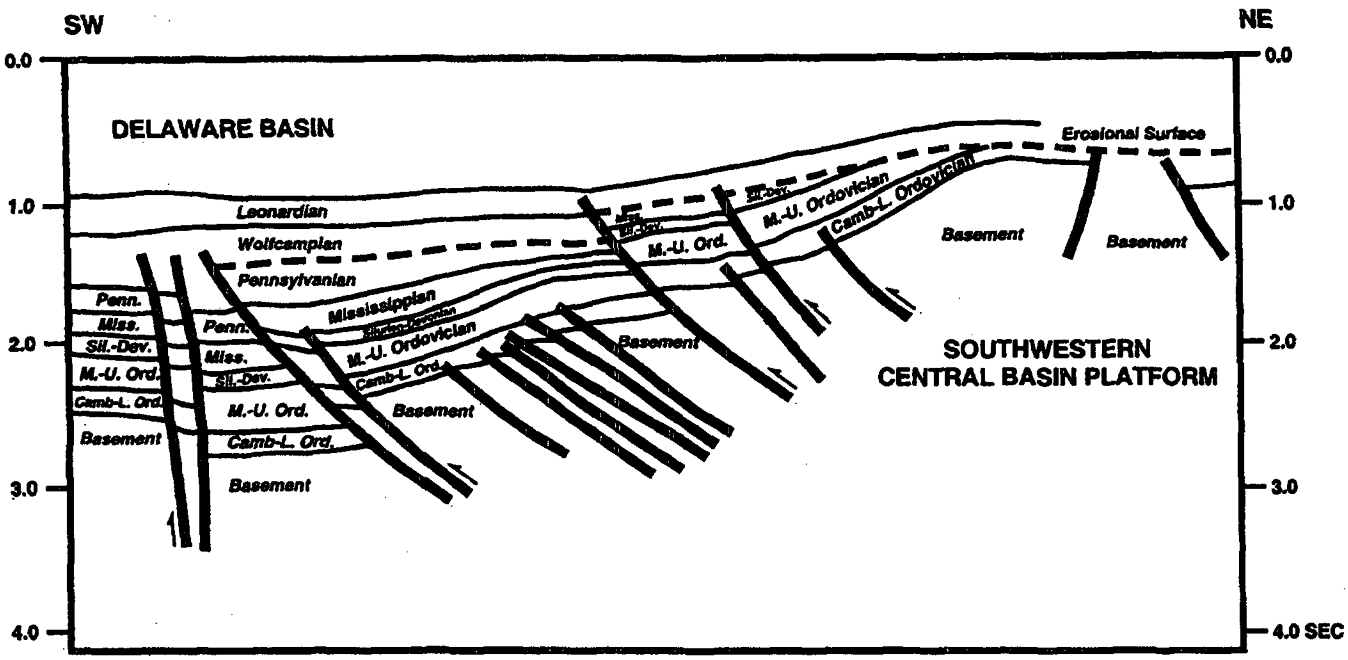


Figure 6. Line drawing interpretation of a migrated seismic profile across the SW corner of the Fort Stockton Block (re-drawn from Yang and Dorobek, 1995a; see Figure 1 for location). Note the east-dipping reverse and thrust faults and the post-Pennsylvanian erosional surface over the Central Basin Platform. The greatest structural relief and basement shortening along the entire Central Basin Platform are found at this corner of the Fort Stockton Block.

4, 5; Gardiner, 1990a; Turmelle, 1992; Yang and Dorobek, 1995a). Asymmetrical flower structures associated with high-angle reverse and thrust faults are typical of convergent strike-slip (transpressional) deformation zones (Lowell, 1972, Sylvester and Smith, 1976; Harding, 1985).

Styles of faulting are different on the eastern and western sides of the CBP. The eastern structural boundary of the CBP is characterized by asymmetrical flower structures, but has lower structural relief and less basement shortening than the western boundary (Figure 5; Yang and Dorobek, 1995a). The jagged pattern of short fault segments along the eastern margin of the Fort Stockton Block suggest that strike-slip deformation did not progress to the point where a major through-going strike-slip fault developed along the principal displacement zone (Figures 1, 2a). Northeast and northwest trending faults within the complex fault zone may represent synthetic Riedel and P shears, indicating that the deep-seated basement faults did not cut completely to the surface during intermediate stages of a strike-slip deformation (Bartkett et al., 1981). In contrast, locally continuous faults characterized the western structural boundary of the Fort Stockton Block. These faults change dip direction along the western boundary of the Fort Stockton Block and transition from steeply dipping reverse faults in the south to high-angle normal faults northward. These characteristics of the fault zone along the western boundary of the Fort Stockton Block indicate development of a through-going strike-slip fault system (Figure 1). The western boundary fault zone was probably the product of multiple fault strands and fault braiding. NNW-NW trending subsidiary faults are comparable to the orientation of synthetic Riedel shear, P shear, or secondary reverse faults that trend into or are truncated by the master fault. In addition to their similar styles of strike-slip deformation, both the eastern and western boundaries of the CBP are characterized by high-angle reverse and thrust faults with significant structural relief, vertical stratigraphic separation, and basement shortening, which suggests there was a compressive component during deformation (Figures 1, 5, and 6; Yang and Dorobek, 1995a).

