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Structural style of the Marathon thrust belt, West Texas

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ABSTRACT

The Marathon portion of the Ouachita thrust belt consists of a highly deformed allochthonous wedge of Cambrian-Pennsylvanian slope strata (Marathon facies) that was transported to the northwest and emplaced over Pennsylvanian foredeep sediments. The foredeep strata in turn overlie early-middle Paleozoic shelfal sediments which are deformed by late Paleozoic basement-involved reverse faults. The Dugout Creek thrust is the basal thrust of the allochthon. Shortening in this sheet and overlying sheets is ~80%. Steep imbricate faults link the Dugout Creek thrust to upper level detachments forming complex duplex zones. Progressive thrusting and shortening within the allochthon folded the upper level detachments and associated thrust sheets. The Caballos Novaculite is the most competent unit within the Marathon facies and controlled development of prominent detachment folds.

Deeper imbricate sheets composed of the Late Pennsylvanian foredeep strata, and possibly early-middle Paleozoic shelfal sediments developed concurrently with emplacement of the Marathon allochthon and folded the overlying allochthon. Following termination of thrusting in the earliest Permian, subsidence and deposition shifted northward to the Delaware, Midland and Val Verde foreland basins.

1. Introduction and regional setting

The Marathon thrust belt of West Texas is an exposed part of the mostly buried Late Paleozoic Ouachita thrust belt that extends across the states of Arkansas, Oklahoma and Texas of the south-central United States and into the northern Mexican states of Coahuila and Chihuahua (Fig. 1). The thrust belt is interpreted to have formed as a result of the progressive collision of the South American and North American plates during the late Paleozoic (Pindell, 1985; Viele and Thomas, 1989; Wickham et al., 1976). The Marathon segment is exposed in a 50 km by 70 km inlier surrounded by post-tectonic strata.

The belt is of special structural interest because of the combination of complex folds, imbricates, duplexes, and refolded structures that are well exposed in plunging structures. The mechanical stratigraphy of the deformed sequence had a strong influence on the style of deformation (Muehlberger and Tauvers, 1989). A thin, pre-tectonic section resulted in the development of relatively small wavelength folds, while multiple decollement horizons led to the formation of large-scale duplex zones. The presence of the competent Caballos Novaculite within this otherwise mechanically weak section resulted in the prominent development of detachment folds. These folds are a striking feature of the thrust belt. As a consequence of these stratigraphic characteristics, the style of much of the Marathon thrust belt contrasts with thrust belts that consist of a few large imbricate sheets underlain by thrusts with ramp-flat profiles. This paper focuses on the structural style of the Marathon thrust belt as illustrated by a regional cross section across the belt, and the close relationship between the mechanical stratigraphy and the structural style.

Excellent surface mapping by P.B. King (King, 1937, 1980) has documented the exposed structure and framework stratigraphy of the Marathon area and laid the groundwork for more detailed delineation of the region's stratigraphy (Folk and McBride, 1978; McBride, 1964, 1969a,b, 1970, 1978, 1989; Palmer et al., 1984; Ross, 1967; Thomson and Thomasson, 1978). More recent structural studies have further documented the structure of the belt (DeMis, 1983; Muehlberger and Tauvers, 1989; Tauvers, 1985). The complex sub-surface structure has been outlined by a series of regional cross sections constrained by seismic interpretations, wells, and surface geology (Muehlberger et al., 1984; Muehlberger and Tauvers, 1989; Reed and Strickler, 1990). Unfortunately, many of these publications are in local geologic society publications that are not widely distributed internationally.

2. Stratigraphy

The allochthonous strata of the thrust belt are collectively referred to as the Marathon facies. They include a pre-tectonic

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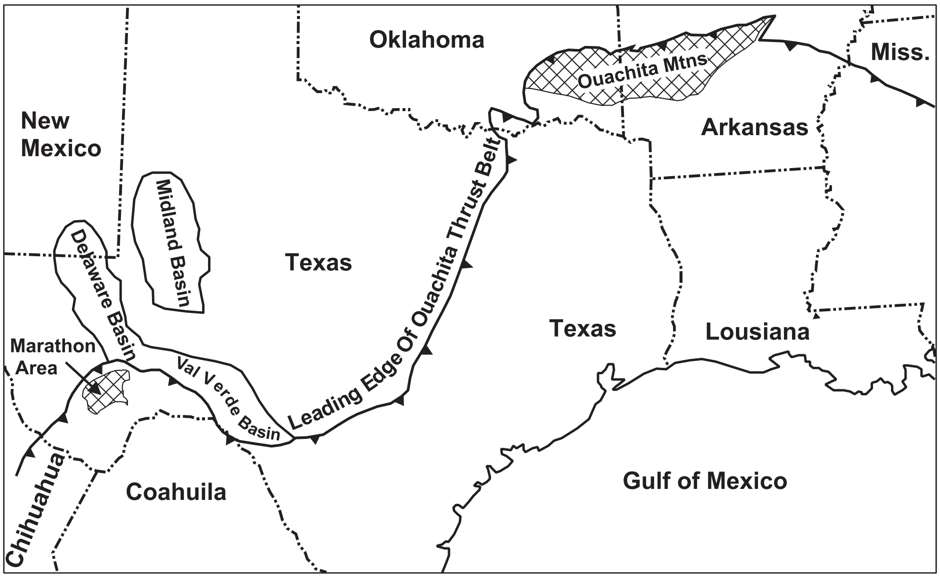

Fig. 1. Index map showing the location of the Marathon area and Permian foreland basins relative to the overall Ouachita thrust belt.

sequence of Late Cambrian–Devonian or Early Carboniferous (Early Mississippian) that is about 975–1100 m thick and a Late Carboniferous–Early Permian syn-tectonic sequence that has a composite thickness of about 5600 m (King, 1977) (Fig. 2). The pre-tectonic sequence consists of generally thin-bedded limestone, shale, chert and shaly sandstone that are interpreted to have been deposited in continental slope to outer shelf settings. Deep wells show that this pre-tectonic sequence is structurally emplaced over a similar age sequence of shelfal strata that rests on Precambrian crystalline rocks. This cratonic sequence consists of a slightly thicker packet of shallow marine strata that is generally lithologically similar to the slope sequence.

