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Seismic geomorphology of Palaeozoic collapse features in the Fort Worth Basin (USA)

E. C. SULLIVAN[1], K. J. MARFURT[1], C. BLUMENTRITT[1], & M. AMMERMAN[2]

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Abstract: Modern multi-trace geometric attributes produce three-dimensional volumes that can facilitate the recognition of karst geomorphology by avoiding the need to pre-interpret irregular horizons and by enhancing subseismic lateral variations in reflectivity. These geometric attributes include the well-established coherence technology, coupled with recent developments in spectrally limited estimates of volumetric curvature. Coherence measures lateral changes in waveform, and as such, is often sensitive to joints, small faults, sinkholes and collapse features. The many components of reflector curvature, including the most negative, most positive, Gaussian curvature and related shape indices (e.g. valleys, saddles, domes), are complimentary to coherence measures. Short wavelength estimates of curvature will illuminate small-scale lineaments while longer wavelength estimates of curvature illuminate more subtle flexures and compaction features. We show the results of applying a variety of multi-trace geometric attributes to a three-dimensional seismic volume from the Fort Worth Basin, where a collapse system extends vertically some 800m from the Ordovician Ellenburger carbonates through the dominantly siliciclastic Mississippian–Pennsylvanian interval. The collapse features in our data set appear as rounded, sinkhole-like appearances on time and horizon slices in the Pennsylvanian Marble Falls Limestones and the Ellenburger horizon displays features that can be interpreted as cockpit karst, dolines and frying pan valleys. Although a variety of palaeocave breccia facies in core and image logs indicate that the Ellenburger surface has been karsted, these breccias are not confined to the mega collapse features visible in seismic. The large (up to 700 m diameter) collapse chimneys can be shown in multi-spectral curvature attributes to have elongate rhombohedral shapes associated with intersections of Pennsylvanian age, field-scale to basin-scale, basement lineaments and faults. Isochores indicate greatest tectonic growth on faults from Mississippian until early Pennsylvanian, coincident with thickest fill of collapse features. Thus we interpret the origin of the chimneys to be primarily tectonic. The multi-trace geometric attributes permit better imaging of the three-dimensional shapes of the collapse features, provide better constraints on timing of their formation, allow us to begin to separate karst processes from tectonic processes and provide a means of predicting most likely locations of fluid movement along faults.

Collapse chimneys, visible in the Palaeozoic section of 3-D seismic from the northern Fort Worth Basin (Fig. 1), extend vertically some 800 m from the Ordovician Ellenburger Formation to the middle Pennsylvanian Caddo Limestone (Figs 2 and 3). Vertical collapse features in carbonates commonly compartmentalize reservoirs (Kerans 1990; Bagdan & Pemberton 2004), and in parts of the Fort Worth Basin, they have persisted as topographic features (Fig. 4), influencing the distribution and reservoir behaviour of Pennsylvanian sandstone reservoirs (Hardage *et al.* 1996*a*). Because collapse features can result from combinations of processes related to subaerial karst, subsurface cavern collapse, tectonic movement and hydrothermal brecciation and dissolution (Berger & Davies 1999; McClay & Boora 2001; Loucks *et al.* 2004; Sagan & Hart 2004), it is important to determine the relative contribution and sequence of each process. Multi-trace geometric attributes facilitate the recognition of collapse geomorphology and the processes of collapse formation by eliminating the need to accurately pick irregular horizons and by enhancing subseismic lateral variation in reflectivity. The objectives of this paper are to demonstrate the use of multi-trace seismic attributes to image collapse chimneys and geomorphologic surfaces, and to unravel the processes of formation of the vertically extensive collapse features in the Palaeozoic section of the northern Fort Worth Basin. We begin with a brief overview of the geometric attributes used in this paper, and the geologic setting of the study area. We then examine the geomorphology of the karst and collapse chimneys in the three-dimensional (3D) survey area by integrating our new attributes with conventional seismic displays. Finally, we use these new images to support our hypothesis that the formation of the collapse features is controlled more by tectonics than by subaerial karst or hydrothermal processes.

Multi-trace geometric attributes

Seismic attributes belong to three families: waveform, reflector shape, and amplitude (Marfurt 2006).

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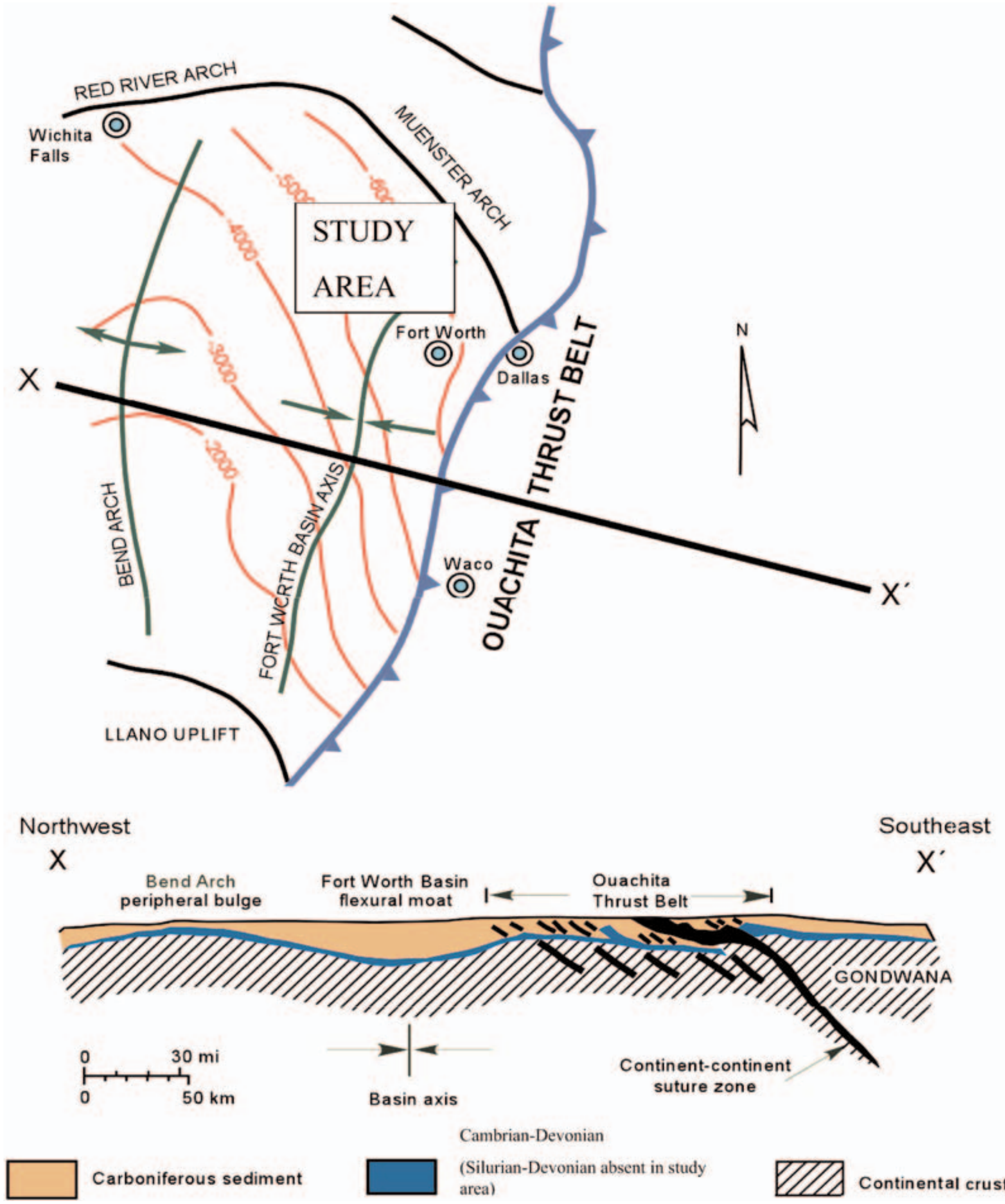

Fig. 1. The Fort Worth Basin formed as a foredeep to the Ouachita fold and thrust belt. Collapse chimneys in the Palaeozoic section are most pronounced in areas where erosion exposed the Ellenburger along peripheral bulges, prior to the deposition of upper Mississippian deepwater shales. The basin underwent compression and wrench faulting during the Pennsylvanian, followed by at least two periods of extension. Contours are structure on the Ellenburger (after Hardage *et al.* 1996*a*).