Local Structural Evidence for Strike-Slip Deformation: Numerous local faults and structural relationships also indicate a strike-slip origin for the CBP. Along the western boundary of the Fort Stock Block, the strike of the boundary fault zone changes orientation from N10°W in the north to N45°W at the SW corner of Fort Stockton Block (Figure 1). This fault zone again changes orientation to N25°W along the Puckett-Grey Ranch fault zone before it dives beneath the Marathon fold-and-thrust belt (Figure 1). This change in strike along a right-lateral strike-slip fault would create a restraining bend (Crowell, 1974), which easily explains why thrust faults, large-scale overturned folds, and the greatest structural relief and basement shortening associated with the CBP are found at the SW corner of the Fort Stock Block (Figure 6; Shumaker, 1992; Yang and Dorobek, 1995a; Ye et al., 1996). Similar southward changes in fault strike are also found along the western margin of the Andector Block, where contractional styles of deformation such as trapdoor structures or compressive fault blocks have been identified at Keystone and similar fields at its SW corner (Figure 1; Harding and Lowell, 1979; Lowell, 1985).

The sigmoidal San Hills Fault within the Fort Stockton Block has a Z-shaped trace and changing senses of throw along strike (Figure 1). These characteristics are comparable to the sigmoidal cross faults that form between right-lateral convergent faults in analog models and indicate that the Sand Hills Fault formed under the influence of right-lateral transpression (Schreurs, 1994; Schreurs and Colletta, 1998).

The boundary between the Andector and Fort Stockton blocks has been interpreted as an ENE-WSW cross fault zone (Figure 1; Yang and Dorobek, 1995a). In addition to flower structures and near vertical faults (Yang and Dorobek, 1995a), laterally offset anticline on either side of the fault zone (e.g., Jordan field) indicates left-lateral strike-slip deformation (Figure 1; Moody, 1973). In the southwestern Midland Basin, N-NNE trending fold axes at Sweetie Peck, Warsan, and Pegasus fields are not coaxial with the consistent NW-trending en echelon anticlines within the Pegasus-Amacker structural trend (Figure 2a). We suspect these "anomalous" fold axes within an overall NW-trending regional fold pattern may reflect deformation above a deeply buried E-W trending left-lateral strike-slip fault that may extend from the E-W trending left-lateral cross fault zone between the Andector and Fort Stockton blocks (Figures 1, 2a).

Age of Uplift along the CBP: A pre-Atokan (late Mississippian–early Pennsylvanian) unconformity across parts of the CBP reflects the timing of initial uplift of the proto-CBP (Hills, 1970). Structural relief from the crest to the flank of various structural highs was apparently negligible after this initial deformation, which allowed for subsequent onlap of middle to late Pennsylvanian carbonate platform strata (Frenzel et al., 1988; Hanson et al., 1991). Another major regional unconformity, however, marks major uplift of the CBP (Bebout and Meador, 1985; Yang and Dorobek, 1995a). This intense uplift removed most Pennsylvanian strata and parts of the lower Paleozoic section along the margins of the CBP, whereas the interior of the CBP was eroded down to Precambrian basement (Gardiner, 1990a; Ewing, 1991). Uplift of the CBP reached a peak during late early Wolfcampian time and because most faults terminate below the Leonardian section, faulting and uplift of the CBP were probably over by late Wolfcampian time (Ewing, 1991; Yang and Dorobek, 1995a; Tai and Dorobek, 1999).

Summary of Late Paleozoic Deformation History of the CBP: On the basis of our observations, it appears that the fold and fault patterns mapped across the southwestern Midland Basin and eastern margin of the CBP were produced by right-lateral strike-slip deformation with an additional component of shortening during late middle Pennsylvanian-Wolfcampian time. Although normal faults are documented at the NW corner of the Fort Stock Block and SE corner of the Andector Block, the dominance of contractional structures strongly suggests a convergent strike-slip (transpressional) origin for the structural features of the CBP, eastern Delaware Basin, and western Midland Basin. These late Paleozoic contractile structures in the Permian Basin may be the products of transpressional strain transmitted through the basement by the Marathon fold-and-thrust belt, or the contractile component of partitioned transpressional stress (cf. Jones and Tanner, 1995; Teyssier et al., 1995). The timing of deformation can be inferred from regional unconformity development and fault terminations, which suggest that the initial uplift of the northwest-north trending anticlines across parts of the eastern Delaware Basin, proto-CBP, and western Midland Basin began in late Mississippian-middle Pennsylvanian time. Subsequent deformation distributed regionally across the eastern Delaware Basin, CBP, and western Midland Basin during late Pennsylvanian time. After late Pennsylvanian time, deformation became localized along the faulted boundaries of the CBP, where significant basement shortening and uplift took place. Faulting and uplift of the CBP ceased by late Wolfcampian time.

KINEMATIC ANALYSIS OF THE CBP BOUNDARY FAULTS

Descriptions of the boundary fault zones of the CBP are given elsewhere (Shumaker, 1992, Yang and Dorobek, 1995a), but little has been published regarding the slip motion and amount of displacement along the boundary faults (Hills, 1970; Gardiner, 1990b; Shumaker, 1992; Yang and Dorobek, 1995a). We begin our analysis of the CBP by examining the orientation of fold axes that can be used to estimate the direction of maximum principal stress. Because there was no apparent fold axis rotation during deformation, the NW-SE trending folds across the eastern Delaware Basin, CBP, and western Midland Basin appear to be related to NE-SW directed compressional stress (Hills, 1970), which would have been oblique to the boundary fault zones of the CBP. If this is true, the CBP's boundary fault zones must have accommodated

