EARLY LEONARDIAN TO LATE WOLFCAMPIAN, DEEP-WATER CARBONATE SYSTEMS IN THE PERMIAN BASIN: EVIDENCE FROM WEST TEXAS OUTCROPS

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ABSTRACT

Outcrops in the Victorio Flexure area of the Sierra Diablo Mountains, West Texas, provide evidence suggesting that (1) Ouachita-related tectonism remained active throughout Early Permian time in the Delaware Basin and (2) margin-to-slope topography generated from these tectonic events can focus sediment downslope, resulting in channelized carbonate debris accumulations. In the late Wolfcampian, a distally steepened carbonate ramp (Hueco 'C' Formation) developed near the Victorio Flexure monocline along the western margin of the Delaware Basin. In the latest Wolfcampian, significant rotation of the Victorio Flexure monocline increased slope height by more than 170 m and slope gradient by more than 6°. Preexisting ramp sediments were slump deformed, and significant reentrant topography formed along the upthrown hinge of the monocline. These reentrants and slump topography acted as downslope focusing mechanisms for early Leonardian (lower Abo Formation) carbonate debris. This debris bypassed the upper slope and was deposited at the lower slope/toe of slope in the form of amalgamated channel complexes that display proximal to distal relationships.

Knowledge of late Wolfcampian tectonic activity provides additional information to constrain the waning of Ouachita-related tectonism in the Delaware Basin and, perhaps, throughout the Permian Basin system. Shelf-margin and upper-slope topography as sediment-focusing controls are critical components of carbonate-slope channelization and basinward sediment transport. Basinal, grainy, carbonate accumulations can survive diagenetic deterioration of reservoir quality, and channelization linked to differential topography may help to predict their distribution.

INTRODUCTION

Outcrops near the Victorio Flexure (VF) monocline, Sierra Diablo Mountains, west Texas, provide a continuous dip exposure of an Early Permian, distally steepened carbonate ramp (Read, 1985) and slope deposits (late Wolfcampian lower and upper Hueco 'C' Formations and early Leonardian lower Abo Formation) along the western margin of the Delaware Basin (figs. 1, 2). These strata conformably overlie terrestrial to shoreline siliciclastics of the mid- to late Wolfcampian Powwow Formation (fig. 2). The Powwow through Abo Formations comprise the oldest Permian sediments near the VF and unconformably overlie uplifted Precambrian basement strata of the Hazel Formation (King, 1965). The VF, first identified by King (1965), is a deep structure that was active during Ouachita deformation and is expressed as a northward-plunging, WNW-trending monocline at the surface. Hueco 'C' ramp paleogeography and the distally steepened inflection are coincident with the upthrown, southern hinge point of the Victorio Flexure (SHVF). The mapped study area includes as much as 190 m of section and approximately 7 km of continuous, oblique dip exposure, outcropping along the VF (fig. 2).

Early Permian VF outcrops were comprehensively described by King (1965) and recently studied by Wilde (1995b), Kerans (2001), and Playton (2003a, b). This exposure especially highlights carbonate-slope deposits with a range of sediment gravity flows, including slump complexes and channelized to unchannelized debris-flow complexes. Because the exceptional dip continuity allows for correlation of ramp-crest to slope environments, slope facies and architectural element organization can be observed within a platform-constrained sequence stratigraphic context. Evidence suggests, however, significant northward rotation of the VF monocline and consequent deformation of the Hueco ‘C’ ramp in the latest Wolfcampian. This deformation implies that the latest Wolfcampian slope deposits were tectonically induced and not deposited as a result of typical ramp-slope depositional processes. Additionally, post-tectonic slope sediments of the early Leonardian Abo Formation show a clear response to antecedent differential topography generated from the latest Wolfcampian tectonic event. Therefore, tectonically induced slope deposits and the effects of tectonically generated topography on subsequent slope deposition are of interest and available for study. Field-data collection included measured sections with samples and thin sections, plan-view maps, and detailed interpreted photomosaics.

EARLY PERMIAN PALEOGEOGRAPHY OF THE WESTERN DELAWARE BASIN

The late Paleozoic Ouachita deformation reactivated deep-rooted structural features across North America (Yang and Dorobek, 1995). Flexural loading and structural reactivation associated with North American plate subduction formed a complex foreland basin system, the Permian Basin, in present-day Texas and New

Mexico (Yang and Dorobek, 1995). The Central Basin Platform was an intraforeland uplift that subdivided the Permian Basin into the Delaware Basin to the west and the Midland Basin to the east. The Diablo Platform was a structurally positive area that defined the western shelf of the Delaware Basin, along which were several north-dipping, WNW-trending, east-plunging monoclines, formed as a result of transtension (Yang and Dorobek, 1995). These structures were first mapped by King (1965) and called 'flexures,' which represent deep-rooted, half-graben structures that were surficially expressed as large-scale, rotated fault blocks along hinge points (monoclines).

Early Permian paleogeography strongly reflects the underlying flexure-controlled structure (fig. 3; King, 1965). The monoclinal flexures were expressed as large embayments along the primarily N-S striking, western Delaware Basin margin. These embayments acted as local depocenters and developed shelf-to-basin stratigraphy during their fill (fig. 4). The study area's outcrop belt is an example of such and represents the northward advance of siliciclastic and carbonate systems into the VF embayment.

Early Permian strata unconformably overlie Precambrian basement in the study area (fig. 1). South of the VF monocline, Wolfcampian strata overlie an uplifted block of Proterozoic Hazel Formation sandstone. North of the SHVF, Hazel exposures plunge into the subsurface, reflecting the northward tilt of the VF monocline (King, 1965). Large-scale depositional geometries of the overlying Hueco 'C' and Abo sediments reflect this monoclinal structure, where flat-lying strata are observed south of the VF and north-dipping strata are observed along the VF monocline (fig. 1). This flexure-controlled, paleogeographical arrangement defines the southern edge of the VF-controlled embayment along the Delaware Basin shelf margin (figs. 3, 4).

MID- TO LATE WOLFCAMPIAN DEPOSITIONAL EVOLUTION

Mid- to late Wolfcampian strata in the VF area can be subdivided into three large-scale facies tracts that record uplift and subaerial erosion, transgression, and development of a low-angle, distally steepened carbonate ramp. These facies tracts are, in stratigraphic order, the mid- to late Wolfcampian Powwow Formation, the late Wolfcampian lower Hueco 'C' Formation, and the late Wolfcampian upper Hueco 'C' Formation (fig. 1).

The *mid- to late Wolfcampian Powwow Formation,* a nonmarine to shallow marine siliciclastic wedge, represents the oldest Permian strata in the area (fig. 5a). The Powwow directly overlies uplifted basement and marks a substantial angular unconformity. The wedgelike morphology reaches a maximum thickness at the SHVF of 60 to 65 m and thins in both directions along dip. Powwow sediments consist of siliciclastic conglomerates, sandstones, and siltstones that transition from basal alluvial fan/braided fluvial facies to capping shoreline facies. The Powwow succession displays an overall retrogradation of depositional systems and represents (1) subaerial erosion of uplifted basement blocks to the south of the VF, (2) development of alluvial-fan and braided fluvial terrestrial systems, (3) marine transgression, and (4) development of shallow marine shoreline systems (fig. 5a).