In this paper, we focus on waveform and reflector shape. Multi-trace geometric attributes exploit the mathematical relations between reflector events in time and spatial domains. These attributes, which include reflector curvature, coherence and reflector rotation, provide improved technology for imaging small-scale and subtle geologic features and for tracking changes in these features through time. Reflector curvature (Fig. 5) calculated from discrete interpreted horizons is well correlated to

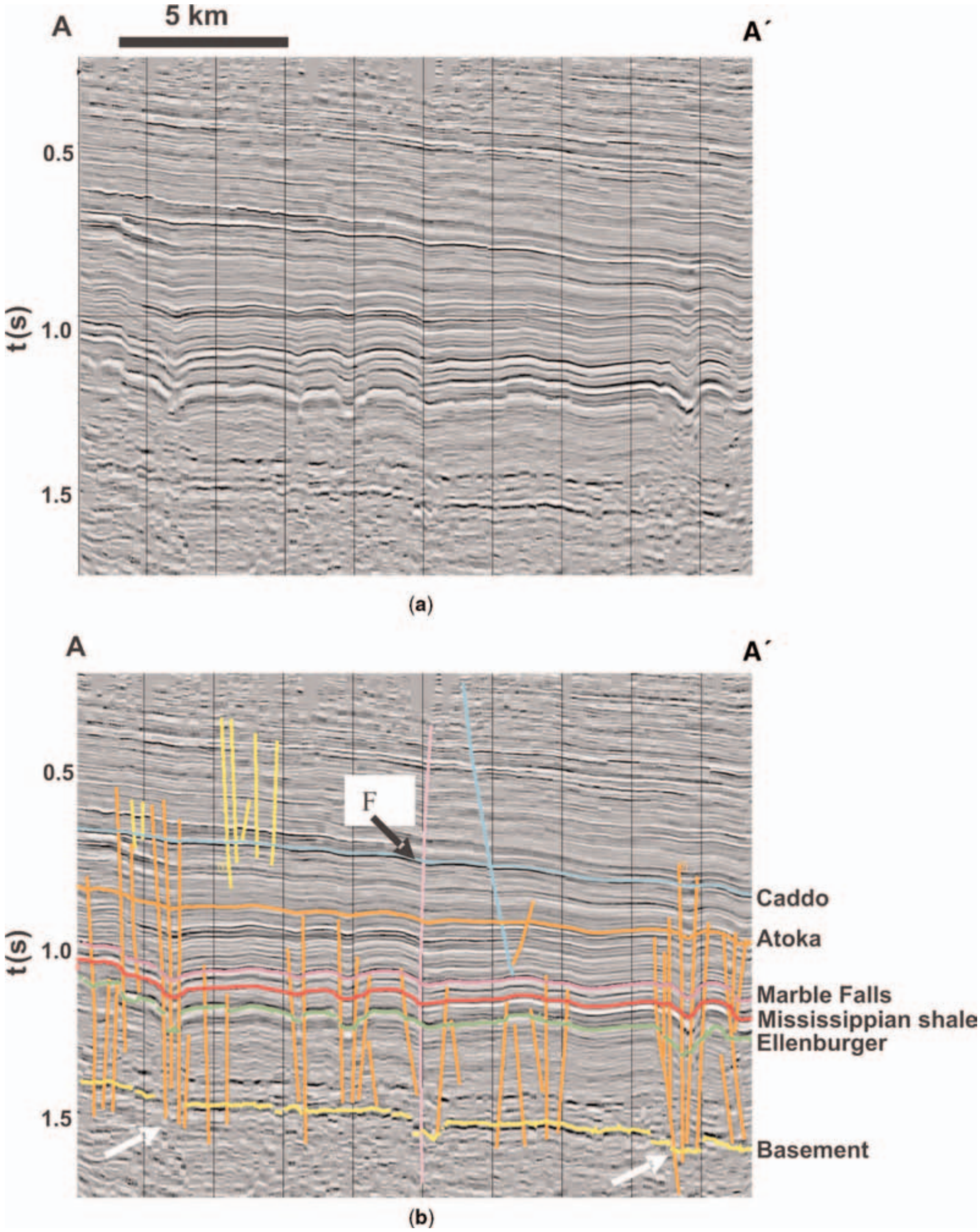

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Fig. 2. North–south line AA′ through the horizon extraction shown in Figure 3; (**a**) without and (**b**) with interpretation. The cyan is the Pennsylvanian Caddo limestone; the green horizon is the Lower Ordovician Ellenburger limestone. Orange faults penetrate the basement (white arrows); yellow faults are confined to strata above the basement. Vertically extensive collapse features indicated by white arrows can be tracked from the basement to post Caddo horizons, over some 800 m. Fault 'F' is well imaged in time slice and horizon extractions, and displays dip–slip and possible strike–slip motion.

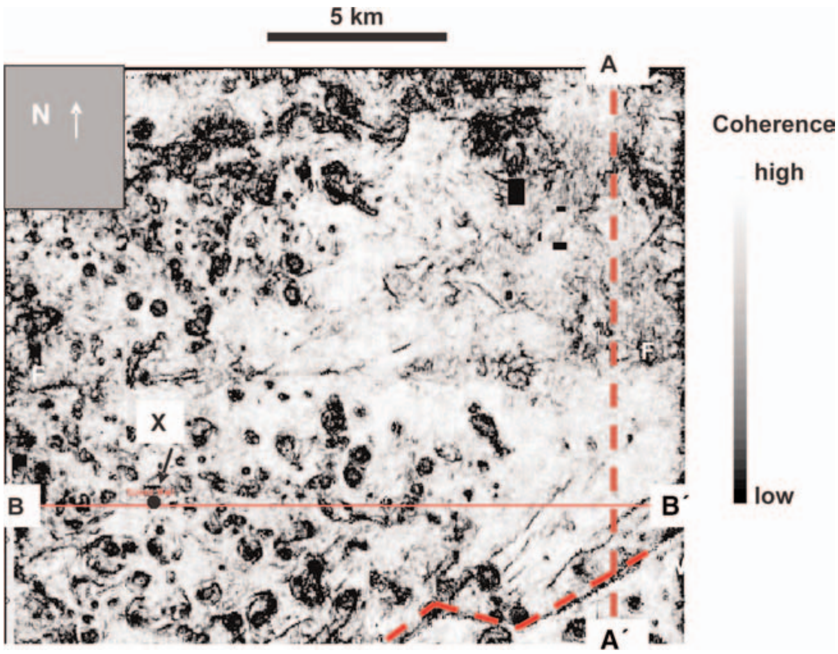

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Fig. 3. Coherence extraction along the Ellenburger horizon. Darker shades indicate less coherent or broken reflectors. The dark elongate and circular features are collapse chimneys, many of which extend vertically from the Precambrian crystalline basement to the Pennsylvanian interval. These collapse features tend to be aligned in conjugate NW–SE and SW–NE trends. A–A′ is the seismic cross-section shown in Figure 2; line B–B′ is shown in Figure 14. A regional wrench fault (W) is visible in the southeast corner, and the east–west lineament in the centre is the fault 'F' in Figure 2. Ellenburger core from Well X contains a variety of karst fabrics.

fracture intensity (Lisle 1994; Roberts 2001). We have expanded this curvature technology to volumetric applications and to prediction of azimuth of open fractures (Blumentritt *et al.* 2006), and to multi-spectral estimates of volumetric reflector curvature, which allow interpreters to view long (800 m) and short (30 m) wavelength geologic features (al-Dossary & Marfurt 2006). Coherence is a well-established technology that measures lateral changes in waveform and is sensitive to breaks in reflectors that include joints systems, small/faults and sinkholes. Components of reflector curvature, including the most negative, most positive, Gaussian curvature and related shape indices, are complimentary to coherence measures. Reflector rotation and combinations of coherence, curvature, dip and azimuth, can be used to show subtle components of wrenching along faults, which may localize fluid flow.

Geologic setting

The Fort Worth Basin developed during the Mississippian as a foreland basin westward of the advancing Ouachita fold and thrust belt, which is associated with oblique convergence of the Laurentian and South American plates (Walper 1982). The shallow water carbonates of the lower Ordovician Ellenburger Group were regionally exposed and karsted prior to the deposition of upper Ordovician Viola limestones (Kerans 1990; Franseen *et al.* 2003), and were subjected to a second generation of erosion and deep karstification during the Mississippian (Grayson & Merrill 1991; Montgomery *et al.* 2005) along the peripheral bulge of the developing Fort Worth Basin. Subsequent subsidence placed upper Mississippian organic-rich, deep-water shales in direct contact with the karsted Ellenburger (Fig. 6) over large areas of the Basin (Bowker 2003). The shallow water siliciclastics and carbonates of the Marble Falls and Atoka record accommodation-limited basin filling during the early to middle Pennsylvanian (Walper 1982; Grayson & Merrill 1991; Hardage *et al.* 1996*b*).