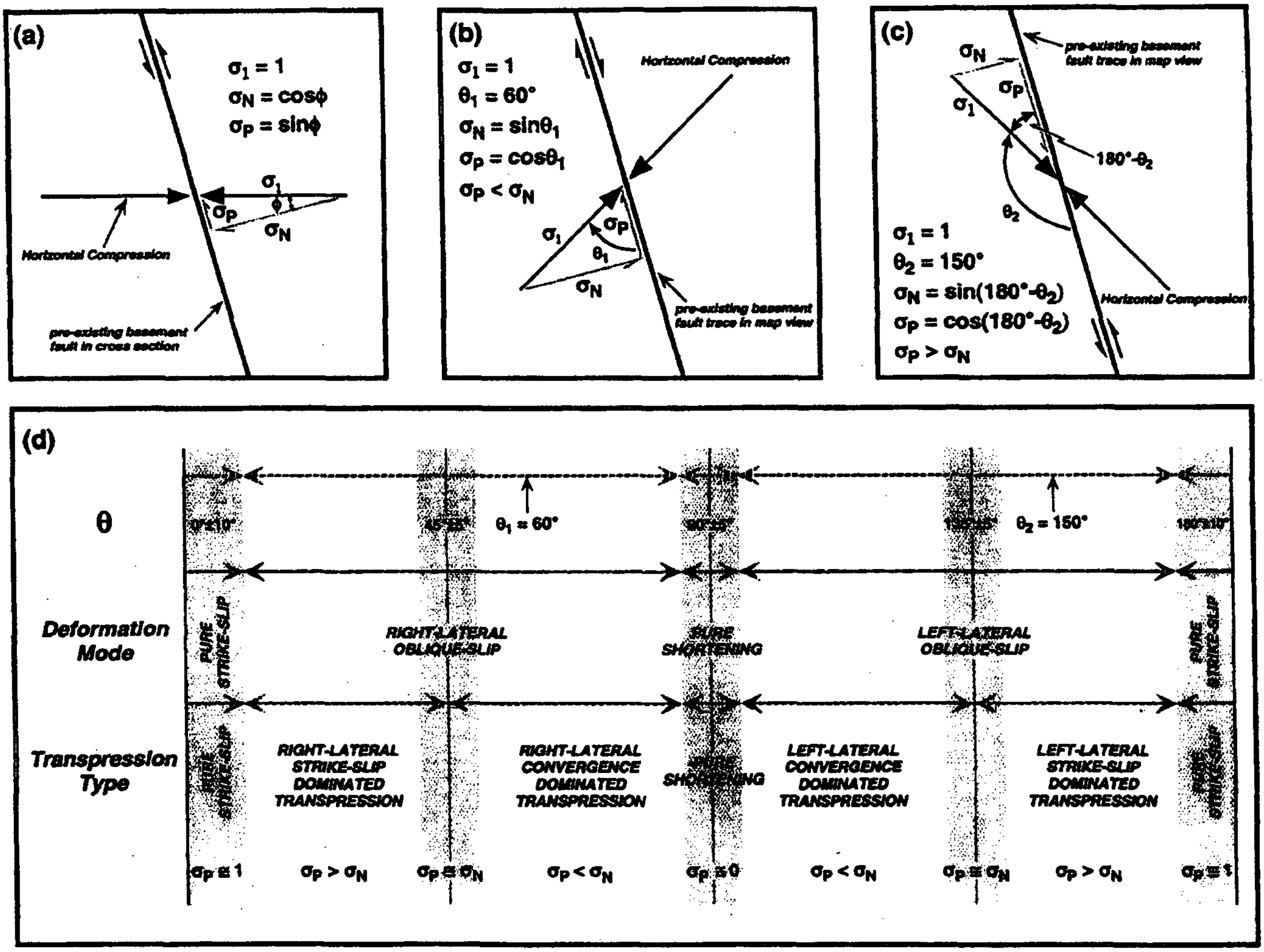


Figure 7. Representation of the geometric method used in this study to infer the slip motion on a pre-existing basement fault. (a) This diagram shows a horizontal compressive stress applied to a steeply dipping fault in cross section. (b) Map view a steeply dipping fault which shows how application of a horizontal compressive stress will result in right-lateral transpression. (c) Map view of steeply dipping fault where horizontal compressive stress results in left-lateral transpression. (d) Summary diagram that illustrates how the value of angle q defines the types of transpression that may occur along a pre-existing fault. In case (b), q1 is measured in a clockwise direction from the fault trace and is 60°, suggesting a right-lateral convergence dominated transpression (see text for a more detailed discussion).

oblique-slip motion.

In order to evaluate possible slip motion along the boundary faults of the CBP that could have occurred in response to obliquely applied stress, a simple geometric method was developed (Figure 7). Three assumptions were made to justify our analysis. (1) The structures used in our analysis are assumed to have the same tectonic origin. The en echelon faulted fold sets within the eastern Delaware and western Midland basins and the reverse and thrust faults along the boundaries of the CBP are all contractional structures. The similarities and close spatial and temporal relationships (see below) between these structures suggest they are related to similar tectonic stresses. Changes in the orientation of stresses during late Paleozoic deformation as suggested by Hills (1970) are not likely, because most of these contractional structures are compatible with NE-SW directed compressive stress. (2) The structures used in our analysis are assumed to have from at about the same time. Our analysis focused only on the late Pennsylvanian-Wolfcampian aged folds and faults because they are better preserved than the late Mississippian-middle Pennsylvanian structures. The Strawn Formation is the first stratigraphic interval to show regional thickness variations across the eastern Delaware Basin, CBP, and western Midland Basin; this suggests that major deformation commenced at about the same time (post-Strawn) across these areas. The short period of time (less than 5 million years) during which the post-Strawn and post-Pennsylvanian unconformities developed over the crests of the en echelon folds across the study area also supports this assumption. (3) Late Paleozoic deformation across the study area reflects reactivation of pre-existing deep seated weaknesses within basement rocks. Most boundary faults of the CBP are basement-involved, steeply-dipping reverse and thrust faults (Hills, 1970; Yang and Dorobek, 1995a). In transpressional settings, sub-vertical to vertical faults at depths tend to splay upward into thrust and reverse faults at shallower depths (Lowell, 1972; Sylvester and Smith, 1976). Thus, these CBP's boundary faults probably coincide with pre-existing basement fault zones that were reactivated during late Paleozoic deformation (Hills, 1970; Wuellner et al., 1986; Marshak et al., 2000).