The *late Wolfcampian lower Hueco 'C' Formation* is an open marine limestone blanket that conformably overlies and drapes the Powwow across the exposure (fig. 5b). The lower Hueco 'C' maintains a relatively constant thickness of 25 to 30 m and displays a consistent upward facies succession throughout the study area, implying a relatively flat paleo-seascape during deposition. Lower Hueco 'C' limestones are thin bedded, nodular, and structureless, and they grade upward from basal silty skeletal wackestones/

packstones, into fusulinid wackestones/packstones, into capping crinoid wackestones. This succession records increasing paleo-water depth throughout lower Hueco 'C' time, where substorm wave-base (SWB), distal outer-ramp environments transitioned into basin-floor carbonate environments. Thus, the lower Hueco 'C' represents (1) initial submergence of a low-relief siliciclastic landscape, (2) waning of siliciclastic input during onset of carbonate production, and (3) continued transgression during distal outer-ramp carbonate accumulation (fig. 5b).

The *late Wolfcampian upper Hueco 'C' Formation* conformably overlies the lower Hueco 'C' and represents the youngest Wolfcampian strata in the area (fig. 5c). The upper Hueco 'C' tapers in thickness from more than 110 m south of the VF to less than 15 m north of the VF (fig. 1) and displays a northward transition from dolomite to limestone. The interval also shows a change from undeformed strata south of the VF to disrupted, slump-deformed, and resedimented strata along and north of the VF, respectively. These disrupted deposits are interpreted to be the result of a postlate Hueco 'C' deformation event (further explained in later sections); however, thickness distributions and facies constraints allow for reconstruction of the undeformed precursor accumulation (fig. 6). Reconstructed upper Hueco 'C' facies are arranged into a hierarchy of landward- and seaward-stepping packages and display Waltherian facies relationships. The most updip (southward) facies are dominated by dolomitic peloidal-fusulinid packstones/grainstones with high-energy SWB stratification. These facies transition northward across the VF monocline into skeletal lime packstones/wackestones with lower-energy SWB features. North of the VF, facies are assumed to have been similar to those of the lower Hueco 'C' distal outer ramp to basinal limestones but were disturbed and resedimented after deposition. The reconstructed upper Hueco ‘C’ accumulation is interpreted as the sub-fair-weather wave base (FWWB) part of a larger-scale carbonate-ramp system (fig. 5) that prograded across the lower Hueco ‘C’ blanket. Facies record a northward transition from (1) high-energy, storm-dominated outer-ramp environments just below FWWB into (2) lower-energy, storm-dominated outer-ramp environments into (3) sub-SWB, distal outer-ramp to basin-floor environments (fig. 5c). A distally steepened break in slope marked by facies and thickness changes coincides with the SHVF monocline. A calculated slope gradient from reconstruction (Figure 6) of between 1° and 2° supports a ramp-profile interpretation. Thus, the upper Hueco ‘C’ represents (1) change from transgressive to regressive conditions; (2) development of a low-angle, distally steepened carbonate ramp; and (3) postdepositional deformation of partly lithified ramp sediments (further explained in later sections; fig. 5c).

Wolfcampian facies tracts in the VF area can be arranged into a sequence stratigraphic framework with systems tracts. Basal Powwow sediments represent lowstand (LST) conditions recording exposure, unconformity generation, and subaerial erosion. Upper Powwow and lower Hueco ‘C’ sediments represent transgressive (TST) conditions recording retreat of terrestrial systems, marine inundation of the landscape, and increasing paleo-water depth during sub-SWB carbonate deposition. Upper Hueco ‘C’ sediments represent highstand (HST) conditions where relative sea level stabilized, sedimentation filled in existing accommodation, and SWB carbonate depositional environments prograded. Early Leonardian lower Abo Formation slope deposits overlie Hueco ‘C’ shallow outer-ramp environments, suggesting a significant earliest Leonardian transgression and forcing a sequence boundary at the Wolfcampian/Leonardian contact.

Hueco ‘C’ deposition was approximately 7 Ma in duration (Wilde, 1995a); thus the Powwow/Hueco ‘C’ sequence is of 3rd-order composite sequence scale (Mitchum and others, 1977) and marks the basal sequence within the 2nd-order late Wolfcampian to late Leonardian supersequence (PW3 to L6 of Kerans, 2001, and Fitchen and others, 1995).

LATEST WOLFCAMPIAN TECTONIC ACTIVITY AND SEDIMENT DEFORMATION

Previous sections describe development of the late Wolfcampian, low-angle (1° to 2°) Hueco ‘C’ ramp, with a distally steepened break in slope at the SHVF (fig. 5). Assumptions of the low-angle nature of the ramp are based on uniform vertical facies succession and thickness of the lower Hueco ‘C’ (implying a flat, pre-Hueco ‘C’ landscape) and gradual thickness trends and facies changes of the upper Hueco ‘C.’ As exposed today, the outcrop displays the Hueco ‘C’ profile as a flat-topped shelf with flat-lying strata south of the VF, inclined strata dipping northward at 7° along the VF monocline, and gently dipping strata (1° or less) north of the VF (fig. 1). Depositional and stratal relationships of overlying Leonardian deposits reflect and conform to the present-day exhumed Hueco ‘C’ profile, suggesting that it represents latest Wolfcampian (post-Hueco ‘C’) paleogeography (fig. 1). Upper Hueco ‘C’ sediment deformation is stratigraphically constrained to the latest Wolfcampian because overlying Leonardian sediments are undeformed. Coherent failure features in deformed upper Hueco ‘C’ sediments suggest lithification of sediments and ramp development prior to failure. Therefore, a phase of structural rearrangement and slope adjustment occurred after Hueco ‘C’ deposition and prior to Leonardian deposition (constrained to latest Wolfcampian time). This tectonic event transformed the low-angle (1° to 2°) upper Hueco ‘C’ ramp profile into a flat-topped shelf with a 7°-dipping slope along the VF monocline.

Tectonic movement along the VF monocline in the latest Wolfcampian is most likely responsible for the paleogeographic adjustment and resulting deformation of upper Hueco ‘C’ sediments. Reflecting late-phase Ouachita shearing (Yang and Dorobek, 1995), fault blocks to the north of the study area downdropped and caused significant northward rotation of the Victorio Flexure monocline, increasing shelf-to-basin relief by more than 170 m and slope gradient by more than 6° (figs. 5d, 6). This rotation relocated the preexisting upper Hueco ‘C’ outer ramp into an upper-slope position just basinward of a prominent break in slope at the SHVF. Former distal outer-ramp and basinal sediments of the upper Hueco ‘C’ were shifted into a gently dipping lower-slope position north of the VF. This change in paleogeography and slope gradient resulted in postdepositional failure of upper Hueco ‘C’ sediments.

Latest Wolfcampian tilting of the VF increased slope gradients enough to cause substantial instability and failure of preexisting upper Hueco ‘C’ sediments (fig. 7). At the SHVF, dramatic extension and coherent failure occurred in lithified outer-ramp sediments, resulting in high-relief, slump topography and reentrant formation. Along the tilted VF monocline, partly lithified outer-ramp sediments detached coherently on the less-coherent, underlying lower Hueco ‘C’ and display a spectrum of brittle to ductile deformation features, rotation, and translation. At the NHVF and northward, less-lithified distal outer-ramp and basinal sediments experienced less tilting but underwent noncoherent failure and resedimented into mud-supported breccias with skeletal WS clasts, interpreted as debris flows. The debris flows stacked into unconfined, mounded complexes that display hierarchical organization and compensational stacking. These complexes coalesced to form a tabular debris-flow apron at the newly defined lower-slope position. This paleogeographical adjustment and resulting sediment deformation episode mark the terminal observable event in the Wolfcampian.