The syn-tectonic sequence of the thrust belt consists of flysch and overlying molasse. The Late Mississippian-Early Pennsylvanian Tesnus Formation is composed dominantly of shaly sandstone and shale representing submarine fans, channel complexes and hemipelagic sediment deposited on the older Marathon facies strata. The source of this sediment was dominantly from the southeast, probably from the landmass that collided with North America (McBride, 1969a, 1989). The Tesnus Formation is overlain by Dimple Limestone which consists of slope and re-sedimented limestones derived from the north (Thomson and Thomasson, 1978). Boulder beds from the overlying Atokan-age (Middle Pennsylvanian) Haymond Formation contain a variety of clasts including exotic

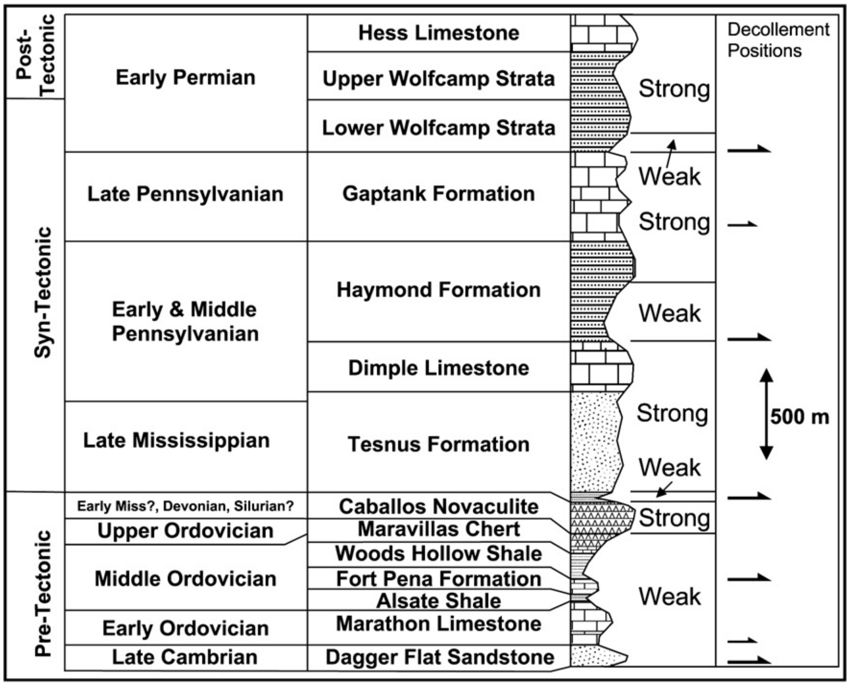

Fig. 2. Stratigraphic column of the Marathon area. For simplicity early and middle Paleozoic formations of the cratonic sequence are not shown. Mechanical behavior of strata (strong versus weak) and the position of major and minor decollements are based on field observations and the cross section.

sedimentary, igneous, and metamorphic rocks, clasts derived from older Marathon units, and Cambrian limestone clasts probably derived from the miogeocline (King, 1977; Palmer et al., 1984) and mark a period of strong deformation. These latter strata and the older Marathon facies rocks are thrust over conglomerates, sandstones, and shales of the Late Pennsylvanian Gaptank Formation that were deposited by fan deltas and deltas (Reed and Strickler, 1990) in a foreland basin that developed north of the thrust belt. The foreland basin deposits and the thrust belt sequence are capped by post-tectonic upper Wolfcampian clastics and limestones.

2.1. Mechanical stratigraphy

Mechanical stratigraphy, or the characterization of a sequence of layered rocks based on the varying physical properties of the layers, has been recognized as a key control on the deformation of sedimentary sequences (Currie et al., 1962). The effects of mechanical stratigraphy are especially important in regions of thin-skinned thrusting where fault trajectories commonly follow bedding (Woodward and Rutherford, 1989; Chester, 2003). The structural style of the Marathon thrust belt is strongly influenced by (1) the relative thinness of the sequence of pre-tectonic strata, (2) the thin-bedded character of much of the pre-tectonic Marathon facies strata, (3) the mechanically strong Caballos Novaculite, (4) the presence of several mechanically weak layers that act as decollements, and (5) the thick sequence of syn-tectonic clastic strata (Muehlberger et al., 1984). These characteristics led to the formation of relatively small-scale folds, the presence of several levels of decollement, and the development of numerous duplex zones and progressive refolding of early structures. Major decollements within the allochthonous sequence occur at (1) the base of the Dagger Flat Sandstone, (2) near the base of the Alsate Shale, (3) within the Woods Hollow Shale, and (4) near the base of the Tesnus Formation. Numerous local decollements are also present.