We first considered a hypothetical pre-existing, steeply dipping fault and then applied a horizontal compressive stress at various angles to this fault. In cross section and map view, respectively, the horizontal compressive stress can be resolved into a strike-normal component (σ_N) and a strike-parallel component (σ_P) (Figure 7a). In cross section, the strike-parallel or shearing component (σ_P) will contribute to significant uplift when it is applied to a moderately to steeply dipping basement fault. In contrast, a nearly vertical fault would tend to lock up because there is a very little shear stress applied along the fault plane (Figure 7a).

In map view, the behavior of a basement fault can be determined by the angle θ between horizontal compressive stress and the strike of a basement fault (Figure 7b-d). We arbitrarily defined three transitional boundaries to differentiate between pure strike-slip, oblique-slip, and pure shortening deformation. A θ of about 0°±10° or 180°±10° is assigned to the pure strike-slip regime, because these angles of θ facilitate pure strike-slip deformation along pre-existing faults. A θ of ~90°±5° is assigned to the pure shortening regime, where the compressive stresses acting normal to a pre-existing fault would cause pure shortening along the fault (Lowell, 1995). Any other applied angle θ of horizontal compressive stress would reactivate the basement fault by oblique-slip deformation. Right-lateral or left-lateral strike-slip motion along the reactivated fault can be predicted by measuring the angle θ in a clockwise direction from the fault trace (Figure 7b, c). Acute angles for θ would be favorable for right-lateral strike-slip displacement on the reactivated basement fault; an obtuse angle for θ would make left-lateral strike-slip motion more likely (Figure 7b, c). By arbitrarily defining the value of the horizontal stress as unity (one), the resolved strike-normal component (σ_N) is sinθ and the strike-parallel component (σ_P) is cosθ, where θ is less than 90° (Figure 7b). The resolved strike-normal component (σ_N) is sin(180°-θ) and the strike-parallel component (σ_P) is cos (180°-θ), where θ is greater than 90° (Figure 7c). We can then determine the relative importance of shortening and strike-slip motion along the reactivated fault by knowing the value of resolved σ_N and σ_P. We defined 45°±5° as the critical θ angle where there is a transition between right-lateral strike-slip dominated transpression and right-lateral convergence-dominated transpression, and 135°±5° as the value for θ where there is a transition from left-lateral strike-slip dominated transpression to left-lateral convergence-dominated transpression (Figure 7d). In other words, if the value of resolved σ_N is greater than σ_P along a fault trace, or if the θ is between 45° and 90° or between 90° and 135°, this fault would undergo a convergence-dominated transpressional deformation (Figure 7b, d). In contrast, a strike-slip dominated transpressional deformation would occur if the value of resolved σ_N is smaller than that of resolved σ_P along a fault trace, or if the θ is ranged between 0° and 45° or between 135° and 180° (Figure 7c, d).

Figure 7d shows how θ can be plotted versus σ_P and σ_N to define the modes of deformation. By knowing or estimating the direction of principal compressive stress and the strike of the fault, we can measure the angle θ, and in turn, determine the likely modes of deformation along the CBP's boundary faults (Figures 7d, 8). Regional mapping and structure contour maps of individual oil-and-gas fields indicate the average orientation of NW-SE trending fold axes across the eastern Delaware and western Midland basins is N34°W. If we assume average direction of principal compressive stress, which should be normal to the average orientation of fold axes, is N56°E, we can then estimate angle θ and easily determine the likely modes of deformation along the CBP's boundary faults.

The approximate trend of the western boundary faults along the Andector and Fort Stockton blocks is N10°W (Figure 1), and the angle θ between the principal compressive stress direction and the strike of the western boundary faults is 66°, which suggests right-lateral convergence-dominated transpression (convergent strike-slip deformation) likely occurred during late Paleozoic deformation (Figures 7d, 8). The approximate strike of the eastern boundary faults is N16W°, so angle θ is 72°, which also indicates right-lateral convergence-dominated transpression (Figures 7d, 8). Faults that define the SW corners of the Andector and Fort Stockton blocks trend ~N45°W (Figure 1). For these faults, angle θ is ~101°, which suggests a strongly convergence-dominated transpression should have occurred at these corners (Figures 7d, 8). This is supported by the great structural relief, vertical separation, thrust faults, and compressive fault block structures found there. Similar analytical results can be derived from fault trends at the NE corner of the Andector Block (Figures 7d, 8; Yang