LEONARDIAN LOWER ABO FORMATION CHANNELIZATION

The *early Leonardian lower Abo Formation* (L1 TST of Kerans, 2001, and Fitchen and others, 1995) conformably overlies the upper Hueco 'C' and is concentrated primarily north of the VF, reaching thicknesses in excess of 40 m near the NHVF and thinning northward (fig. 5e). Along the VF monocline, the lower Abo pinches and swells along strike from 0 to more than 25 m and was not included in this study south of the VF. Lower Abo limestones are dominated by thick-bedded, polymict, matrix-supported carbonate breccias, with minor fractions of stratified packstones and laminated mudstones. Breccias are arranged into a hierarchy of compensational beds and contained within larger-scale erosional surfaces defining channel-form features. A discontinuous veneer of hemipelagic wackestone/mudstone locally appears at the base of the lower Abo along the VF monocline, suggesting a period of slope quiescence after the latest Wolfcampian VF rotation and supporting a Leonardian-age interpretation. The lower Abo possesses characteristics of a deep-water, channelized, slope or toe-of-slope carbonate environment composed of allochthonous debris in the form of various sediment gravity flows. Matrix-supported breccias are interpreted as submarine debris flows, and the packstone to mudstone facies represent varying concentrations of turbidites. The substantial increase in thickness coincident with a loss in slope gradient at the NHVF indicates net-sediment bypass across the VF monocline and net-sediment deposition north of the VF. Occurrence of well-developed channelized complexes implies an updip sediment-focusing mechanism where allochthonous material is repeatedly exported through the same downslope pathway over time. The source of lower Abo debris is poorly constrained owing to lack of outcrop, but it is assumed to be shed from an early Leonardian platform that backstepped significantly relative to the terminal Wolfcampian margin, aggraded, and oversteepened (Kerans, 2001; Fitchen and others, 1995). Thus, the lower Abo represents (1) slope quiescence after the latest Wolfcampian tectonic event, (2) downslope focusing of allochthonous debris promoting channelization, (3) net-sediment bypass across the VF monocline, and (4) net-sediment deposition north of the VF in the form of amalgamated channel complexes (fig. 5e).

Perhaps the most striking features generated during the latest Wolfcampian VF rotation are high-relief reentrants and coherent slump topography present at the SHVF (fig. 7). This dramatic differential topography provided a sediment-funneling mechanism where early Leonardian debris (lower Abo) focused between and around positive areas at the SHVF, reoccupied the same downslope sediment pathways along the VF monocline, and were deposited as amalgamated channelized complexes north of the VF. This feedback between margin differential topography (that is, reentrants) and sediment focusing provides a mechanism for development of carbonate-slope channelization.

Lower Abo channel complexes display interesting downdip variations in plan-view architecture and thickness from the VF and northward (fig. 8). Near the SHVF along the VF monocline (proximal upper-slope position), lower Abo breccias primarily fill a thick (>25 m), single, strike-discontinuous debris axis with erosive margins, capped by a laterally continuous, thinner (<10 m) breccia veneer. Farther north along the VF monocline (distal upper-slope position), breccias are thin (5–10 m) and strike-discontinuous and represent multiple smaller-scale sediment axes, as opposed to one primary axis observed updip. These architectural relationships along the VF monocline (upper slope) define a proximal primary feeder channel directly downdip of an active reentrant at the SHVF. This feeder channel bifurcated into multiple smaller scale channels toward the NHVF, partly in response to upper Hueco 'C' slump mass topography, but also as a function of increasing distance from the sediment focal point and decreasing slope gradient (fig. 8). North of the VF (lower-slope and toe-of-slope positions), lower Abo breccias thicken significantly to more than 40 m across the NHVF inflection and thin gradually northward. They form well-developed, amalgamated channel complexes that display slight sinuosity, offset relative to previous channel topography, and become less amalgamated (isolated) to the north (fig. 8). These plan-view architectural relationships and thickness changes of the lower Abo (figs. 5e, 8) represent a change from net-sediment bypass along the VF to net-sediment deposition north of the VF, reflecting increasing distance from the sediment focal point and a change in slope gradient from 7° to 1°across the NHVF.

Lower Abo internal channel architecture and channel shape also exhibit proximal to distal transitions (fig. 9), representing downdip increases in depositional versus erosional processes. Fill of the primary feeder channel at the SHVF (upper-slope position) is highly amalgamated, where bedding surfaces are difficult to recognize and track laterally. In contrast, channel complex internal architecture north of the VF (lower-slope and toe-of-slope positions) is beautifully preserved and displays hierarchical organization of compensationally shingled, individual debris flows (fig. 9). Despite relatively small changes in gradient (1° dip) north of the VF, lower-slope, amalgamated channel complexes near the NHVF change northward from narrow (<150 m), flat topped, and highly incisional to broad (>200 m), mounded, weakly erosional, and isolated from other complexes at the toe of slope (fig. 9). These changes in channel-fill preservation and morphology reflect a basinward (upper slope to lower slope/toe of slope) increase in deposition:erosion ratio, as distance from the sediment source and focusing mechanism increases and slope gradient decreases.

SUMMARY AND DISCUSSION

The VF outcrop exposure records Early Permian carbonate-ramp development, tectonic deformation, and slope channelization. During the mid- to late Wolfcampian in the VF area, uplifted basement south of the VF was eroded and provided a source for siliciclastic alluvial and shoreline systems of the Powwow Formation. Transgression inundated the landscape, siliciclastic sources were choked, and the Hueco 'C' distally steepened carbonate ramp evolved in the late Wolfcampian. In the latest Wolfcampian, after Hueco 'C' ramp development, substantial northward rotation of the VF monocline increased slope height by more than 170 m and slope gradient by more than 6°, transforming gently dipping Hueco 'C' outer-ramp and basin-floor carbonate environments into upper- and lower-slope/toe-of-slope environments, respectively. This tectonic adjustment of the depositional profile triggered substantial failure of upper Hueco 'C' sediments and created reentrant topography at the SHVF that later acted as a sediment-focusing mechanism for early Leonardian (lower Abo Formation) carbonate debris. Consequently, channelized lower Abo debris bypassed the VF monocline (upper slope) and ponded north of the VF (lower slope/toe of slope) in the form of amalgamated debris-flow channel complexes. Late Wolfcampian through early Leonardian exposures near the VF offer excellent examination of tectonically induced carbonate-slope deposits, as well as effects of tectonic-related differential topography on subsequent slope deposition.

VF outcrops provide stratigraphically constrained evidence suggesting local tectonic activity along the Delaware Basin margin in latest Wolfcampian time. This tectonism reflects the transtensional structural regime associated with waning stages of Ouachita deformation (Yang and Dorobek, 1995). Thus, Ouachita-related tectonic activity, at least locally, persisted throughout the Wolfcampian stage along the western Delaware Basin margin and perhaps elsewhere in the Permian Basin system. Latest Wolfcampian VF movement substantially postdates the Mid-Wolfcampian Unconformity (Ross, 1986; Candelaria and others, 1992; Fitchen and others, 1995; Yang and Dorobek, 1995).

VF outcrops represent a well-exposed outcrop analog for channelized carbonate-slope systems. They underscore the importance of updip sediment-focusing mechanisms (differential topography on the upper slope or margin) in the development of carbonate-slope channels, especially considering the strike-elongate nature of periplatform and margin sediment sources. In this case, local tectonic readjustment and slumping along the VF were responsible for reentrant formation that focused later Leonardian debris. In other reef-rimmed systems with steep, early-lithified margins, gravitational collapse of the margin and upper slope is a common process (Cook and others, 1972; McIlreath and

James, 1978; Playford, 1984; Coniglio and Dix, 1992) that results in differential margin topography and reentrant formation. Additionally, products of these collapse events are coarse, slope-megabreccia deposits that are often laterally discontinuous and mounded, creating differential topography on the slope itself. Thus, reentrants and slope-megabreccia topography generated from reef-margin collapse also provide mechanisms for sediment focusing and potential channel development.