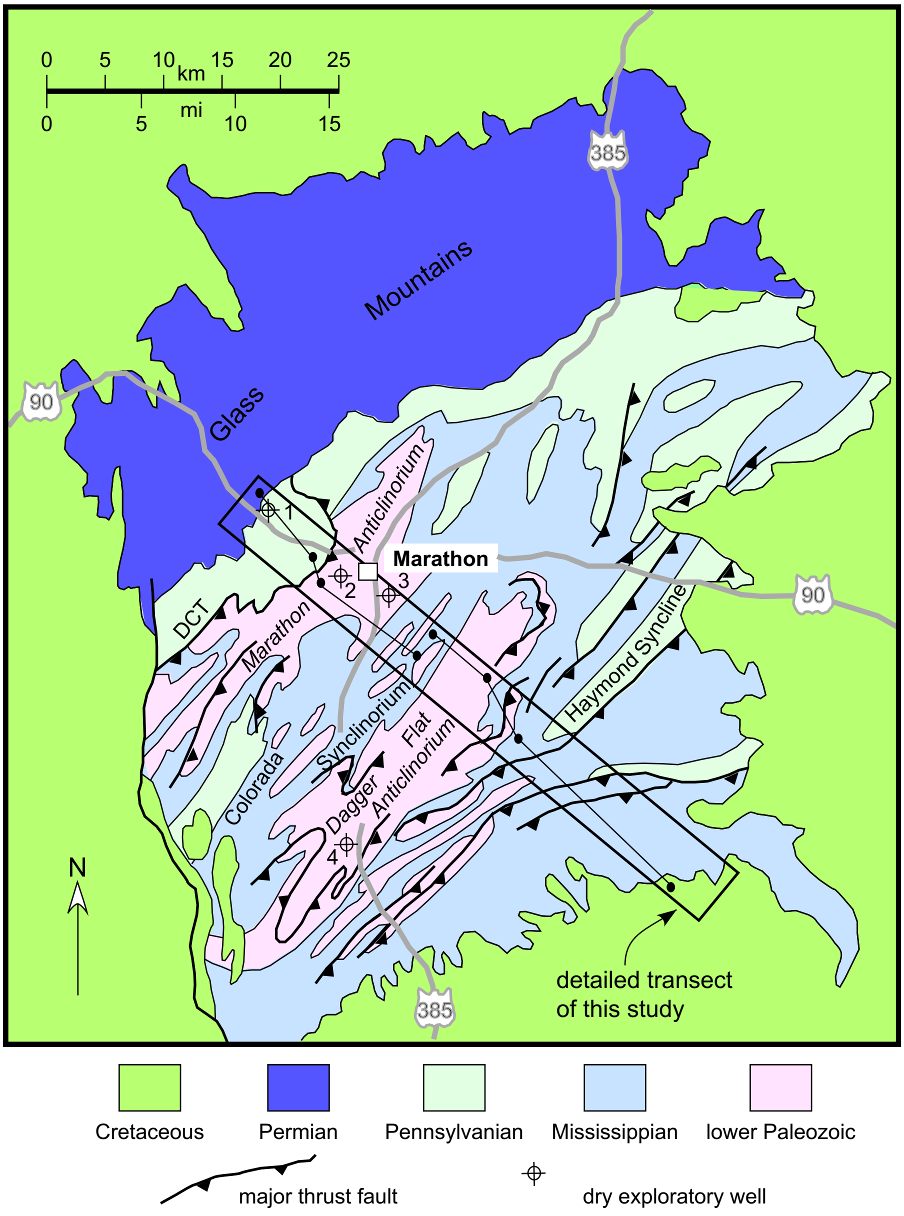

Fig. 3. Regional geologic map of the Marathon area (after King, 1977). The location of study area and the regional cross section are highlighted. The wells shown are: 1, Slick-Urshel #147; 2, Mobil Oil Adams #1; 3, Gulf #1 Combs; 4, Turner #1 Combs.

The Caballos Novaculite strongly influences the structural style of the belt because it forms a thick, competent member within the otherwise thin-bedded, mechanically weak pre-tectonic part of the Marathon sequence. It is involved in the formation of both detached buckle folds and fault-propagation folds.

In the northeastern part of the Marathon inlier, outside the area of this study, thrust sheets involving only the late Paleozoic syn-tectonic formations are exposed at the surface (Fig. 3). Well and seismic data (Reed and Strickler, 1990) suggest that this relationship is due to a north-northwest-trending lateral ramp northeast of the Dagger Flat and Marathon anticlinoria along which the basal thrust ramps upward to the Woods Hollow Shale to the northeast. Lacking multiple decollement horizons, the structure of this northeastern area is dominated by a series of large fault-propagation folds and adjacent synclines more reminiscence of "typical" thrust belts (Rodgers, 1990; Mitra, 1992).

3. Structure

This study is based on a 49 km long by 7 km wide transect extending in a generally northwest–southeast direction across the Marathon inlier (Fig. 3). Within this corridor, the surface geologic mapping of King (1937) and limited existing well data were augmented by detailed structural measurements, and additional mapping. With these data we constructed a regional cross section across the orogen (Fig. 4). The earlier studies demonstrated that the style of contraction within the Marathon region is markedly different that that observed in many other more "typical" thrust belts. Apparent extreme internal shortening within mechanically incompetent units precluded the use of typical cross sectional balancing techniques that employ fault-bend fold or fault-propagation fold geometries. Thus, we attempted to balance our section using competent units, such as the Caballos Novaculite, as the control on original line length. Incompetent units were then approximately area balanced (Mitra and Namson, 1989). As with all sections, ours is most certainly not correct in detail, but represents one viable solution of many.

Several aspects of the cross section are striking and some of the features set the Marathon thrust-fold belt apart from better known thrust belts such as the Appalachians or Canadian Rockies. The cross section clearly indicates that tectonic transport of the Marathon facies rocks has been tens of kilometers and possibly much larger. Good evidence in the form of map patterns and constraints of geologic balancing indicate that the basal Dugout Creek thrust is tightly folded. This implies substantial progressive internal deformation of the allochthonous rocks and the underlying late Paleozoic foredeep deposits.

The southeast part of the transect crosses imbricate thrusts cutting Tesnus Formation at the surface. Along strike these thrusts cut strata ranging from Woods Hollow Shale through Haymond Formation. The central part of the transect crosses the Dagger Flat and Marathon anticlinoria which consist of imbricates and duplexes involving early and middle Paleozoic strata. Finally, the northern part of the transect crosses folded and thrusted strata of the late Paleozoic Gaptank Formation that were deposited in the foreland of the thrust belt. At the level of surface exposure, much of the internal shortening of the allochthonous rocks is by tight folding rather than major imbrication. Internal shortening of these rocks by both folding and thrusting is at least 80% and could be much greater. Extreme shortening across major anticlinoria resulted in the development of upper level detachments and duplex zones. Toward the interior of the belt (southeast), where late Paleozoic strata are widely exposed, imbricate thrusting appears to be more important. However, this may be a perception based on the structural depth exposure.

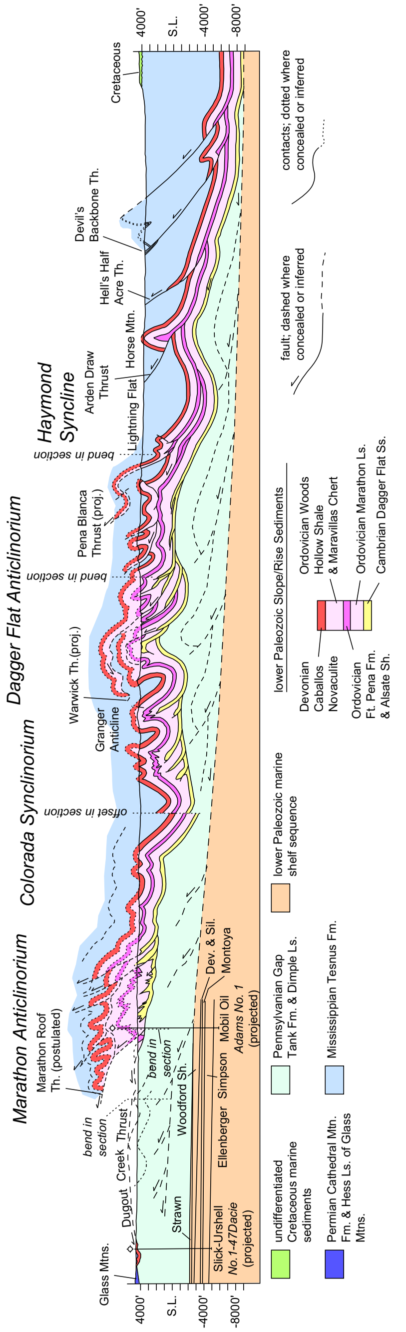

Fig. 4. Cross section across the Marathon region.