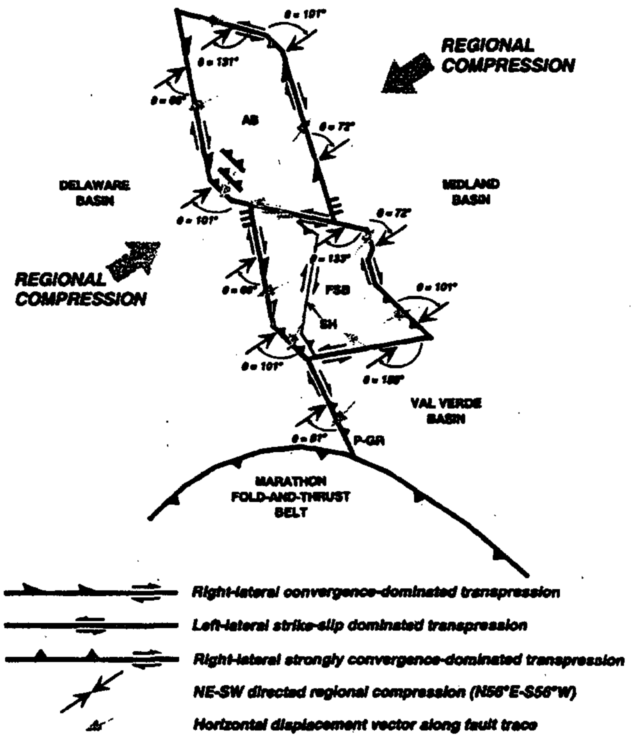


Figure 8. Inferred type of transpression and derived displacement vector for the boundary faults of the Central Basin Platform. AB = Andector Block; FSB = Fort Stockton Block; SH = Sand Hills Fault; P-GR = Puckett-Grey Ranch Fault Zone (see text for a more detailed discussion).

and Dorobek, 1995a).

The cross fault zone between the Fort Stockton and Andector blocks trends approximately N80°W; angle θ between this fault zone and the inferred principal compressive stress direction is 136°, which suggests left-lateral strike-slip dominated transpression for this cross fault zone (Figures 7d, 8). The sense of strike-slip motion along cross faults is expected to be opposite to that along master faults with respect to the regional sense of shear (Schreurs, 1994). According to Yang and Dorobek (1995a), left-lateral strike-slip displacement was the consequence of right-lateral displacement along the CBP boundaries and was necessary to accommodate the clockwise rotation of the Andector and Fort Stockton blocks. Left-lateral strike-slip dominated transpression also can be found along the southern fault boundary of the Fort Stockton Block, which has a strike of N80°E and an inferred angle θ of 156° (Figures 7d, 8). South of the Fort Stockton Block, the Puckett-Grey Ranch fault zone trends approximately N25°W (Figure 1). The inferred angle θ of 81° suggests a strongly convergence-dominated transpression (Figure 7d), which is also supported by the high structural relief and steeply dipping faults that characterize this fault zone (Figure 8; Shumaker, 1992; Yang and Dorobek, 1995a).

In order to corroborate our analytical results, we also applied McCoss's (1986) geometric method to derive a two-dimensional displacement field for the late Pennsylvanian-Wolfcampian structures of the CBP and adjacent areas. Here we briefly describe the procedures for the derivation (Figure 9). First,

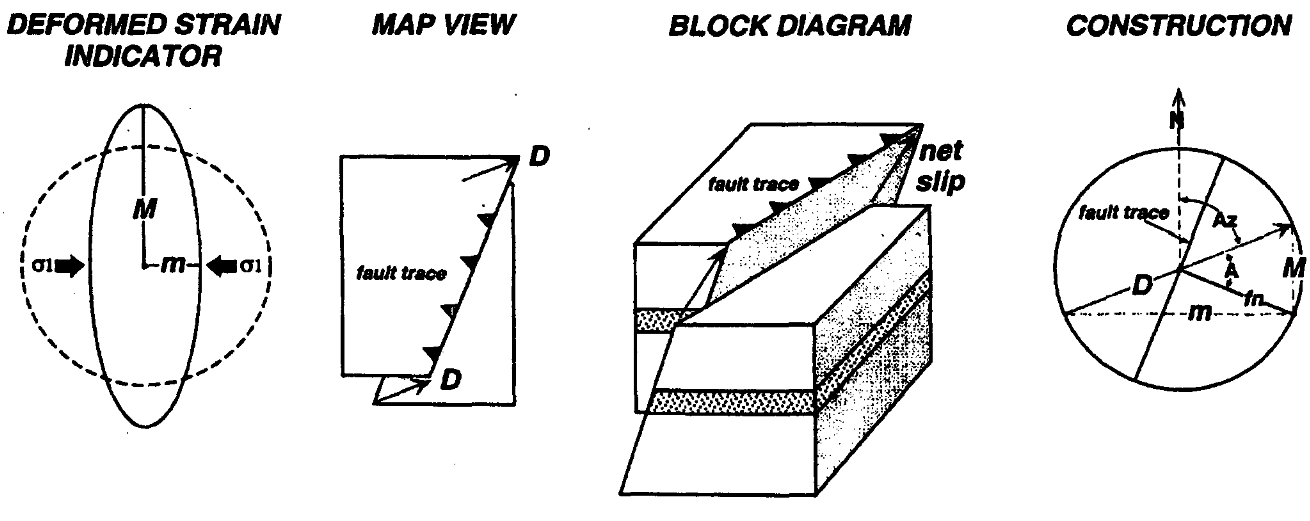
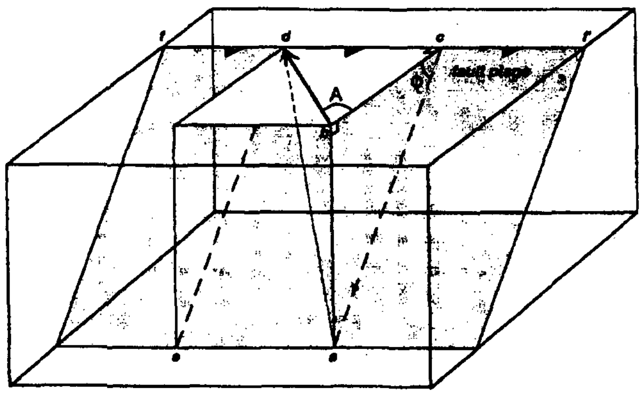