Many of the productive deep-water carbonate reservoirs in the Permian Basin system are grain-rich, toe-of-slope to basinal accumulations associated with channelization. Carbonate deposits with primary porosity in these environments can survive diagenetic overprints that deteriorate reservoir quality in more proximal positions. Thus, these accumulations have significant reservoir potential, especially if associated with pelagic source rocks and stratigraphic seals. Powell Ranch field, eastern Midland Basin (Montgomery, 1996), is a late Wolfcampian/early Leonardian example of such a reservoir system. Mud-poor, grainy deposits on the basin floor are somewhat anomalous, considering that they should come to rest at higher angles of repose on the slope (Kenter, 1990). Channelization, as a more efficient sediment-transport process, could explain how these sediments bypass their preferred gradient range for deposition and are deposited in a substantially more distal, lower-gradient position. Therefore, as shown from VF outcrops, mapping reentrants and rugosity along shelf margins can delineate potential sediment-focusing mechanisms. Identification of these mechanisms provides another tool for predicting slope channelization and economic basinal accumulations. Additionally, occurrence of collapse-derived, slope-megabreccia deposits implies an associated updip collapse scar or reentrant in the margin, offering another predictive tool for delineating sediment-focusing mechanisms. Considering the Permian Basin system, VF outcrops recorded tectonic activity and reentrant formation during latest Wolfcampian time. Similar local tectonism and margin topography development may have occurred elsewhere in the Permian Basin during this time and could help predict distribution of Wolfcampian/Leonardian-age basinal carbonate reservoirs.

ACKNOWLEDGMENTS

I thank the members of my Master's Thesis Committee at The University of Texas at Austin—Charles Kerans, Scott Tinker, and Bob Goldhammer—for their constructive input. Thanks also to the Bureau of Economic Geology and Jackson School of Geosciences at The University of Texas at Austin for providing support to this research. Critical funding was provided by the Reservoir Characterization Research Laboratory at the Bureau of Economic Geology, the Jackson School of Geosciences Geology Foundation, the Chevron Scholarship Program, and the AAPG Grants-In-Aid Program. I also wish to express my appreciation to former owners, managers, and caretakers of the Sierra Diablo and Corn Ranches in west Texas for land access. Finally, special thanks go to Jerome Bellian, Roger Wagerle, Chris Rhea, Jerry Lucia, Stephen Ruppel, and Bureau of Economic Geology scientists and staff for support both in the field and in the office.

REFERENCES

Candelaria, M. P., Sarg, J. F., and Wilde, G. L., 1992, Wolfcampian sequence stratigraphy of the eastern Central Basin Platform, *in* Mruk, D. H., and Curran, B. C., eds., Permian Basin Exploration and Production Strategies, West Texas Geological Society Publication No. 92-91, p. 27–44.

Coniglio, M., and Dix, G. R., 1992, Carbonate slopes, *in* Walker, R. G. and James, N. P., eds., Facies models: response to sea-level change: Geological Association of Canada, p. 349–374.

Cook, H. E., McDaniel, P. N., Mountjoy, E. W., and Pray, L. C., 1972, Allochthonous carbonate debris flows at Devonian bank (‘reef’) margins, Alberta, Canada: Bulletin of Canadian Petroleum Geology, v. 20, no. 3, p. 439–497.

Fitchen, W. M., Starcher, M. A., Buffler, R. T., and Wilde, G. L., 1995, Sequence stratigraphic framework and facies models of early Permian carbonate platform margins, Sierra Diablo, West Texas, *in* Garber, R. A., and Lindsay, R. F., eds., Wolfcampian-Leonardian shelf margin facies of the Sierra Diablo—Seismic scale models for subsurface exploration: West Texas Geological Society Annual Field Trip Guidebook, No. 95-97, p. 23–66.

Kenter, J. A. M., 1990, Carbonate platform flanks: slope angle and sediment fabric: Sedimentology, v. 37, p. 777–794.

Kerans, C., 2001, Stratigraphy and reservoir facies development: slope-basin carbonate and mixed clastic-carbonate systems: The University of Texas at Austin, Bureau of Economic Geology, RCRL Annual Field Trip Guidebook, 22 p.

King, P. B., 1965, Geology of the Sierra Diablo region, Texas: U.S. Geological Survey Professional Paper 480, 185 p.

McIlreath, I. A. and James N. P., 1978, Facies models; 13, Carbonate slopes: Geoscience Canada, v. 5, 189–199.

Mitchum, R. M., Jr., Vail, P. R., and Thompson, S., III, 1977, Seismic stratigraphy and global changes in sea level; Part 2, The depositional sequence as a basic unit for stratigraphic analysis, *in* Payton, C. E. ed., Seismic stratigraphy—applications to hydrocarbon exploration: American Association of Petroleum Geologists Memoir 26, p. 53–62.

Montgomery, S. L., 1996, Permian ‘Wolfcamp’ limestone reservoirs; Powell Ranch Field, eastern Midland Basin: American Association of Petroleum Geologists Bulletin, v. 80, p. 1349–1365.

Playford, P. E., 1984, Platform-margin and marginal-slope relationships in Devonian reef complexes of the Canning Basin, *in* Purcell, P. G., ed., Canning Basin Symposium, Proceedings: Perth, Geological Society of Australia and Petroleum Exploration Society of Australia, p. 189–214.

Playton, T. E., 2003a, Tectonic deformation of a late Wolfcampian carbonate ramp, *in* Hunt, T. J., and Lufholm, P. H., eds., West Texas Geological Society, Publication No. 03-112, Fall Symposium, October 8–10, p. 143–164.

Playton, T. E., 2003b, Tectonic deformation of a late Wolfcampian carbonate ramp and resulting channelization, Victorio Flexure, west Texas: The University of Texas at Austin, Master’s thesis, 199 p.

Read, J. F., 1985, Carbonate platform facies models: American Association of Petroleum Geologists Bulletin, v. 69, p. 1–21.

Ross, C. A., 1986, Paleozoic evolution of the southern margin of the Permian Basin: Geological Society of America Bulletin, v. 97, p. 536–544.

Wilde, G. L., 1995a, Recent observations on the Hueco and Bone Springs Formations, Sierra Diablo, with subsurface analogies, *in* Garber, R. A. and Lindsay, R. F., eds., Wolfcampian-Leonardian shelf margin facies of the Sierra Diablo—seismic scale models for subsurface exploration: West Texas Geological Society Publication, No. 95-97, p. 105–122.

Wilde, G. L., 1995b, Wolfcampian-Leonardian biostratigraphy, Sierra Diablo: its relationship to sequence stratigraphic markers on the surface and in the subsurface, *in* Garber, R. A. and Lindsay, R. F. eds., Wolfcampian-Leonardian shelf margin facies of the Sierra Diablo—Seismic scale models for subsurface exploration: West Texas Geological Society Publication, No. 95-97, p. 67–82.

Yang, K. and Dorobek, S. L., 1995, The Permian Basin of west Texas and New Mexico: tectonic history of a "composite" foreland basin and its effects on stratigraphic development, *in* Dorobek, S. L. and Ross, G. M., eds., Stratigraphic evolution of foreland basins: SEPM (Society for Sedimentary Geology) Special Publication No. 52, p. 149–174.