3.1. Structure of the interior part of the belt

The most interior part of the thrust belt is exposed southeast of the Peña Blanca Mountains (Fig. 3). Surface exposures are largely of folded Tesnus Formation. Exposed structures are chiefly open synclines that are cut respectively on their southeast flanks by three southeast-dipping thrusts, the Devil's Backbone, Hell's Half Acre, and Arden Draw thrusts (Fig. 4). In the area of the cross section the Devil's Backbone thrust consists of two imbricates with a series of folds in the sliver between the thrusts. The Horse Mountain anticline is interpreted to be a transported fault-propagation fold developed above the Arden Draw thrust (Fig.1). The Hell's Half Acre thrust is developed on the backlimb of the Horse Mountain anticline. In the eastern part of the Marathon inlier, Muehlberger et al. (1984) recognized that the Hell's Half acre thrust is an out-of-sequence feature since blocks of Pennsylvanian Dimple and Haymond derived from underlying thrust sheets or folds occur in the fault zone.

Locally, a cleavage parallel to the axial surfaces of folds is developed within shaly layers of the Tesnus Formation (Fig. 5). On the flanks of Horse Mountain and other folds a pencil cleavage (Ferrill, 1989) formed by the intersection of this cleavage with bedding is developed in the Tesnus. This lineation parallels the plunge of the folds. These cleavages indicate that these strata have undergone significant strain (Hobbs et al., 1976).

The deep structure of this part of the thrust belt is poorly known. Based on the involvement of Caballos Novaculite and Woods Hollow Shale in the Horse Mountain anticline, it is inferred that all three of the thrusts join a decollement near the base of the Alsate Shale. In the cross section (Fig. 4) the Caballos and older formations above the thrusts are portrayed as being largely unfolded. However, because these units are folded everywhere that they are exposed, it is likely that they are folded into relatively small-scale folds at depth.

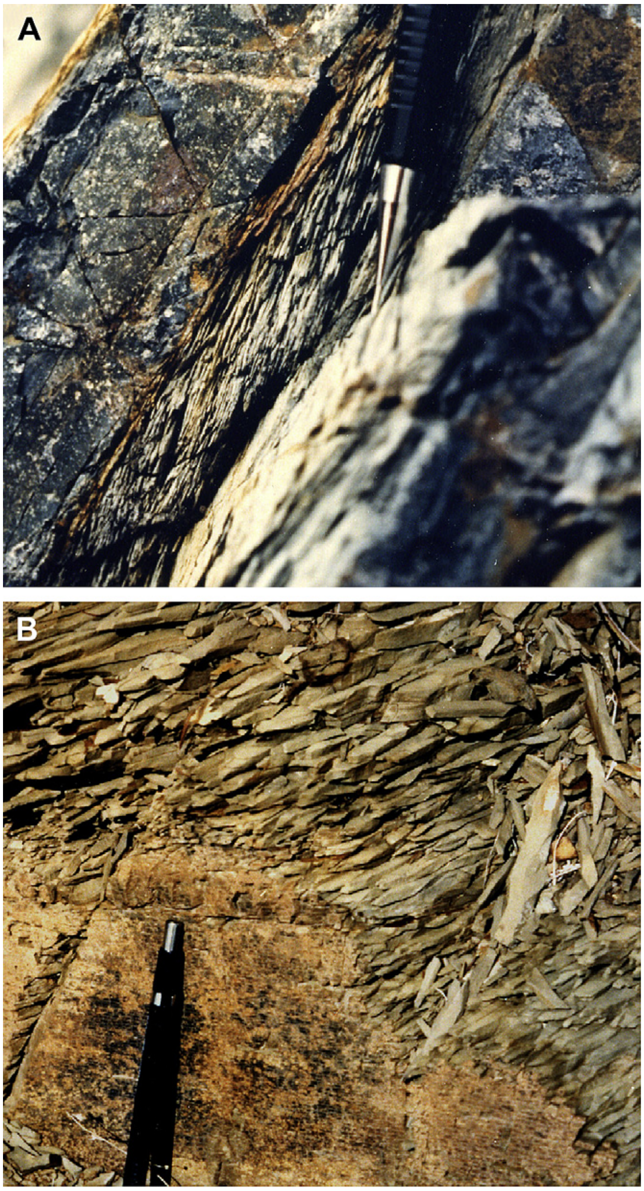

Fig. 5. (A) Axial plane cleavage developed in pelitic layer of the Tesnus Formation on the flank of Granger anticline (see Fig. 4 for location); (B) Pencil cleavage lineation developed in shales of the Tesnus Formation of the Peña Blanca Mountains. Pencils are parallel to the plunge of regional folds.

3.2. *Structure of the central part of the belt*

At the surface, the central part of the thrust belt consists of two anticlinoria of complexly deformed pre-tectonic Marathon facies strata, separated by a synclinorium of Tesnus Formation (Fig. 4).

3.2.1. *Dagger Flat anticlinorium*

The Dagger Flat anticlinorium is most southerly of the complexly deformed zones. The flanks of the anticlinorium are marked by resistant ridges of steeply dipping Caballos Novaculite. The core of the structure consists of folded and imbricated Ordovician and Cambrian strata. The folds are tight, high-amplitude chevron folds with wavelengths of 150–300 m. All dips in the core of the fold are steep (Fig. 4).

Exposures to the northwest, and wells indicate that the Dugout Creek thrust, which is the basal thrust involving Marathon strata in this region, dips southward beneath the Dagger Flat anticlinorium. This makes it likely that the exposed imbricate thrusts ramp upward from the Dugout Creek thrust. Down-structure viewing of mapping in the Warwick Hills area (King, 1937) at the northeasterly plunge of the anticlinorium reveals that the imbricates are structurally overlain by tightly folded thrust sheets composed of the entire Marathon sequence that are detached in the Lower Ordovician shales (Fig. 6). An integration of the subsurface, surface, and projected down-plunge geology shows the overall structure of the "anticlinorium" to be a complex series of folded duplexes (Fig. 4B). The folded thrusts of the Warwick Hills area are the roof thrusts of the highest duplexes. High-relief detached folds above the roof thrusts accommodate shortening at a shallower level. Local shortening of the strata of the roof thrusts by thrusting and folding was extreme and may exceed 80%. Deformation of these roof thrusts was progressive because the Warwick Hills thrust is less folded that the underlying unnamed thrust (Fig. 4B).