Continental collision and continued westward advance of the Ouachita fold-trust belt resulted in late Pennsylvania–early Permian structural inversion and erosion of part of the Pennsylvanian basin fill (Ball & Perry 1996; Pollastro *et al.* 2003). Structures formed during this time indicate both compression

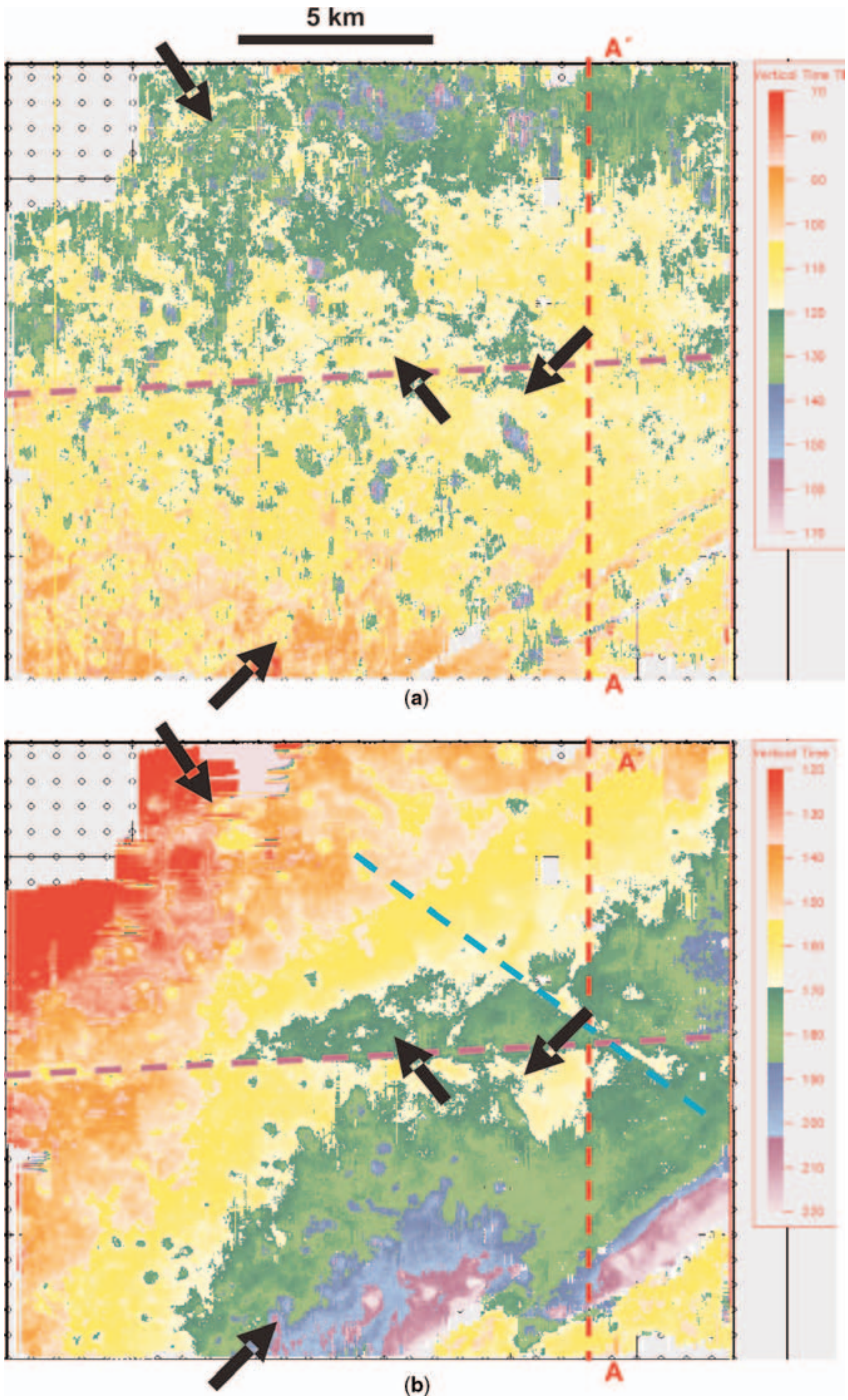

Fig. 4. Isochores between (**a**) the Ellenburger and Marble Falls horizons and (**b**) Marble Falls and Atoka horizons. Hot colours indicate thins, cool colours indicate thicker time intervals. Arrows show collapse features. Note differential thickness reflecting fault activation, and continued chimney collapse after Marble Falls deposition. Line AA′ corresponds to the vertical section in Figure 2 (after Sullivan *et al.* 2006).

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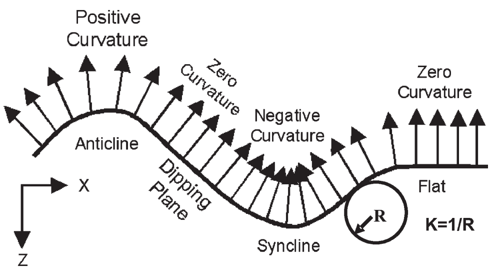

Fig. 5. Curvature of a two dimensional surface. Curvature (K) is the inverse of the radius (R) of a circle that is tangent to the surface at any point. By convention, positive curvature is convex and negative curvature is concave; flat surfaces and uniformly dipping surfaces have zero curvature (after Roberts 2001; Blumentritt *et al.* 2006).

and basin scale wrenching (Montgomery *et al.* 2005). The Palaeozoic rocks of the Ft Worth Basin were overprinted by late extensional tectonics related to the Mesozoic opening of the Gulf of Mexico and to Miocene uplift and formation of the down-to-the coast Balcones and Mexia/Talco fault systems (Hoskins 1982). Evidence for hydrothermal and basinal scale fluid flow associated with these tectonic events is recorded in cements in cores and outcrops (Kupecz & Land 1991; Montgomery *et al.* 2005). Ellenburger carbonate breccias exposed at the southern margin of the Fort Worth Basin contain baroque dolomite precipitated from high-temperature fluids during the Pennsylvanian and from warm-water fluids during the Cretaceous (Loucks *et al.* 2004).

The geomorphology of karst terrains may contain distinct features such as sinkholes, cockpit landforms (Fig. 7) and round-ended 'frying pan' valleys (Cansler & Carr 2001). Cave and potential collapse systems most commonly develop at or above water tables, generally within the upper 100 m of an exposed carbonate surface (Kerans 1990). Most of the buried Ellenburger cave systems of West Texas collapsed prior to the end of the Ordovician, as evidenced by the age of their fill. The associated cave fill deposits contain Ellenburger breccias and stratified deposits of transgressive upper Ordovician sandstones that regionally overlie the Ellenburger in West Texas (Fig. 8). Irregular Ellenburger topography is often completely filled by the first 20–50 m of transgressive deposition (Kerans 1990). In contrast, the collapse chimneys in the Fort Worth Basin persist through about 800 m of section (Hardage *et al.* 1996*a*, and this study).