Figure 9. Schematic diagram shows the procedures to derive the displacement vector along a pre-existing fault (modified from McCoss (1986) and Granath (1989)). D = displacement vector; fn = fault normal; M = maximum strain axis of the strain ellipse; m = minimum strain axis of the strain ellipse; A = angles between the displacement vector and fault normal; Az = azimuth of the displacement vector.



ff': fault trace
ab: vertical separation
ac: dip-slip displacement
ad: net slip (line lies on the fault plane)
ae: strike-slip displacement (ae = cd)
bc: shortening normal to fault strike (parallel to the fault normal direction)
bd: displacement vector (horizontal projection of net slip (ad))
A: Angle between displacement vector (bd) and fault normal (bc)
ϕ: dip angle of fault plane
Angle abc = angle bcd = 90°
Tanϕ = ab/bc
TanA = cd/bc = ae/bc
Tanϕ/TanA = ab/cd = ab/ae

Figure 10. Three-dimensional relationships between net slip vector and other components of slip along an oblique-slip reverse fault.

a unit circle is centered on a fault trace with its fault normal (fn) pointing out from the center of the unit circle. Two lines are then drawn from the intersection of the fault normal with the unit circle and are extended till they intersect the circle; the orientation of these two lines is the same as the orientation of maximum (M) and minimum (m) strain axes on the strain ellipse. The displacement vector (D) for the fault can be determined by connecting a line from the intersection of the minimum strain axis with the unit circle, through the center of the circle, to the intersection of the maximum strain axis with the unit circle (Figure 9). In this study we use fold axis orientations as strain ellipse indicators to determine the displacement vectors along the boundary fault zones. The basic assumptions used in McCoss's method are similar to those for our method (McCoss, 1986; Granath, 1989). For a detailed description of derivation and construction of this geometric method, see McCoss (1986).

Using McCoss's geometric method, southwestward (azimuth 210°) and northeastward (azimuth 37°) displacement vectors were derived for the western and eastern boundary fault zones of the CBP, respectively (Figure 8). This suggests that the western part of the CBP was thrust in a southwesterly direction toward the Delaware Basin, whereas the eastern part of the CBP was directed northeastward toward the Midland Basin. An azimuth of 245° was derived for the SW corners of the Andector and Fort Stockton blocks and suggests more southwestward displacement vectors at these corners (Figure 8). An azimuth of 65° was derived for the NE corner of the Andector Block and for the SE corner of the Fort Stockton Block. The small angle of 9° between the direction of principal compressive stress (azimuth 56° and 236°) and the azimuth of displacement vectors (65° and 245°) also explains the crustal shortening that occurred at these corners. An azimuth of 85° was derived for the displacement vector along the cross fault zone between the Andector and Fort Stock blocks (Figure 8). For the Puckett-Grey Ranch fault zone, we derived a displacement vector with an azimuth of 224°, which suggests southwesterly movement along this fault zone (Figure 8). In summary, these estimated displacement vectors obtained from McCoss's geometric method agree with our slip motion analyses and indicate that both the western and eastern boundary fault zones of the CBP mainly underwent right-lateral transpressional deformation, which is consistent with the clockwise block rotation model of Yang and Dorobek (1995a).

Another important issue regarding the kinematic history of the CBP is the amount of lateral displacement along the boundary fault zones. Lack of piercing points such as offset igneous bodies or steep dipping rock units, the relatively invariant thickness of lower Paleozoic stratigraphic units on either side of the boundary fault zones, and isopach contours that are sub-parallel to the trend of the boundary faults make it difficult to estimate the lateral offset along the boundary fault zones.

Hills (1970) postulated that a few tens of miles was the maximum lateral offset along the western boundary of the CBP, with probably lesser amounts of offset along the eastern boundary zone. Gardiner (1990b) proposed a smaller lateral offset of 1.9-4.4 miles (3-7 km) on the strike-slip boundary fault zones of the CBP, although the method used for this estimation was not presented. By correlating the E-W trending Big Lake and Grisham fault zones on either side of the CBP, Yang and Dorobek (1995a) implicitly estimated about 30-40 miles of right-lateral offset along the boundary faults zone of CBP.