The southeastern flank of the Dagger Flat anticlinorium is bounded by left-stepping, high-relief folds involving the Woods Hollow Shale through lower Tesnus Formation. The transect crosses this fold train in the area of the Peña Blanca Mountains (Figs. 3 and 7). At the surface these folds are detached in the Woods Hollow Shale and are cut by thrusts (Figs. 4B and 7). The folds have wavelengths of about 450 m and have amplitudes of 150–700 m. The shape of the folds is controlled by the Caballos Novaculite which acts as a thick competent layer within a sequence of thin-bedded shales, cherts and limestones. The Caballos Novaculilte is typically folded into a concentric shape, while in the cores of anticlines the Maravillas Chert and Woods Hollow Shale are deformed into smaller wavelength box- and chevron-shaped folds (Fig. 8).

The thrusts cut across the competent Caballos Novaculite at high angles (60–90°) suggesting that the folds initially developed as detached buckle folds and, after significant shortening, were cut by thrusts. Because strata older than the Woods Hollow Shale are not exposed, these thrusts are interpreted to sole above the Marathon Limestone (Fig. 4B). Map patterns show that the associated thrusts such as the Peña Blanca thrusts are tightly folded (Fig. 4B). The spatial relationship of these folds and folded thrusts to the Dagger Flat anticlinorium, and their similarity to the structure of the Warwick Hills area suggests that they formed contemporaneously with the Warwick Hills structures and represent upper level compensation for deeper-level shortening beneath the Dagger Flat anticlinorium.

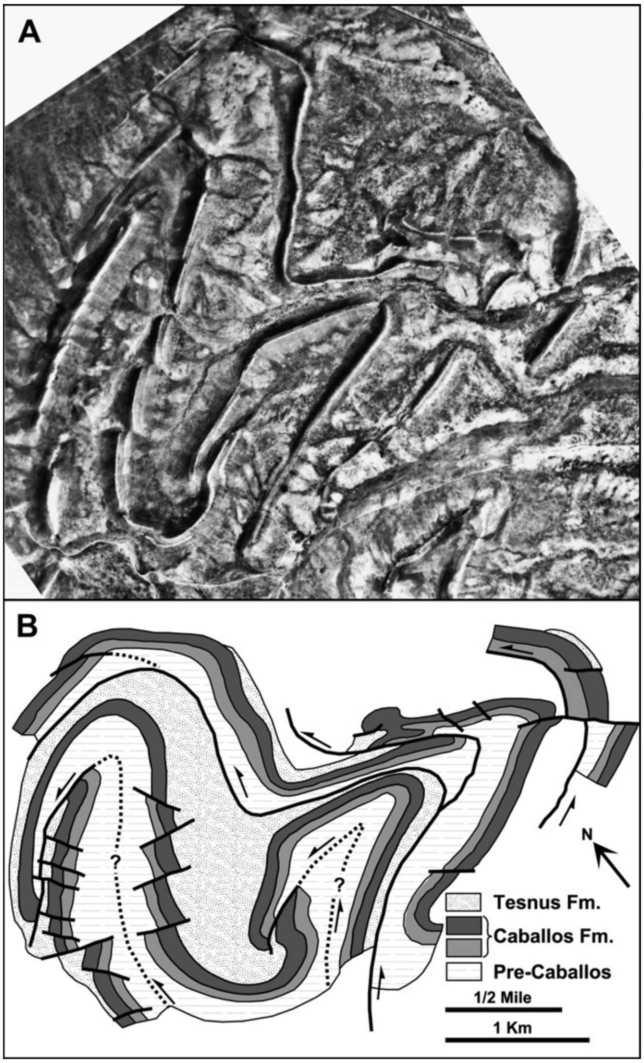

Fig. 6. (A) Aerial photograph of the Warwick Hills area and (B) down plunge interpretation of the area of the aerial photograph.

Folds within the Dagger Flat anticlinorium are cut by minor northwest-striking, nearly vertical faults with horizontal slickensides. These faults have displacements up to 100 m and are unfolded. We interpret these to comprise late-stage tear faults within the allochthon that helped to accommodate thrust transport or differential shortening of the folds.

3.2.2. *Colorada synclinorium*

The Colorada synclinorium lies northwest of the Dagger Flat anticlinorium. Here, surface exposures consist of tightly folded Tesnus and Caballos Formations (Fig. 4). The folds are tight, high-amplitude folds with a parallel geometry. The folds are upright or northwest-verging. Two sizes of macroscopic folds are present. The largest have wavelengths of about 1200 m and amplitudes of up to 1800 m. The smaller folds have wavelengths and amplitudes of about 300–450 m. The wavelength and geometry of the folds appears to be largely controlled by the Caballos Formation. The tightness of these folds and their high amplitudes results in substantial stratal shortening. Shortening across this zone as a result of macroscopic structures is about 35%. In order to maintain similar amounts of shortening at depth beneath the larger anticlines, nearly isoclinal folding, imbrication or a detachment is required. On the cross section this shortening is accomplished by imbrication of the Cambrian and older Ordovician strata and by tight folding of younger Ordovician strata.