The collapse chimneys in the Fort Worth Basin may record a complex history, similar to the history interpreted by Lucia (1996) for outcrops at the

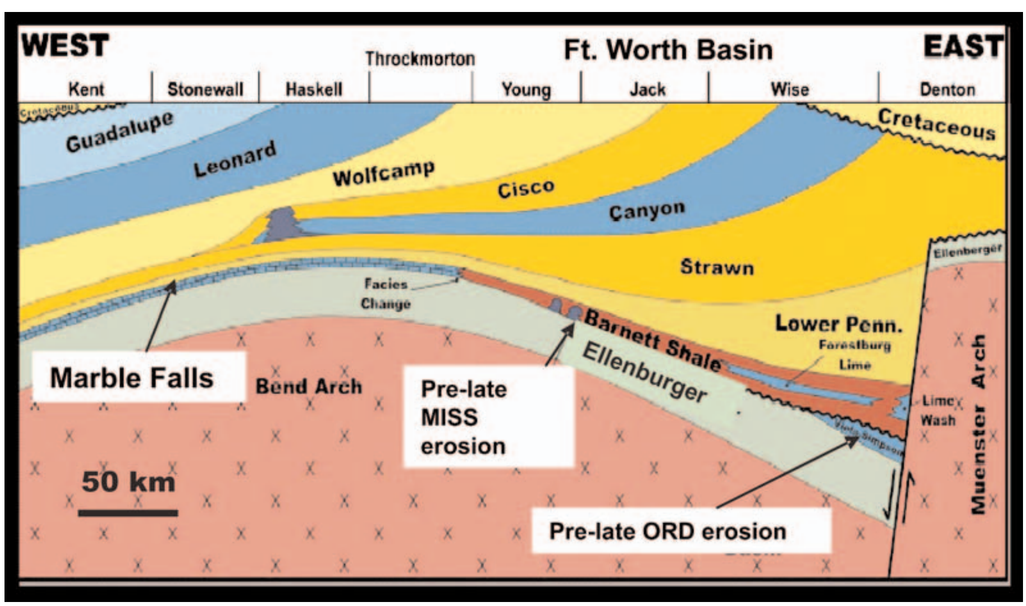

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Fig. 6. Schematic west–east cross section across the northern Fort Worth Basin, with relation of a migrating peripheral bulge to erosion of the Ordovician carbonates. Mississippian erosion along the bulge stripped the upper Ordovician Viola and exposed the Ellenburger to a second time of subaerial karst processes. Subsequent subsidence and deposition placed upper Mississippian deepwater shales in direct contact with the karsted Ellenburger over large parts of the basin (after Pollastro *et al.* 2003).

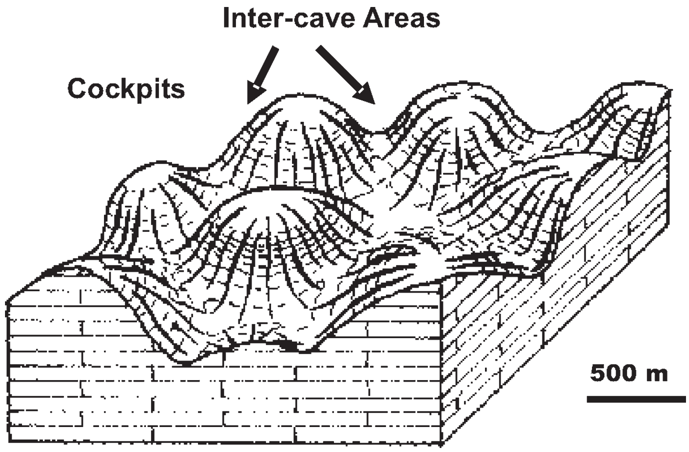

Fig. 7. Mature 'cockpit' karst geomorphology results from a combination of dissolution and preburial collapse of cave systems. In this process, well cemented, low porosity inter-cave areas persist as rounded knolls and hills (after Cansler & Carr 2001).

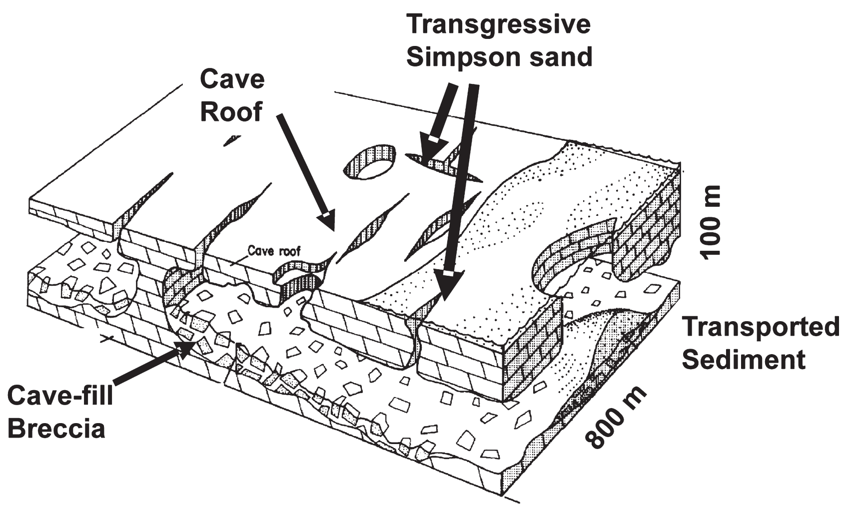

Fig. 8. Karst features associated with subaerial weathering and erosion of West Texas Ellenburger carbonates. These palaeocave systems most commonly fill with collapse breccias and sediments associated with subsequent marine transgressions (after Kerans 1990).

McKelligon Sag outcrop, near El Paso, Texas (Fig. 9). These outcrops record a vertical collapse system of 760 m that includes collapse of individual Ordovician, Silurian and Devonian cave systems over a period of 100 my. Here again, once collapse ended, the surface topography quickly healed with about 16 m of additional sediment deposition. Outcrops of Ellenburger limestones immediately south of the Fort Worth Basin in the Llano uplift also record coalesced palaeocave systems (Loucks *et al.* 2004). These collapse systems contain Devonian and Mississippian conodonts but do not contain evidence of extensive vertical chimneys. Unlike the McKelligon outcrops, carbonates overlying the Ellenburger in the Llano uplift (the Marble Falls) do not display pronounced palaeokarst surfaces or vertically extensive collapse chimneys (Kier 1980; Loucks *et al.* 2004).

Methodology

The conventional P-wave seismic surveys used in this study were acquired and processed by a petroleum company through a standard commercial

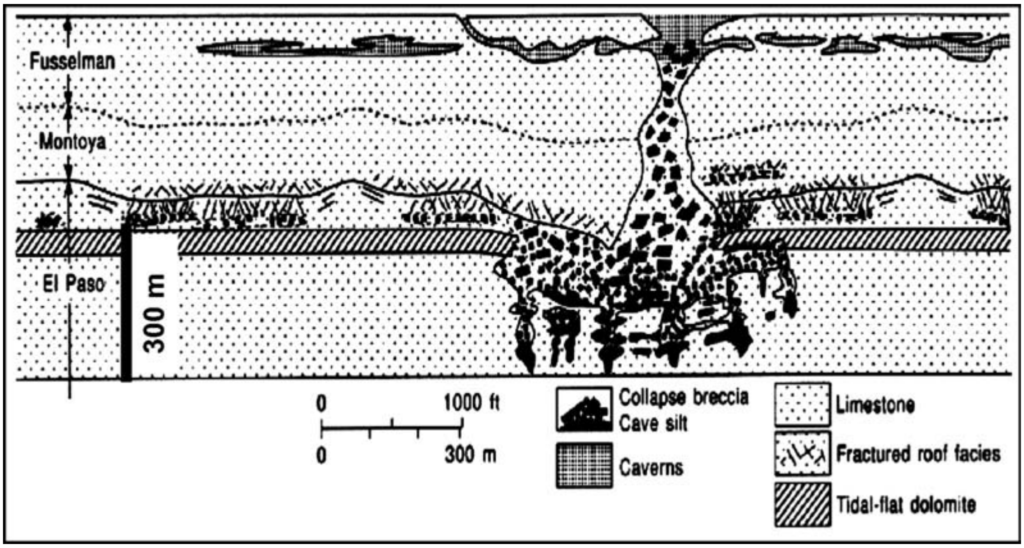

Fig. 9. Diagrammatic view of the complex lower Palaeozoic collapse structure at McKelligon Sag, near El Paso in West Texas. Fossils and field evidence indicate this feature formed from the collapse of individual Ordovician, Silurian and Devonian cave systems over some 100 million years (after Hardage *et al.* 1996, based on Lucia 1996). Kupecz and Land (1991) state that isotopes in the associated baroque dolomite cements indicate a minor Pennsylvanian hydrothermal overprint. **Q10**

workflow. We applied edge-preserving principal component filtering (al Dossary *et al.* 2002; al Dossary & Marfurt 2003) to the post stack data volume (Fig. 2). This filtering, which suppresses random noise and sharpens event terminations, has minimal impact on waveform and amplitude. Next we generated a coherence volume and a suite of geometric seismic attribute volumes, along with more conventional single trace attributes. For these multi-trace coherence and dip/azimuth attribute volumes, we used nine overlapping 9-traces, and a vertical analysis window of ±10 ms. To calculate the multispectral curvature and rotation volumes, we used circular analysis windows between 13 traces (for short wavelength calculations) and 78 traces (for long wavelength calculations). We found the long wavelength most positive and most negative curvatures, and the principal component estimate of coherence to be especially useful in our interpretation of faults fractures and karst features.