In this study, we modified McCoss' (1986) two-dimensional geometric method in an attempt to estimate the amounts of strike-slip displacement along the boundary fault zones of the CBP. The relationships between displacement vector, net slip, the fault normal (line bc in Figure 10), vertical stratigraphic separation, the dip angle of the fault plane, and the amounts of strike-slip and dip-slip displacement can be represented in three dimensions (Figure 10). By knowing the angle (A) between the displacement vector and the fault normal (Figure 9; McCoss, 1986), the dip (ϕ) of the fault plane, the amount of basement shortening (cf. Yang and Dorobek, 1995a), and the vertical stratigraphic separation along the fault, a simple trigonometric relationship between these variables and amount of strike-slip displacement can be written either as:

$$\tan A = \frac{amount of\ strike-slip displacement}{shortening normal to\ fault zone}$$

or

$$\frac{\tan\phi}{\tan A} = \frac{vertical statigraphic separation}{amount of\ strike-slip displacement}$$

As a result, we derived 1.7-2.8 miles (2.7-4.5 km) of right-lateral strike-slip displacement on the western boundary fault zone of the CBP, whereas 0.6-2.2 miles (1-3.6 km) of right-lateral strike-slip displacement likely occurred on the eastern boundary. Our estimation is comparable to Gardiner's (1990) estimation, and is significantly smaller than the estimations of Hills (1970) and Yang and Dorobek (1995a). It should be noted, however, that the amount of strike-slip displacement derived by this technique is possibly the sum of displacement along the fault zone, and thus represents a maximum magnitude of offset along the boundaries of the CBP.

TECTONIC MODEL FOR THE CBP AND ADJACENT AREAS

On the basis of our structural interpretations and kinematic analyses, it appears that the structural styles across the western Midland Basin, along the boundaries of the CBP, and across the eastern Delaware Basin were related to late Pennsylvanian-Wolfcampian right-lateral strike-slip deformation with a significant component of basement shortening. Thus, we attribute deformation and uplift of the CBP to a convergent strike-slip origin, which is a type of transpression dominated by a shortening component (Tikoff and Teyssier, 1994; Teyssier et al., 1995).

In terms of the distribution of the oldest (late Mississippian to mid Pennsylvanian) en echelon structures, we considered the eastern Delaware Basin, CBP region, and western Midland Basin together as comprising a transpressional deformation zone (Figure 11). We infer that this transpressional deformation was shaped like parallelogram and was bounded by two larger rigid basement blocks, the western Delaware Basin Block to the west and eastern Midland Basin Block to the east. The boundaries of the transpressional deformation zone trended NNW-SSE. East and west of this transpressional deformation zone, deformation apparently decreased because there are no apparent NNW-SSW trending faults within more eastern and western parts of the Midland and Delaware basins, respectively (Figures 1, 11).

During late Mississippian-early Pennsylvanian time, the western Delaware Basin block began to move northward and obliquely toward the western

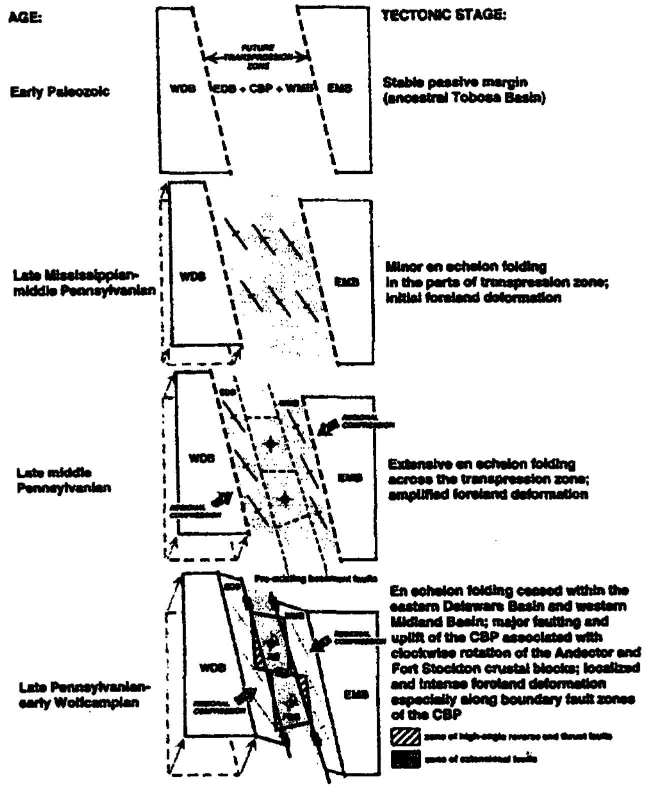


Figure 11. Kinematic model for the late Paleozoic tectonic evolution of the eastern Delaware Basin, Central Basin Platform, and western Midland Basin. The Incipient transpression zone included the eastern Delaware Basin (EDB), Central Basin Platform (CBP), and western Midland Basin (WMB). Shaded area represents the region undergoing deformation during different time period. WDB = western Delaware Basin Block; EMB = eastern Midland Basin Block; AB = Andector Block; FSB = Fort Stockton Block.

boundary of the parallelogram-shaped transpressional zone (Figure 11). The oblique northeastward convergence was probably related to incipient crustal shortening in the Marathon fold-and-thrust belt. The magnitude of shortening in the Marathon fold-and-thrust belt was probably small and only resulted in the initial deformation of the northwest trending anticlines across parts of the western Midland Basin, CBP region, and eastern Delaware Basin. Minor uplift produced the pre-Atokan unconformity over crests of these anticlines.

After a middle Pennsylvanian tectonically quiescent phase (Yang and Dorobek, 1995a), continued shortening in the Marathon fold-and-thrust belt amplified the oblique convergence of the western Delaware Basin Block toward the transpression zone (Figure 11). This angular convergence generated a regionally distributed right-lateral shear couple, which in turn was responsible for the formation of the NW-SE trending, right-stepping en echelon fold sets across the deformation zone (e.g., the Pegasus-Amacker structural trend within the southwestern Midland Basin; Figures 2a, 11). Considerable amounts of crustal shortening across the transpression zone can be inferred because most of the folds are bounded by high-angle reverse faults and the fold axes trend at low angles to the boundary of the deformation zone. A post-Strawn unconformity developed over the en echelon fold sets across the CBP, western Midland Basin, and eastern Delaware Basin. Gentle subsidence of the Delaware and Midland basins was also reportedduring this period (Yang and Dorobek, 1995a).