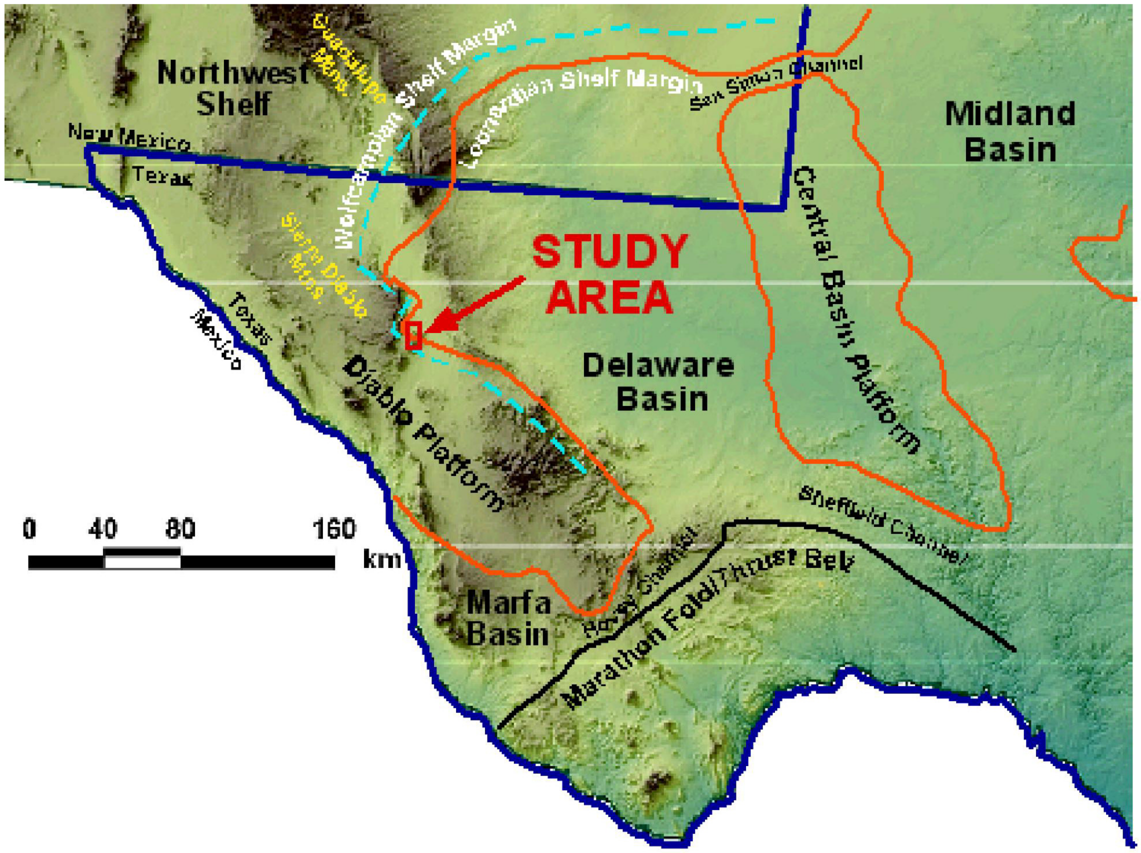

Figure 1. Digital elevation model of Permian Basin in west Texas and southeast New Mexico with outlines of major basins, platforms, structural features, and approximate Wolfcampian and late Guadalupian shelf margin trends.

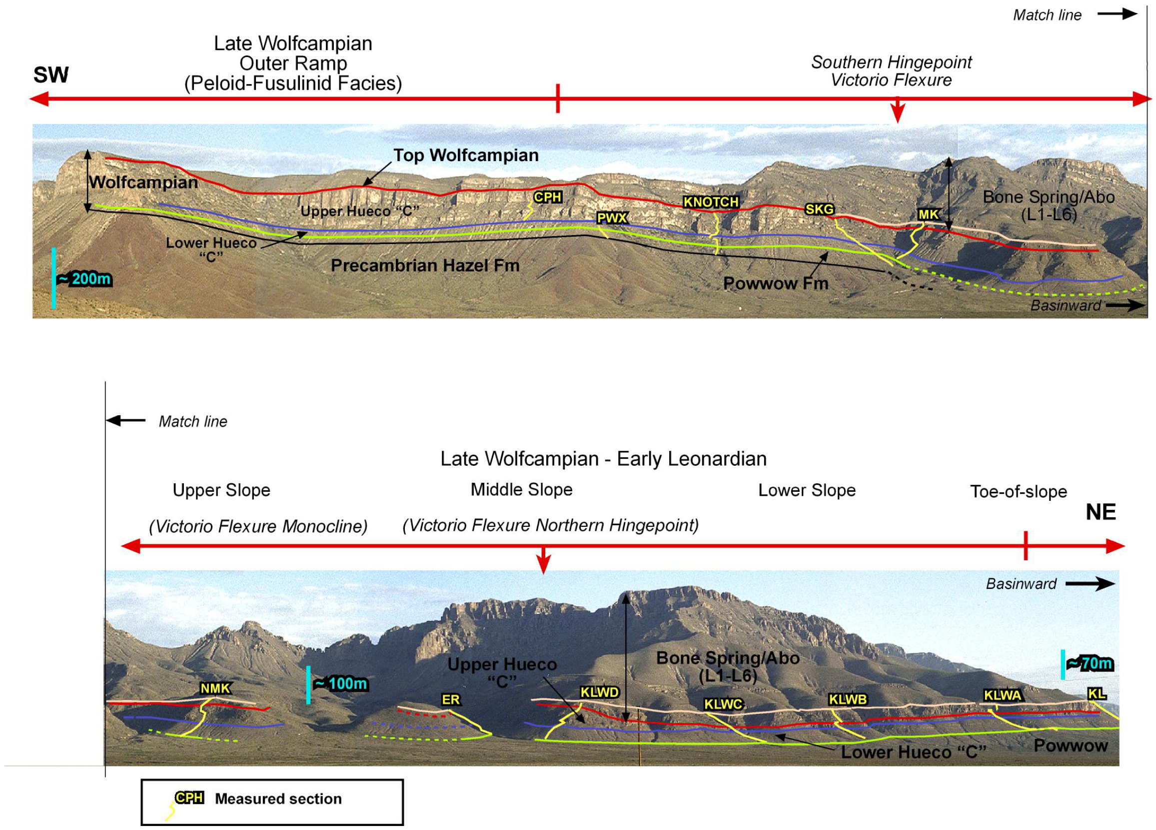

Figure 2. Regional photomosaic panel of study area looking westward along western Sierra Diablo escarpment, with interval break-out and measured section locations.