Data analysis

In Figure 2 we observe that collapse features extend from within the Precambrian metamorphic basement (yellow) through the Ordovician Ellenburger (green), early Pennsylvanian Marble Falls (magenta) and middle Pennsylvanian Caddo limestone (cyan). Productive sandstones within the Atoka and lower Caddo are localized and compartmentalized by these features. We indicate faults that penetrate the deeper part of the section in orange and those that are limited to the shallower section in yellow, and note that most of the faulting does not continue higher than the top of the Caddo. The magenta fault (F) is a persistent feature that displays minor dip slip and possibly strike–slip motion.

The geomorphology of the Ellenburger surface, displayed in Figure 3 as a horizon extraction through the coherence volume, is dominated by elongate and circular depressions, but it is not obvious which features are due to subaerial karst processes and which ones are caused by tectonic collapse. Curvilinear features in the northeast quadrant may be remnants of palaeodrainage. The collapse features tend to be aligned in conjugate NW–SE and SW–NE trends. A regional wrench fault crosses the southeast corner of the map, and the east–west magenta lineament is the fault ‘F’ in Figure 2.

The time isochore map between the Ellenburger and Marble Falls (Fig. 4a) indicates a gentle increase in thickness to the north and pronounced local thickening in some of the collapse features. In contrast, the time isochore for the Marble Falls–Atoka interval (Fig. 4b) shows dramatic thickening to the north of the magenta fault and along the fault in the southeast corner of the map, and thickening along NW and SE lineaments, indicating increased tectonic activity and growth of faults.

The mean curvature attribute, extracted along the top of the Caddo Limestone (Fig. 10) presents a detailed view of a surface affected by minor erosion and by compaction. The most striking feature is the hummocky topography related to compaction over the collapse features; only a few sinkhole shapes appear to actually break the Caddo surface (white arrow). Post Caddo movement along the east–west fault is obvious, overprinted by even later conjugate NW–SE lineaments. A very linear channel incises the Caddo surface in the northwest quadrant, and highly sinuous channels are present in the southeast. The wrinkled surface appearance in the southeast is due to compaction over slump features in the underlying Atoka siliciclastics.

A time slice through the same Mean Curvature attribute volume near the top of the Ellenburger shows the striking vertical extent and shape retention of the three collapse chimneys (white arrow). Features in the extreme western and southern part of the survey resemble cockpit topography of mature karst landscape. Although the composite feature at C is similar to a ‘frying pan’ karst valley, these features align, in fact, with a lineament that cuts the Caddo surface.

While coherence horizon extractions are particularly valuable for mapping smooth stratigraphic features, we find time slices often provide a less biased view of irregular or rugose surfaces. A time slice through the coherence volume near the top of the Marble Falls (Fig. 11) shows a complex system of lineaments and collapse features. There is no record of extensive subaerial karst of the Marble Falls, either in outcrop or subsurface, and many of the collapse chimneys align with those in the Ellenburger in Figure 10(b). A time slice at the same level through a multi-attribute volume that combines coherence, dip and azimuth provides insight into rotation along lineaments and faults that might be conduits for fluids. Here we see evidence of north dip along the central fault, possible rotation along the active wrench fault in the southeast, and two directions (NW–SE and NE–SW) of long wavelength, subtle folds.

We use the criteria of Loucks *et al.* (2004) to identify palaeocave facies (Fig. 12) in core and image log from an Ellenburger well, located on the seismic line in Figure 13. Note that the well is not located in one of the large collapse features. The image log (Fig. 15) reveals over 50 m of fabric and textures indicative of palaeocave facies related to subaerial karst processes, and reveals no indications of pervasive hydrothermal overprint.

To better understand the collapse patterns and their expression in the curvature attributes, we display a folded multi-attribute display (Fig. 16) through the filtered vertical seismic cube corresponding to line AA′ in Figure 12, coupled with a time slice at $t = 1.2$ s, through the most negative (Fig. 16a) and most positive curvature (Fig. 16b) attribute volumes. It is important to remember that while the value of the most negative curvature is always less than the value of the (orthogonal) most positive curvature at any analysis point, both attributes can have negative values (describing a bowl shape) and both attributes can have positive values (describing a dome). Careful examination of Figure 16 confirms this relation. Features that are domes will have a positive value of negative curvature and will show up as red in Figure 16(a). Collapse features have a negative value of positive curvature and show up as green in Figure 16(b). We note in Figure 16 that our collapse features are often linked together, suggestive of cockpit karst and karst collapse features described in Figures 7 and 8. While we expect there is a subaerial karst component to the polygonal features observed in the seismic data, some of the collapse features extend into the Precambrian metamorphic basement, where karst processes cannot operate.

Finally, in Figure 17, we compare the most negative curvature time slices for the Caddo, Marble Falls, Ellenburger and Basement. We clearly image the central fault and a complex system of NW–SE and NE–SW conjugate faults and joints. Many of the collapse features have elongate rhombohedral shapes, some of which are associated with intersections of lineaments that cut the Pennsylvanian interval. Lineaments in curvature volumes are amenable to quantitative analysis, and we note a marked change in the distribution of these lineaments with age, which we show as rose diagrams. While the collapse features are pronounced from basement to just below the Caddo horizon, the tectonic stresses have changed direction over geologic time.

Discussion

The horizontal expression of the vertical collapse features in the Fort Worth data is readily seen on conventional seismic and on isochore maps (Fig. 4), but the relation to faulting is more clearly presented in time slices and horizon extractions through coherence and curvature attribute volumes. We note that the collapse features are intense in the Marble Falls and Ellenburger intervals and cut into the Precambrian crystalline basement in some areas, but are greatly subdued at the Caddo Limestone level. The Caddo horizon (Fig. 10a) shows few active collapse features and only minor erosive features, implying that the hummocky Caddo topography is due to compaction over the collapse features, or due to dissolution from below, rather than to top-down, subaerial karst of the Caddo limestone. Isochrons between the Ellenburger and