As the deformation progressed into late Pennsylvanian and Wolfcampian time, we infer that the orientation of the angular convergence imposed by the western Delaware Basin Block remained the same, but the magnitude was greatly intensified by the approaching Marathon orogen. There was a significant change in the deformational style and in the area undergoing active deformation. Folding within the western Midland Basin and eastern Delaware Basin had essentially ceased at this time (Tai and Dorobek, 1999), but pre-existing NNW-SSE trending zone of weakness in basement rocks were selectively reactivated within the broader shear zone and underwent intense, but highly localized deformation (Figure 11). The locations of the pre-existing weakness coincided with the present structural boundaries of the CBP and may have originally formed during Precambrian rifting events that initiated the ancestral Tobosa Basin (Wuellner et al., 1986; Keller et al., 1980, 1989; Adams and Keller, 1996). This change from previous stage of broad, regional shearing across the deformation zone to concentrated crustal-scale deformation along the CBP boundaries suggests a strain partitioning during the progressive transpressional deformation (cf. Jones and Tanner, 1995).

The right-lateral oblique slip motion imposed by the angular convergence was accommodated along the pre-existing basement weaknesses, which were reactivated as high-angle reverse and thrust faults with a significant component of right-lateral strike-slip motion. High-angle reverse and thrust faults contributed to the intense faulting and uplift of the CBP, whereas right-lateral strike-slip shearing motion would have caused the CBP to split into the Andector and Fort Stockton blocks, which in turn explained clockwise rotation (Figure 11; Yang and Dorobek, 1995a). Local E-W trending left-lateral strike-slip faults within the southwestern Midland Basin may reflect the effect of cross faulting that resulted from clockwise rotation of crustal blocks. Over the uplifted CBP, Pennsylvanian to Precambrian sections were regionally stripped away and a post-Pennsylvanian (pre-Wolfcampian) unconformity developed. Rapid subsidence in the Midland and Delaware basins also occurred during this period and was in part due to the crustal shortening and tectonic loading at the corners of the Andector and Fort Stockton blocks (Yang and Dorobek, 1995b).

CONCLUSIONS

This study documents the late Paleozoic structural styles and deformation history of the eastern Delaware Basin, Central Basin Platform (CBP), and western Midland Basin. A simple geometric technique was applied to evaluate the possible slip motions along the boundary faults of the CBP. Results from this study may help to provide an improved understanding of the late Paleozoic tectonic evolution of the Permian Basin, but we hasten to add that there is much to be learned yet about the history of this complexly deformed foreland setting. Conclusions from this study include:

(1) The western Midland Basin, interior CBP, and eastern Delaware Basin are characterized by numerous NW-SE trending en echelon fold sets. These faulted asymmetrical anticlines are arranged in right-stepping en echelon patterns and are largely oriented at low angles to the boundary fault zones of the CBP. The en echelon pattern, low obliquity, bounding reverse faults, and internal cross faults with small displacements suggest these folds formed under the influence of right-lateral convergent strike-slip deformation.

(2) The eastern and western boundaries of the CBP are characterized by high-angle reverse and thrust faults, asymmetrical flower structures, compressive fault blocks, and a few normal faults. The western boundary fault zone has greater structural relief, vertical separation, and basement shortening than the eastern boundary. The en echelon pattern of crustal blocks, Z-shaped trending Sand Hills Fault, and dominant contractional structures along the boundaries of the CBP indicate that deformation of the CBP was heavily influenced by right-lateral convergent strike-slip motion.

(3) Simple geometric techniques show that during the latest stage of deformation in late middle Pennsylvanian to Wolfcampian time, the western and eastern margins of the CBP were subjected to right-lateral convergence-dominated strike-slip deformation, which is consistent with structural features observed along CBP's fault boundaries. The western margin was thrust southwestward toward the Delaware Basin, whereas lesser shortening along the eastern margin was directed northeastward toward the Midland Basin. The derived slip motions along the boundary faults of the CBP are also consistent with the clockwise crustal block rotation

model of Yang and Dorobek (1995a).

(4)On the basis of structural interpretations and kinematic analyses, our proposed tectonic model suggests that the eastern Delaware Basin, CBP, and western Midland Basin can be considered as a transpressional deformation zone. Three episodes of deformation were recognized across the study area, based on significant changes in deformation styles and in the areas undergoing active deformation over time.

(5)In late Mississippian-middle Pennsylvanian time, minor en echelon folds developed across parts of the transpression zone in response to northeastward convergence of the western Delaware Basin Block. Continued northeastward convergence produced right-lateral convergent shearing across the transpression zone, which in turn caused broad regional en echelon folding and faulting across the eastern Delaware Basin, CBP, and western Midland Basin in late middle Pennsylvanian time. During late Pennsylvanian-Wolfcampian time, the en echelon folding within the sub-basins ceased, but preexisting basement weaknesses were reactivated as high-angle faults within the transpression zone and accommodated most of the intense northeastward convergence of the western Delaware Basin Block toward the transpression zone. Right-lateral oblique slip motions were accommodated along the boundary fault zones of the CBP and contributed to significant faulting and major uplift of the CBP as crustal blocks that comprise the CBP underwent clockwise block rotation.

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