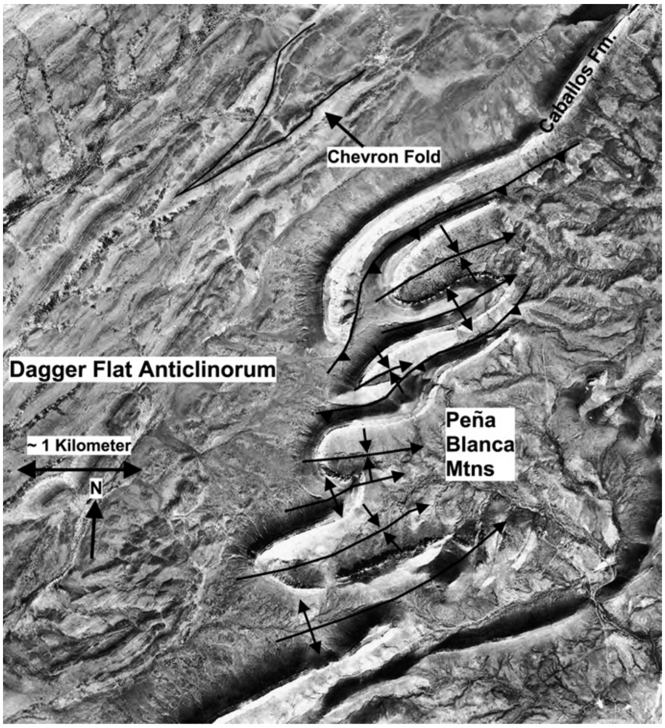

Fig. 7. Aerial photograph of a part of the southeastern flank of the Dagger Flat anticlinorium and the adjacent Peña Blanca Mountains. The cross section (Fig. 4) crosses the folds shown in the photograph. Folds in the Caballos Novaculite are detached, high-relief concentric folds that are cut by thrusts. In contrast, folds in Ordovician strata within the anticlinorium are tight chevron style folds.

3.2.3. *Marathon anticlinorium*

The Marathon anticlinorium is located northwest of the Colorada synclinorium. Folded Ordovician and Cambrian strata are exposed in the anticlinorium (Figs. 3 and 4). The folds are chevron to isoclinal, and verge northwest. The largest of the folds have wavelengths of about 300 m. The combination of nearly isoclinal folds with high amplitudes, and thrusts results in very large

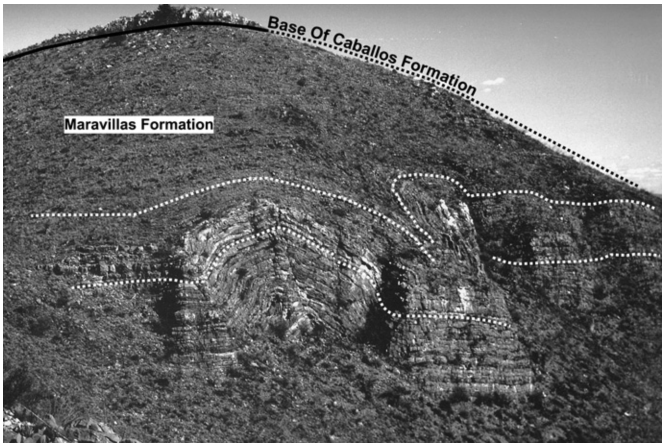

Fig. 8. Photograph of the core of an anticline defined by the base of the Caballos Novaculite near Reed Springs in the Peña Blanca Mountains. In contrast to the open, concentric fold defined by the Caballos, Ordovician strata in the core of the fold are deformed into smaller box- and chevron-shaped folds. The width of the field of view is approximately 300 m.

shortening across this zone. This makes it difficult to draw a balanced cross section showing the younger units that are now eroded from the crest of the anticlinorium (Fig. 4A). In fact, it seems to require that units above the Woods Hollow Shale are separated from the lower units by a detachment. One possibility would be for the steeply dipping thrusts of the anticlinorium to join the detachment to form a duplex zone similar to the one interpreted to be present at the Dagger Flat anticlinorium.

Along the northwestern margin of the Marathon anticlinorium are a series of thin imbricate thrust sheets composed of Maravillas Chert through Dimple Limestone that are emplaced over Late Pennsylvanian Gaptank Formation (Fig. 4A). Since strata as old as the Dagger Flat Sandstone are present in the adjacent anticlinorium, the Dugout Creek thrust must cut up section between the anticlinorium and the imbricates. This suggests that the anticlinorium may have begun as a ramp anticline.

3.2.4. *Marathon foreland*

Northwest of the area of continuous cover of Marathon facies, the Late Pennsylvanian Gaptank Formation is exposed. However, a klippe of Marathon facies strata overlying the Gaptank Formation in the Glass Mountains further to the northwest indicates that prior to erosion the Dugout Creek thrust sheet extended across this entire region. The klippe comprises a tightly folded sequence of Maravillas Chert through Dimple Limestone (King, 1937). The Marathon facies strata are unconformably overlain by a northwestward-dipping homoclinal sequence of Late Wolfcampian and early Leonardian-age Hess Limestone (Reed and Strickler, 1990).

The Gaptank is interpreted to be a foreland basin deposit and consists of conglomerates, sandstones and shales of fluvial through deltaic origin that contain sediment derived from the Marathon facies strata (Ross, 1967). Northwest of the Marathon anticlinorium these strata are folded in to open, northeast-trending folds with wavelengths of 450–600 m (Fig. 4). These folds are interpreted to be either the result of either local thrusting within the foreland sequence or buckle folds developed above a detachment within that sequence. Seismic data support the thrusting interpretation (Reed and Strickler, 1990). Folding and thrusting of the Gaptank apparently occurred almost simultaneously with emplacement of the Marathon allochthon since the upper Gaptank beds are of early Wolfcampian age (Bostwick, 1962) and still younger early Wolfcampian strata are interpreted to have been involved with thrusting in oil fields along the edge of the thrust front a few km to the northeast (Reed and Strickler, 1990).

3.2.5. *Inferred deep structure beneath the Marathon allochthon*

The deep structure beneath the Marathon thrust belt is poorly known. It is likely that the early and middle Paleozoic cratonic sequence underlies the entire exposed part of the thrust belt. Scattered deep exploration wells demonstrate that the cratonic early Paleozoic sequence extends as far southeast as the southern part of the Marathon anticlinorium (Reed and Strickler, 1990). The drastic facies contrast between the Marathon facies strata and the contemporaneous cratonic sequence implies that the allochthon is far-traveled and that the edge of the cratonic sequence lies some distance to the southeast of Marathon facies exposures. This is supported by gravity anomalies that suggest that the rifted North American continental margin lies east of the Rio Grande River southeast of the Marathon area (Handschy et al., 1987; Viele and Thomas, 1989).