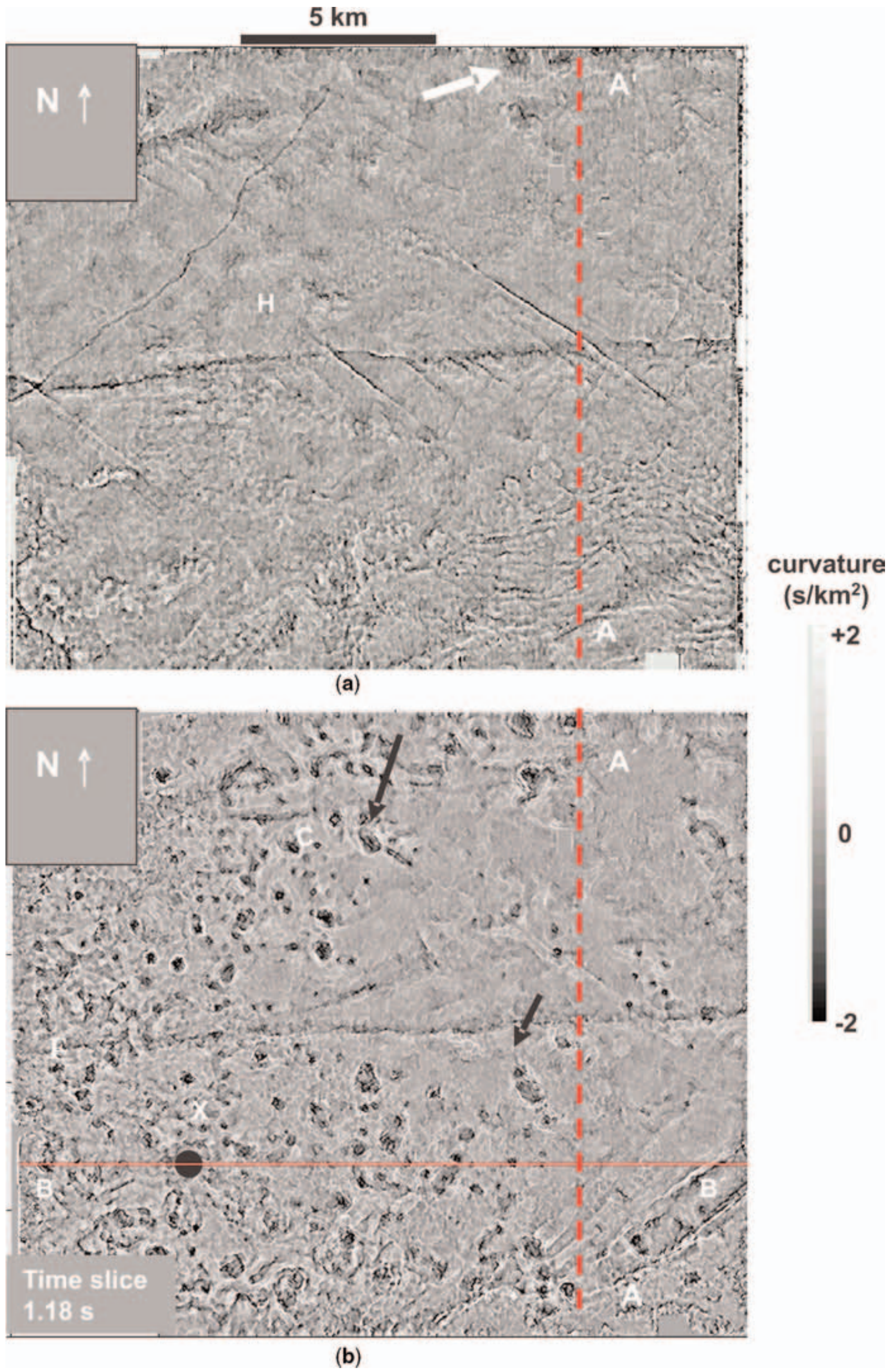

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Fig. 10. Mean curvature extracted along the Caddo Horizon (**a**), and on a time slice (**b**) at 1.180 s, near the top of the Ellenburger. Note persistence of collapse chimneys (black arrows) from the Ellenburger to the middle Pennsylvanian Caddo. The hummocky geomorphology (H) of the Caddo is due to compaction over these collapse features. Features in the western part of the Ellenburger time slice resemble cockpit topography of mature karst landscape. The arrow at C indicates a composite feature similar to a ‘frying pan’ karst valley. Cross Section A–A′ is shown in Figure 2; cross-section B–B′ is shown in Figure 14. A section of the resistivity-based image log from the Ellenburger at Well X (black dot) is shown in Figure 15.

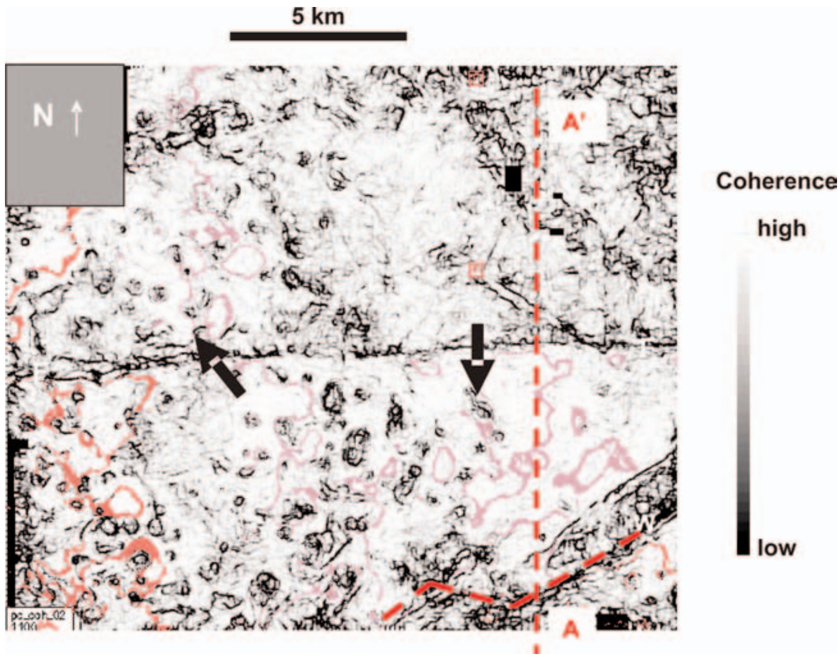

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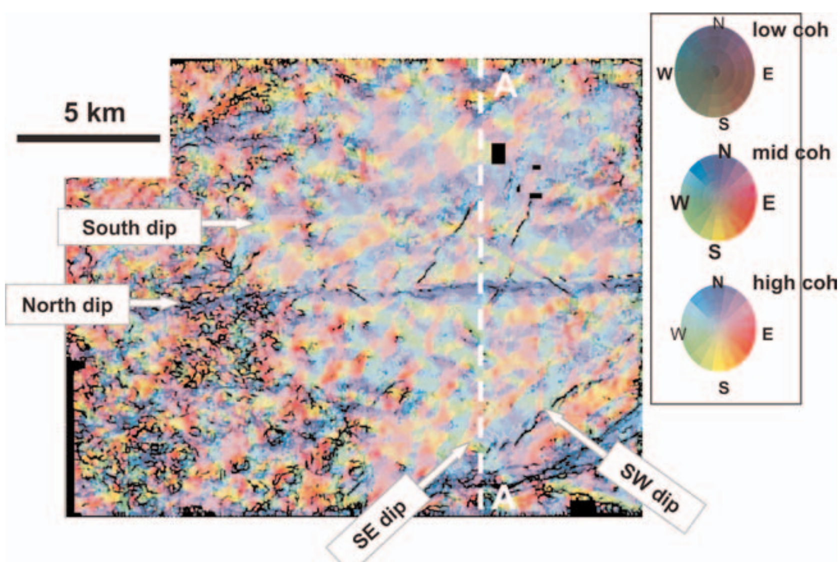
Fig. 11. Time slice through the coherence volume at 1.1 s, near the top of the Marble Falls, using a ±10 ms, nine-trace analysis window. Arrows indicate collapse features, organized along NW–SE and SW–NE trends. The Magenta colour is the top of Marble Falls horizon, red is the top of the underlying Mississippian shale. Note the east–west lineament in the centre of figure, marking a down-to-the-north fault (F) and lineaments in the SE that mark the regional wrench fault (W). Line A–A′ corresponds to the vertical section in Figure 2. Dark areas indicate lack of coherence.



Color

Fig. 12. Multi-attribute time slice combining coherence, dip and azimuth at 1.0 s, near the top of the Marble Falls. This combination of attributes clearly delineates the low coherence of the collapse features in the SW, the North dip along the fault crossing the centre of view, and broad wavelength folds and compaction features that have southeast and southwest dip. Cross section A–A′ is shown in Figure 2.