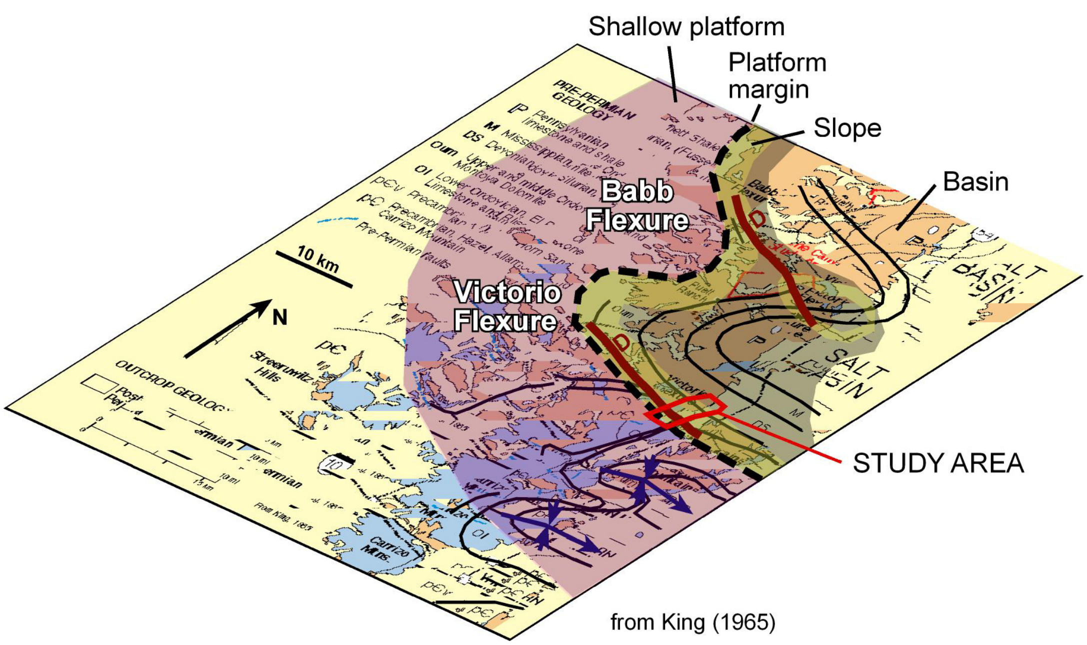

Figure 3. Late Wolfcampian paleogeography superimposed on King's (1965) geologic map of the Sierra Diablo Mountains, with flexures and study area highlighted. Large-scale subcrop synclines and shelf-margin embayments coincide with flexures.

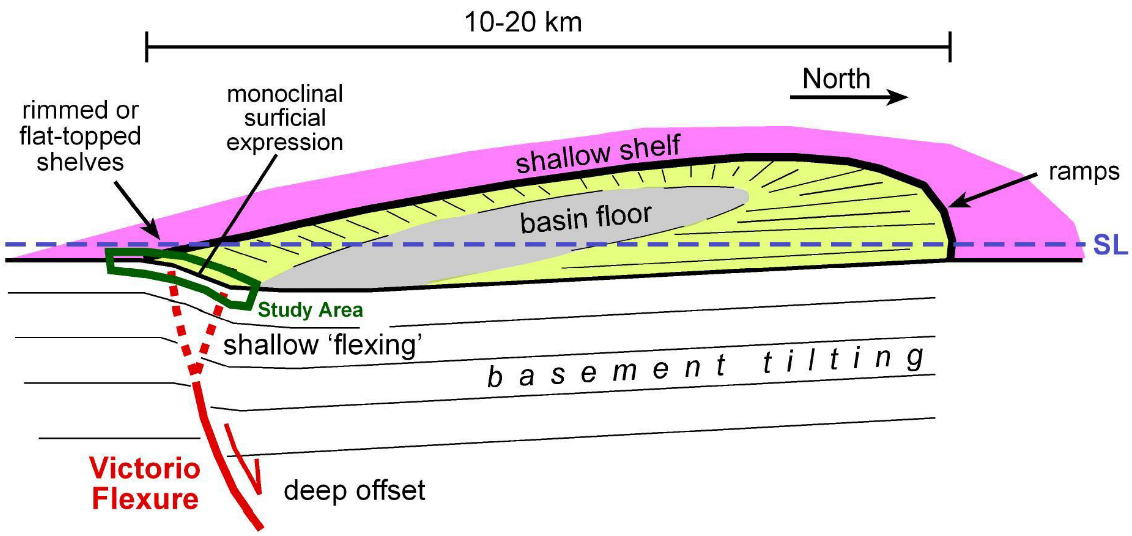

Figure 4. Hypothesized cross-sectional view of the Victorio Flexure showing the deep-rooted half-graben feature expressed as a monocline on the surface, with study area highlighted.

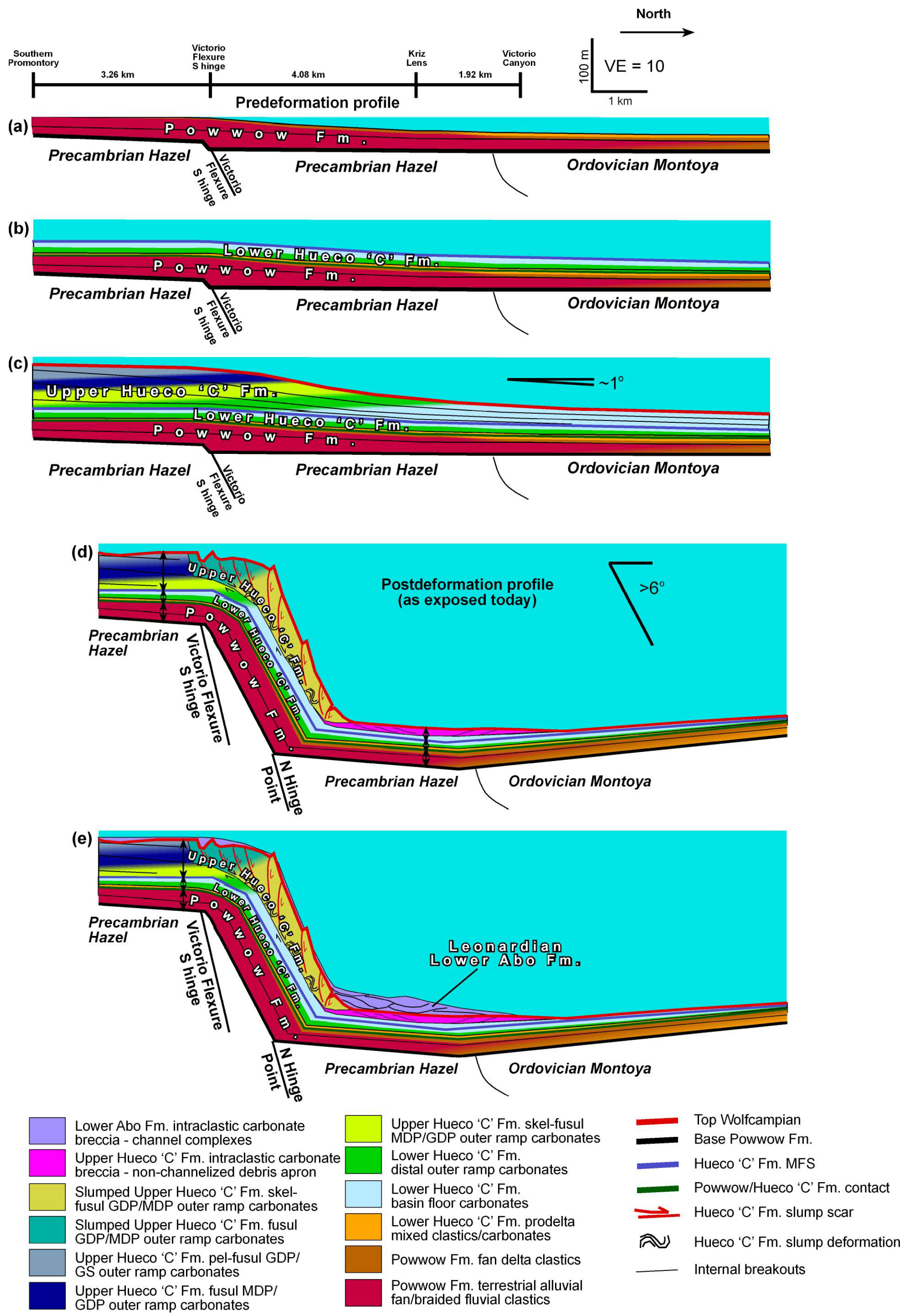

Figure 5. Sequential diagram of depositional and tectonic history of the study area, from mid-Wolfcampian to earliest Leonardian time, with relation to larger-scale ramp system. (a) Powwow terrestrial to shallow marine clastic deposition (mid- to late-Wolfcampian). (b) Lower Hueco 'C' distal outer-ramp to basin-floor carbonate blanket deposition (late Wolfcampian). (c) Upper Hueco 'C' prograding carbonate-ramp deposition (late Wolfcampian). (d) Tectonic rearrangement of slope profile along Victorio Flexure, causing failure of outer-ramp to basin-floor upper Hueco 'C' sediments (latest Wolfcampian). (e) Deposition of lower Abo carbonate debris-channel complexes, resulting from sediment focusing through reentrant topography at the southern hinge point of the Victorio Flexure (earliest Leonardian). Lower Abo debris bypassed the upper slope via a primary feeder channel and dispersed as channel complexes that ponded and amalgamated at the lower slope/toe of slope.