We interpret that the Dugout Creek thrust is the basal thrust for the Marathon allochthon, and that the thrust is tightly folded (Fig. 4). It seems likely that any folding of the base of the allochthon is caused by deeper thin-skinned imbricate thrust sheets. As described above, exposures near the thrust front demonstrate that the allochthon overrode the Late Paleozoic Gaptank Formation at least several km. Data from the Turner Combs #1 well, drilled near the core of the Dagger Flat anticlinorium, seem to extend this relationship further to the southeast since they were interpreted to indicate that the basal decollement of the Marathon allochthon was cut at a shallow level in the well and that structurally Late Pennsylvanian strata underlie the anticlinorium (King, 1980). Along the leading edge of the thrust belt, middle and lower Paleozoic strata of the cratonic sequence are locally involved in sub-allochthon thrusting (Reed and Strickler, 1990), so it seems possible that these strata may be at least locally involved in thrusting toward the interior of the belt. Based on these sparse data, we propose that the Marathon allochthon is likely to be underlain by imbricates of foreland basin strata that may locally involve pre-tectonic cratonic strata (Fig. 4).

3.2.6. *Discussion of structural style*

The Marathon allochthon is characterized by complex, folded duplex zones and prominent detached folds involving the Caballos Novaculite. The mechanical stratigraphy of the Marathon sequence plays a central role in shaping the structural style of the belt (Fig. 2). This pre-tectonic sequence is thin ($\sim$1000 m) and as a consequence, both fault-propagation folds and detached folds deforming it are dimensionally smaller than in most foreland thrust belts. Several weak, shaly units within the pre-tectonic sequence act as decollement surfaces, which led to the formation of duplex zones. Carbonate units within the Marathon sequence are thin-bedded, and consequently also behaved as relatively weak units (Ramberg, 1964). The 125–150 m thick Caballos Novaculite acted as the only competent unit within the sequence and controlled the formation of high-relief, detached folds. The composite thickness of the syn-tectonic units is much greater than the Marathon sequence ($\sim$5600 m) and is dominantly composed of sandy siliciclastics, and thickly-bedded shelfal limestones. Structures developed wholly within these syn-tectonic units are larger and more dominated by faulting than those affecting only the Marathon sequence.

The stratigraphy and structure of the Ouachita thrust belt, 800 km to the northeast, closely resembles than of the Marathon region. One difference is that a much wider zone of deformed syntectonic strata are exposed in the Ouachitas. In contrast, the stratigraphy and structure of the southern and central Appalachians differs greatly from the Marathon-Ouachita belt. In the Appalachians, the Cambrian and Ordovician section is substantially thicker than in the Marathon region and consists dominantly of shelfal carbonates. Major decollements are located in shales in the lower part of the Cambrian, in shales near the top of the Ordovician and near the base of the Pennsylvanian (Rodgers, 1990). Major thrusts have ramp-flat geometries due to the positions of decollements and behavior of the Cambrian-Ordovician carbonate section as a thick stiff structural member. In the exterior part of the belt this faulting style produces fault-bend and fault-propagation folds, while in the more deformed interior part of the belt the deformation results in imbricate thrust stacks and duplexes. In contrast to the Marathon region, detached folds are of minor importance in the Appalachians.

Many thrust-dominated foreland belts have similarities with the Appalachians because they involve sequences of miogeoclinal strata that form thick, stiff structural members separated by thin, relatively weak shales that form multiple detachments. Belts that are dominated by detached folds, such as the Jura Mountains involve a very weak basal salt or shale unit overlain by stiff units (Mitra, 2003; Laubscher, 1972). The Jura folds are larger than the folds of the Marathon region because the stiff layer is much thicker than the Caballos Novaculite. The overall structure of the Jura belt also is simpler than the Marathon region because higher level decollements are minor and because the amount shortening is less than in the Marathons.

4. Tectonic evolution

As pointed out by prior authors, the exposures of deformed Paleozoic strata in the Marathon Mountains and Solitario uplift to the south represent the westward end of a continuous mountain belt that includes the Appalachian and Ouachita Mountains (King, 1937, 1977; Viele and Thomas, 1989). These mountains record the collision of this southeastern and southern part of North America with one or more masses of probable continental origin. Collision was apparently diachronous, closing from east to west (Graham et al., 1975). In addition to sediment sources to the south of the Marathon region (McBride, 1989), sedimentology (Graham et al., 1975, 1976) and Nd-isotopes (Gleason et al., 1995) of flysch sediments shed off the propagating collisional boundary indicate significant axial sediment transport. This collisional margin was fragmented during Jurassic opening of the Gulf of Mexico. Remnants of the collisional terrane(s) are suspected to reside in the present Gulf of Mexico-Caribbean region (Campa and Coney, 1983; Pindell, 1985), northern Mexico (Carpenter, 1997) and perhaps in the subsurface of the Sabine uplift in northern Louisiana (Viele and Thomas, 1989).

The sedimentologic record provides the best evidence of the timing of the development of the Marathon thrust belt. The Paleozoic evolution of the Marathon region can be divided into early-middle Paleozoic and late Paleozoic phases. During the first phase a relatively thin marine sequence was deposited that makes up the older part of the Marathon facies (Dagger Flat Sandstone-Caballos Novaculite). Paleocurrent indicators and stratigraphic evidence indicate that the chief source of clastic sediment was to the north or northwest of the area of Marathon facies accumulation (King, 1977; McBride, 1989). While contrasting strongly with the now subjacent early to middle Paleozoic autochthonous shelf sequence, there are broad lithologic similarities between that sequence and the older Marathon facies strata. Micro- and macrofossils of the Marathon sequence are also similar or identical to North American species. Limited Nd-isotopic data further support a North American cratonal source (Gleason et al., 1995). In addition, phosphorite bearing chert in the Maravillas Fm. appears to have been deposited within a contiguous zone of coastal upwelling along the early to middle Paleozoic, west-facing North American continental margin (Coles and Varga, 1988). Taken together, these factors, plus the present day continental margin setting, support the idea that these strata accumulated in a continental slope setting along an early Paleozoic rifted margin of North America (Fig. 9A).

Late Mississippian and Early Pennsylvanian time marks an abrupt change in sedimentation patterns as clastic material of the Tesnus Formation was deposited on the Caballos sediments. The content of Tesnus Formation sandstones suggests progressive unroofing of an area of regionally metamorphosed rocks. Paleocurrent indicators indicate sediment transport from the southeast to the northwest (McBride, 1969a, 1989). This implies derivation from south of the North American continent. This is supported by the metamorphic component of the Tesnus sandstones, since a nearby North American source of metamorphic detritus does not appear to be present. Tuff beds in the Tesnus imply presence of a nearby volcanic arc (Imoto and McBride, 1990). Drastic thinning of the formation toward the northwest suggests that it was largely or entirely restricted to the allochthonous Marathon sequence (Fig. 9B). Regional reconstructions suggest that the switch in sediment type and source marks the approach of South America or an associated microplate (Wickham et al., 1976) and may signal early thrusting in the interior part of the thrust belt located southeast of the exposed Marathon inlier. North of the Marathon area northwest-trending compressional uplifts and associated basins began to form at this time (Reed and Strickler, 1990).