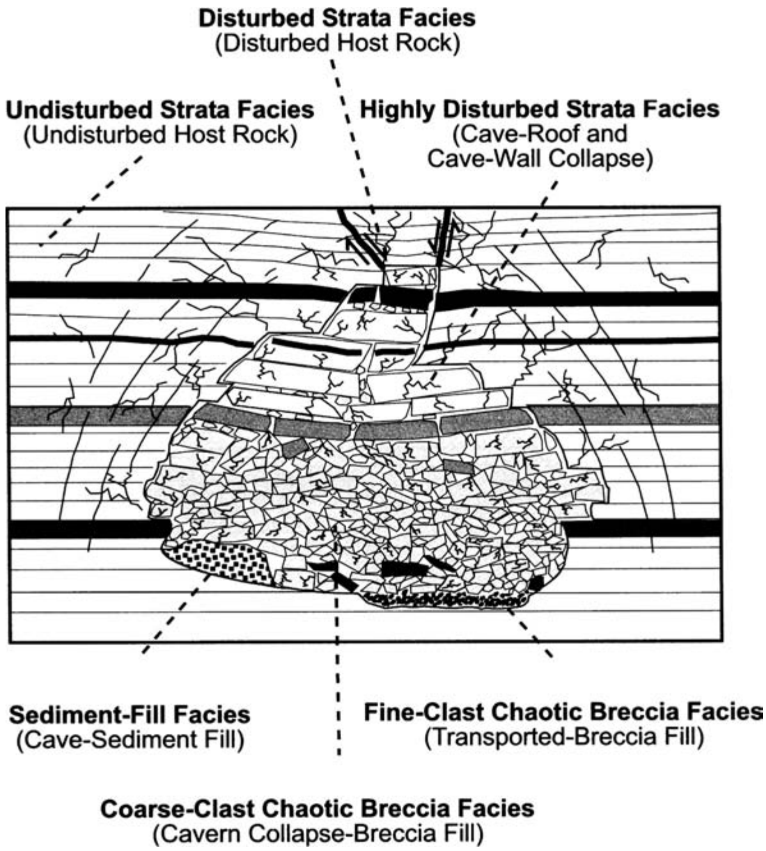
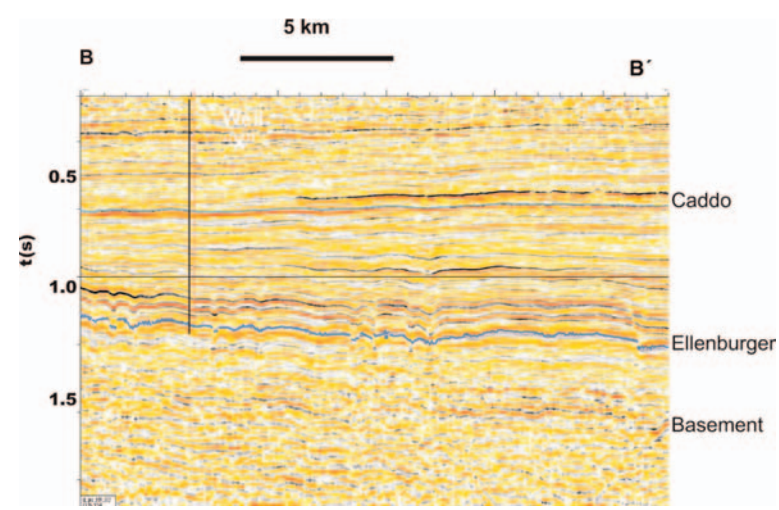
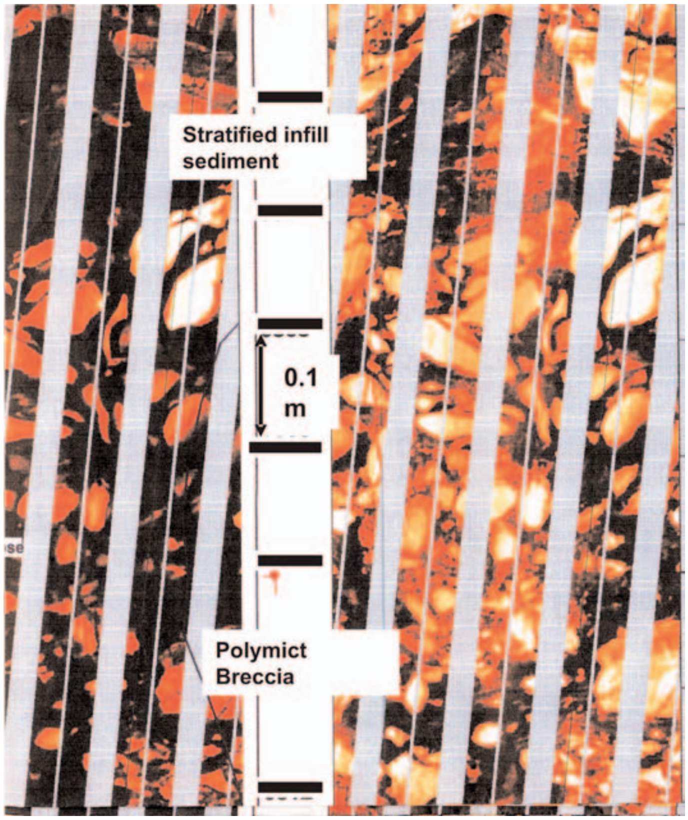


Fig. 13. Textures, sediments and cave facies associated with collapse and fill of palaeocave systems (after Loucks *et al.* 2004). Examples of these cave facies are present in core and image log (Fig. 15) from well 'X' shown in Figure 14.



Color

Fig. 14. East–West line B–B′ through the time slice shown in Figure 10(**b**). Core and image logs (Fig. 15) from the Ellenburger interval of well 'X' display over 50 m of breccias that we interpret as palaeocave facies.



Color

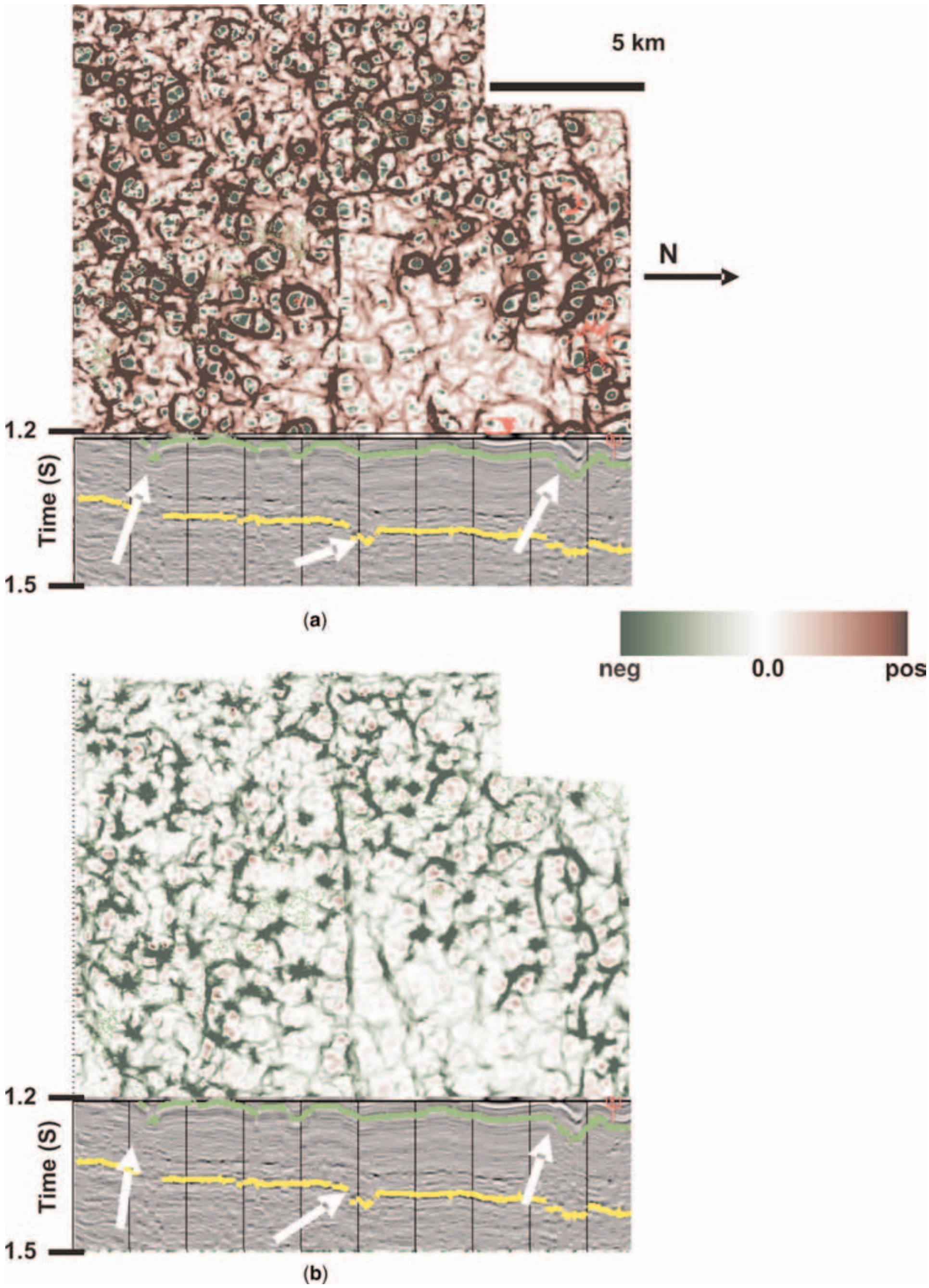
Fig. 15. Image log from the upper part of the Ellenburger interval in Well X, with rotated and rounded clasts (**a**) in a polymictic carbonate breccia, and (**b**) stratified sediment infill. We interpret these breccias, which extend over about 50 m, to be palaeocave deposits.

Marble Falls (Fig. 4a) and between the Marble Falls and Atoka (Fig. 4b) show greatest development of collapse features and fault growth between deposition of the Marble Falls and Atoka, although the wrench fault continued to be active until early Caddo deposition.