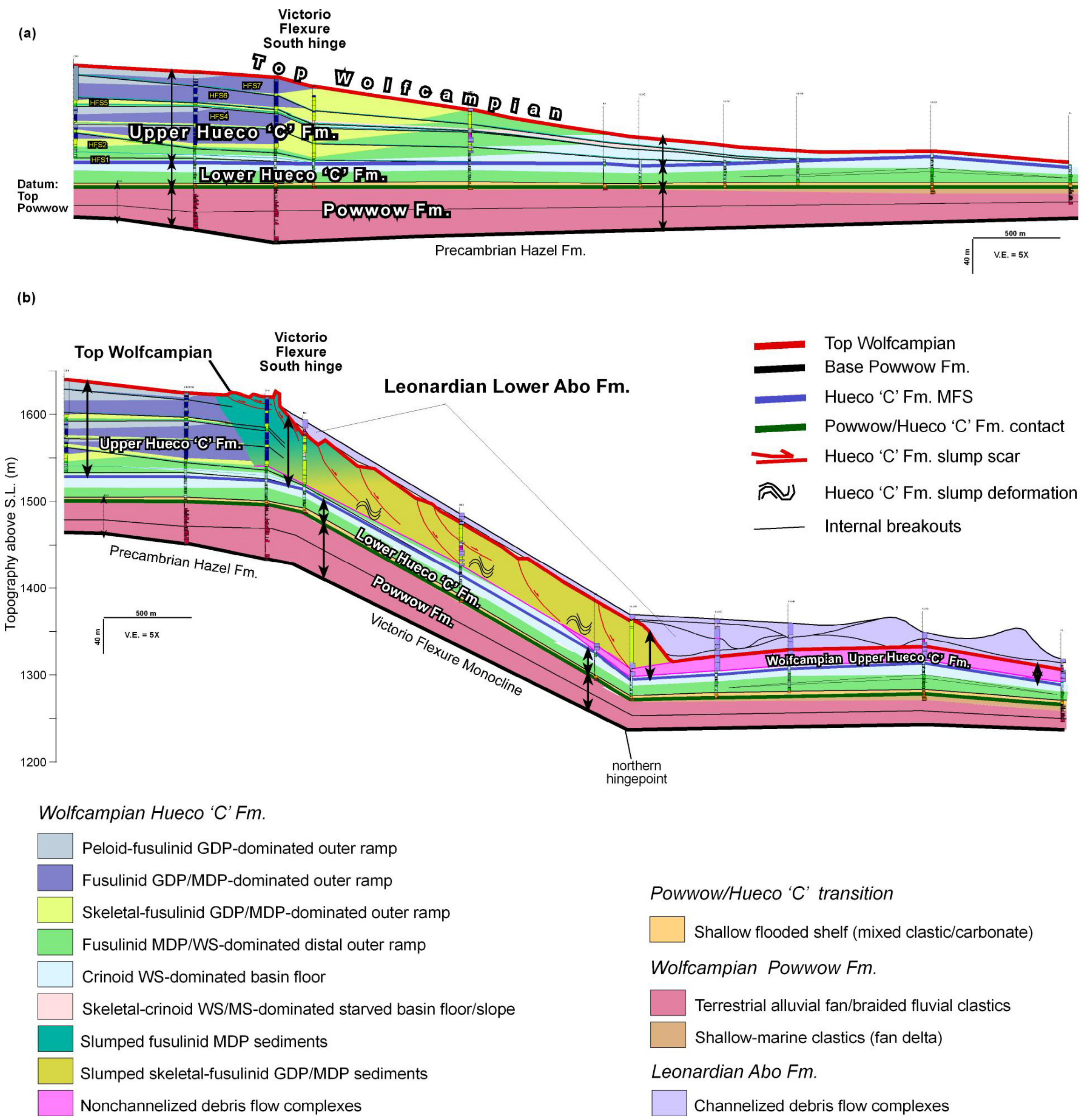

Figure 6. (a) Reconstructed regional cross section of distal part of a late Wolfcampian Hueco 'C' carbonate ramp based on measured section data. Cross section entails mid- to late-Wolfcampian deposition prior to tectonic deformation. Reconstruction was based on conformable facies and thickness relationships. (b) Postdeformation regional cross section as exposed today based on measured section data. Cross section is hung on present-day topography, assuming that exposed geometries are reflective of latest Wolfcampian/earliest Leonardian paleogeography that postdates Hueco 'C' development.

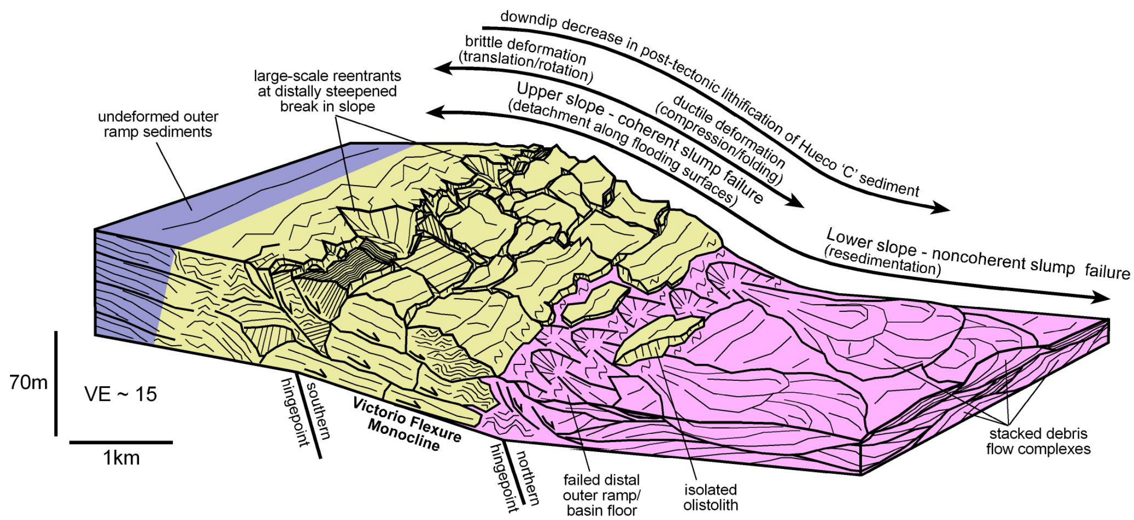

Figure 7. Sediment deformation diagram depicting response of Wolfcampian upper Hueco 'C' strata to latest Wolfcampian rotation along the Victorio Flexure. Coherent slump failure dominates the upper-slope setting, implying predeformation lithification of outer-ramp sediments. Noncoherent slump failure dominates the lower slope where relatively unlithified, muddier sediments completely disaggregated and resedimented as nonchannelized debris-flow lobe complexes that coalesced to form a lower-slope debris apron.