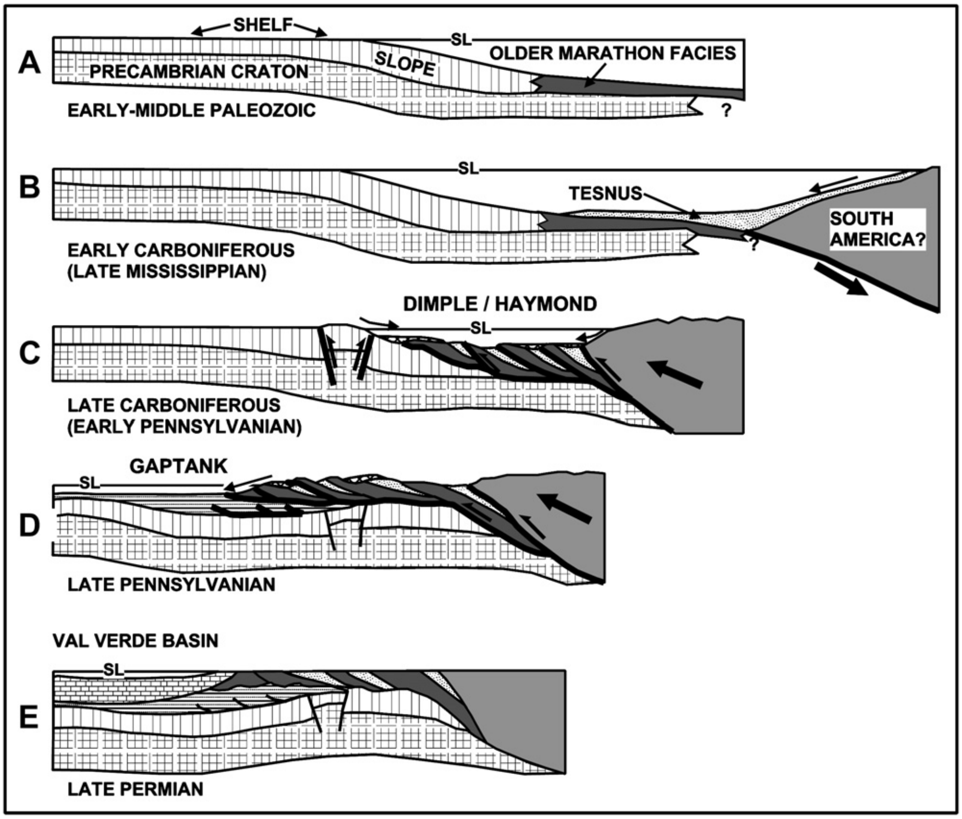

Fig. 9. Schematic diagram showing stages of the evolution of the Marathon thrust belt.

Deposition of the Early Pennsylvanian age Dimple Limestone may indicate a brief waning in tectonism during early Pennsylvanian time. During Dimple deposition, a shelf area lay to the north, and sediments were shed to the southeast into the Tesnus foredeep (Thomson and Thomasson, 1978). The overlying Haymond Formation marks a period of strong tectonism in Middle Pennsylvanian Atokan time. Most of the unit is composed of interbedded deep water shales and arkosic sandstones. Boulder beds within the Haymond contain a variety of clasts including exotic sedimentary, igneous, and metamorphic rocks, clasts derived from older Marathon units, and Cambrian limestone clasts probably derived from the shelf of North America (King, 1977; Palmer et al., 1984). These clasts were probably derived from local uplifts within the incipient Marathon thrust belt, local uplifts along the margin of North America and perhaps from the landmass approaching from the southeast (Fig. 9C). Isotopic dating of crystalline blocks gives a Silurian-Devonian age (Denison et al., 1969) which is inconsistent with any known, proximal North American source region (Gleason et al., 1995).

During Des Moinesian times a foredeep formed north of the developing thrust belt and began to fill with coarse clastic fluvial and deltaic sediments of the lower Gaptank formation. These sediments were derived from both the older Marathon facies rocks and the shelf to the north. As deposition continued to the north, the older Gaptank sediments were folded, thrusted and overridden by the Marathon allochthon (Fig. 9D). By earliest Permian time the allochthon had overridden the Gaptank basin and thrusting ended and the leading edge of the thrust belt was buried by younger Wolfcampian sediments. In the Ouachita portion of the orogen, approximately 800 km to the northeast, two periods of thrusting (Atokian and Des Moinesian) have been recognized (Whitaker and Engelder, 2006) that may match the two peaks of Marathon area thrusting (i.e. Atokan and Des Moinesian-earliest Permian) described above. In Early Permian time clastic sediments derived from the thrust belt were shed north and eastward into the developing Delaware, Midland, and Val Verde basins (Figs. 1 and 9E). During the remainder of the Permian, subsidence continued in these latter basins and thick carbonate sequences accumulated.

5. Summary

The Marathon thrust belt consists of a highly deformed allochthonous wedge of Cambrian-Pennsylvanian slope strata that was transported to the northwest, and emplaced over Pennsylvanian foredeep sediments as a result of collision of the southern part of North America with one or more masses of probable continental origin. Shortening within the allochthon is ∼80%. Steep imbricate faults link the basal Dugout Creek thrust to upper level detachments forming complex duplex zones. Progressive thrusting and shortening within the allochthon folded the upper level detachments and associated thrust sheets. Deeper imbricate sheets composed of the Late Pennsylvanian foredeep strata, and possibly early-middle Paleozoic shelfal sediments developed concurrently with emplacement of the Marathon allochthon and folded the overlying allochthon.

The mechanical stratigraphy of the Marathon sequence plays a central role in shaping the distinctive structural style of the belt. The thinness of pre-tectonic sequence resulted in formation of fault-propagation folds and detached folds that are smaller than in most foreland thrust belts, while several weak horizons within the pre-tectonic sequence led to development of multiple decollement surfaces and the formation of duplex zones. The Caballos Novaculite acted as the only competent unit within the pre-tectonic sequence and controlled the formation of high-relief, detached folds. Progressive shortening folded early thrust sheets and resulted in some out-of-sequence thrusting.

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