Inspection of other 3D surveys from the Fort Worth Basin indicates that regionally, collapse chimneys are larger and more common where the Ellenburger subcrops below the Mississippian than where it subcrops below the Upper Ordovician Viola Limestone. The Mississippian erosion of the Viola and Ellenburger is coincident with the formation of a foreland peripheral bulge, prior to the deposition of Mississippian marine shales. Textures and fabrics diagnostic of palaeocave facies are present in Ellenburger cores within the 3D survey, but the age of the karst is unknown at this time. The large (up to 700 m horizontal and 800 m vertical) collapse structures we observe do not appear to be compound coalescing cave systems that result from multiple subaerial karst episodes. Outcrop data indicate no prolonged subaerial exposure on the Marble Falls, and regional seismic data show no large-scale karst features on the Caddo limestone.

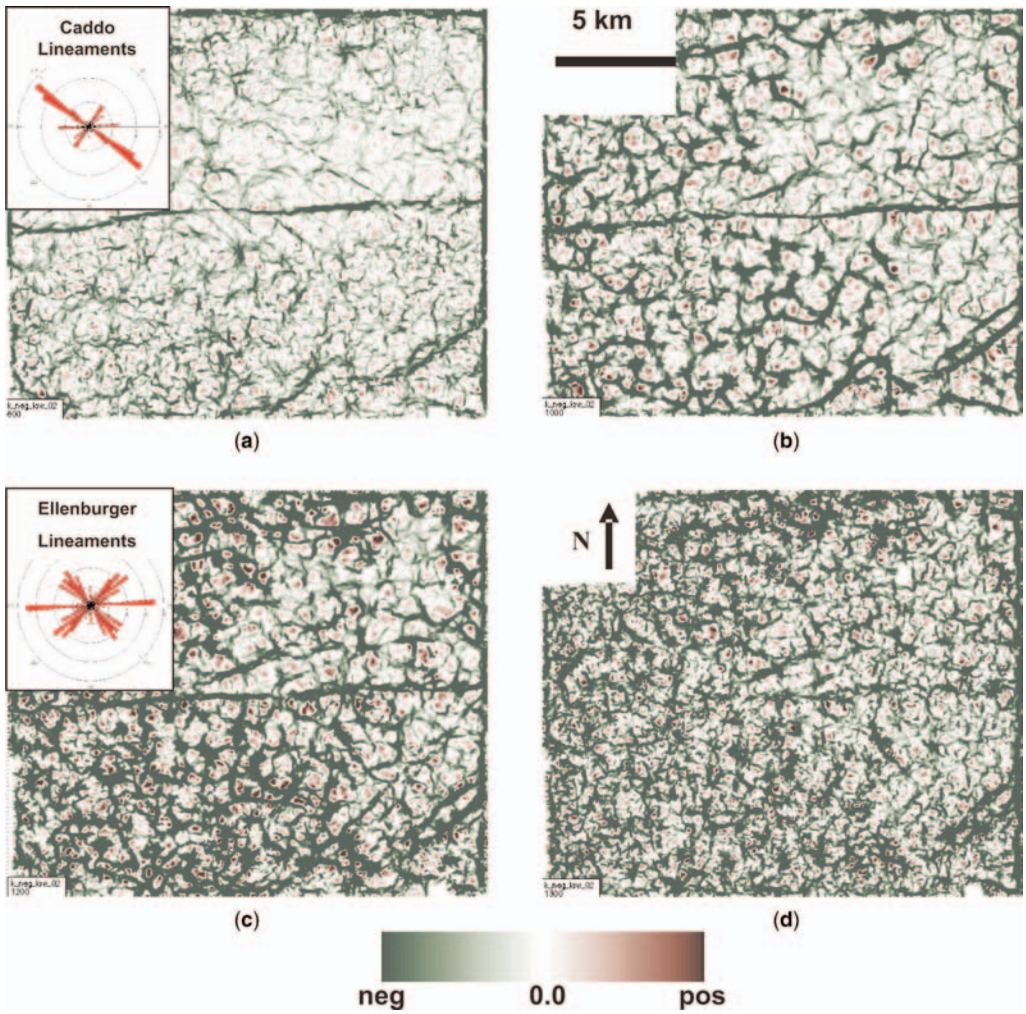
The role of hydrothermal brecciation and dissolution in the formation of the collapse chimneys is unquantified. Ellenburger breccias exposed at the southern margin of the basin contain baroque dolomites precipitated by high-temperature fluids during the Pennsylvanian and by warm-water fluids during the Cretaceous (Kupecz & Land 1991; Loucks *et al.* 2004). Native copper, dolomite and calcite are present in hairline fractures in cores of subsurface Mississippian shales but have not been dated (Montgomery *et al.* 2005). No large-scale hydrothermal fabrics have yet been reported from cores, and hydrothermal minerals are known only from fracture filling cements.

The alignment of Ellenburger collapse features with post-Caddo lineaments and joints, as revealed by our multi-trace attributes, suggests a relatively



Color

Fig. 16. Fold away multi-attribute images along line A–A′ shown in Figure 12. Seismic data is displayed on the vertical face. Long wavelength (**a**) most negative curvature and (**b**) most positive curvature are shown on the time slices at 1.2 s. Positive values (red) on the most negative curvature slice correspond to domes, while negative values (green) on the most positive curvature slice correspond to bowl shapes. The red horizon present in map view is the Mississippian shale. The white arrows mark places where the collapse extends through the non-carbonate, Precambrian crystalline basement (yellow). We interpret these collapse features to be tectonically controlled, linked by a complex system of faults and joints (after Sullivan *et al.* 2006).



Color

Fig. 17. Slices through the Most Negative Curvature volume at (**a**) near the top of the Caddo limestone, (**b**) within the upper Marble Falls limestone, (**c**) within the upper Ellenburger limestone, and (**d**) within the upper part of the Precambrian metamorphic basement. We used a long wavelength calculation with an analysis window of ±10 ms and 75 traces. The colour bar is identical to that used in Figure 16. Domes are red. Bowls and valleys are green. Time slices from the Marble Falls and Ellenburger show the formation of the collapse chimneys at the junction of intersecting lineaments. Lineament azimuths change between the Ellenburger and Caddo levels.

late reactivation of these features. Current maximum horizontal stress in the subsurface Mississippian strata near the study area is N40E (Siebrits *et al.* 2000). Within the study area, open joint systems in surface outcrops of Upper Pennsylvanian rocks are dominated by NNE and NNW sets, which Hoskins (1982) interprets as related to extension along the trans Texas Miocene-age, down-to-the-coast, Balcones fault system (although we speculate there is Mesozoic extension as well). Fractures formed or re-opened during these extensional events may have allowed hot or warm burial fluids to migrate along the collapse chimneys.

Conclusions

Multitrace geometric attributes provide improved imaging of the seismic geomorphology of collapse chimneys in Palaeozoic strata of the Ft Worth Basin, through better horizontal detection of subtle features and by eliminating the need to prepick irregular and rugose surfaces that are prone to operator error. Coherence based attributes detect lateral discontinuities down to one/tenth of a wavelength, and spectral curvature attributes permit separate analysis of short (30 m) to long wavelength (300 m) geomorphologic features. The combination of volumetric rotation attributes and coherence, curvature, and dip azimuth through the use of hue, light, and saturation highlights changes in dip along subtle faults and lineaments. This detection of stratal rotation along faults, combined with estimations of temporal change in stress/strain regime through attribute-based lineament analysis, hold the potential to predict probability of fluid migration pathways. The presence of subaerial karst in the Ellenburger is suggested by seismic geomorphology and supported by features in core and resistivity-based image logs of the upper Ellenburger over at least 50 m. However, we conclude that the largest collapse features are tectonically controlled for the following reasons: (1) many of the chimneys coincide with deep basement faults and with Pennsylvanian and younger lineaments; (2) no regional unconformity is associated with the observed collapse features in the lower Pennsylvanian Marble Falls limestone; and (3) horizon slices on the Middle Pennsylvanian Caddo Limestone lack exposure features of significant magnitude to produce top-down karst through 800 m of mostly siliciclastic section. Finally, the geometries of the collapse features suggest that they may be small tectonic pull-apart features at intersections of regional fault and fracture systems, perhaps similar to restraining stepovers described by McClay & Borora (2001).

The application of our new seismic attributes to 3D seismic volumes allows detection of normally subseismic features and demonstrates great potential for determining timing and nature of features that may be related to karst, tectonic or hydrothermal collapse and for improved mapping of reservoir bodies, permeability fairways and various surfaces associated with weathered and fractured carbonates.

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