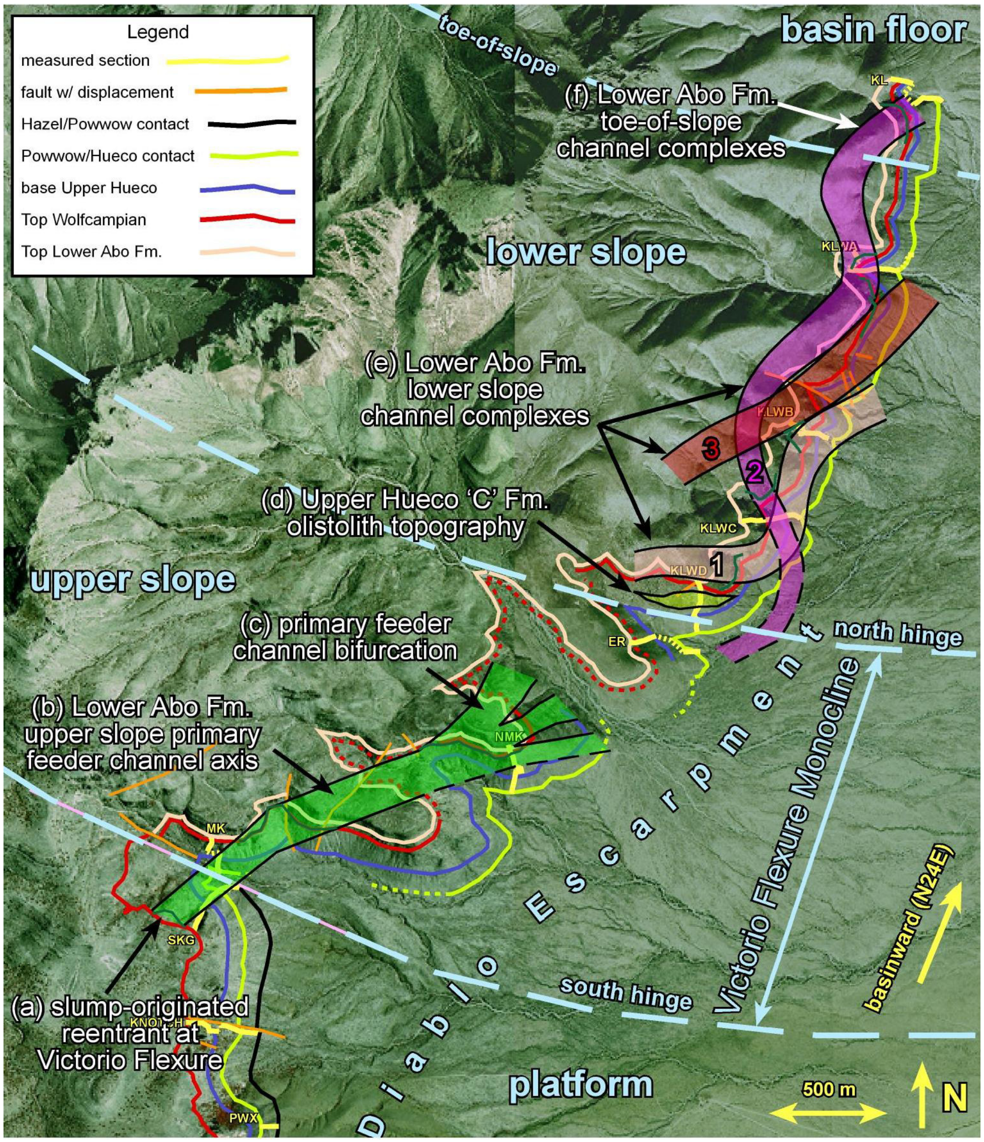

Figure 8. Plan view of lower Abo channel system, with latest Wolfcampian/early Leonardian paleogeography and depositional environments. From south to north, debris is concentrated in a primary feeder channel (b) resulting from sediment focusing through a large-scale reentrant at the southern hinge point of the Victorio Flexure (a). As distance from the updip focusing mechanism is increased and gradient is decreased, channel complexes begin to bifurcate from the primary feeder axis (c) and develop sinuosity. Channel complexes respond and offset relative to antecedent topography generated from the latest Wolfcampian slumping event, especially detached olistoliths at the northern hinge point of the Victorio Flexure (d). Channel complexes pond and erosionally amalgamate at the lower-slope position (e), coincident with the terminus of upper Hueco 'C' slump topography and the gradient decrease at the Victorio Flexure northern hinge-point inflection. As distance from the updip focusing mechanism becomes substantial and gradient continues to lessen, channel complexes become less incisive, more depositional, broader, mounded, and more isolated, marking the toe-of-slope position (f).

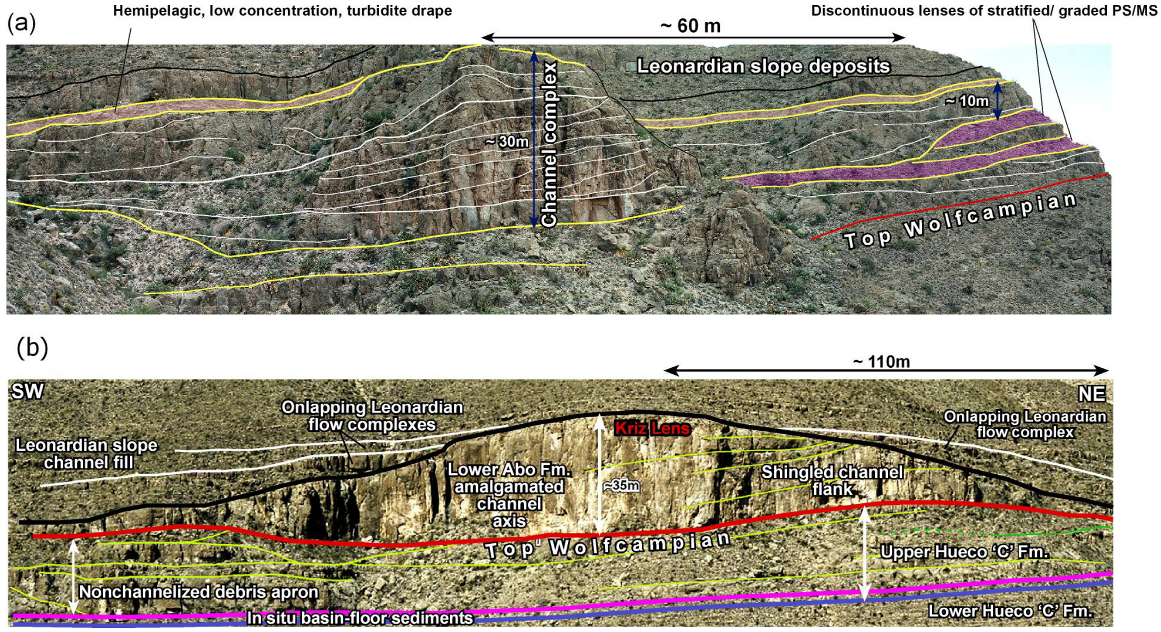

Figure 9. Outcrop photographs of Leonardian-Wolfcampian section. (a) Oblique strike view of lower Abo lower slope-channel complex. Lower slope-channel complexes exhibit higher degrees of incision narrower width and are flat topped relative to toe-of-slope channels. This geometry is due to higher erosion: deposition ratios at the lower-slope position. (b) Oblique strike view of the lower Abo, Kriz Lens, toe-of-slope channel complex. The Kriz Lens displays a mounded top (although erosionally enhanced), a relatively flat base, and it is broader, indicative of lesser erosion:deposition ratios common to the toe of slope.