Discovery of a Probable Meteorite Impact Site of Late Cambrian - Early Ordovician Age in the Permian Basin, Crockett County, Texas, and Its Implications for Hydrocarbon Exploration*

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Search and Discovery Article #10719 (2015)
Posted February 16, 2015

*Manuscript received January 27, 2015; manuscript accepted January 29, 2015.

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Abstract

Horizon mapping of a 3-D seismic survey has led to the discovery of a probable meteorite impact site of Late Cambrian – Early Ordovician age at a depth of about 9200 ft (2804 m) atop the Bouscaren uplift in northwest Crockett County, Texas. The impact site is an oval-shaped simple crater, elongated along a northeast-to-southwest axis 2150 ft x 1550 ft (1.32 km x 0.96 km), and about 450 ft (0.28 km) deep. The crater is located within a petroleum-rich basin on an uplift that is bound on the north side by large normal faults, and is capped by the Ellenburger Group of Early Ordovician age that is about 1300 ft (396 m) thick. No well has penetrated more than 350 ft (107 m) into the Ellenburger on the uplift, leaving the impact breccia associated with the meteor crater undrilled. Petroleum that migrated from one of the basin's premier source rocks (Simpson Group, Middle Ordovician age) likely migrated across a normal fault from the north and entered the shattered and brecciated rocks associated with the impact. Petroleum occurs immediately above the crater in the Ellenburger, as well as Strawn sandstones, indicating migrated oil has entered the Paleozoic rocks found on the structure. It is not often that a meteorite impact crater involving shattered basement rock and ejecta is positioned ideally for its petroleum potential, but the Bouscaren crater is a good candidate. Depth to the brecciated and fractured basement rock is very reasonable for the Permian Basin (9200 to 9700 ft; 2804 to 2956 m), suggesting that the Bouscaren impact crater can be tested at an acceptable cost.

Introduction

A 3-D seismic survey (63 sq. mi) was completed in far western Crockett County, Texas, in 2003 (Figure 1). Horizon mapping within this 3-D seismic survey has led to the discovery of a probable meteorite impact crater of Late Cambrian – Early Ordovician age at a depth of about 9200 ft atop the Bouscaren uplift that occupies the northwest portion of the 3-D survey. The impact site is an oval-shaped simple crater (Figure 2), elongated along a northeast-to-southwest axis 2150 ft x 1550 ft, and about 450 ft deep. The crater is similar in size and shape to the Barringer meteorite impact crater in Arizona (4000 ft wide, 600 ft deep) (Shoemaker and Keiffer, 1974: Grieve, 1990). Meteorite impact craters have been found in a multitude of sizes, geologic ages, and rock types in the past 50 years: some have produced oil and gas (Donofrio, 1997; French, 1998;Grieve, 1998; Mazur, et al, 1999).

General Stratigraphy

Figure 2 shows the general stratigraphy of the central Midland Basin. Due to a major unconformity located at the base of mid-Pennsylvanian, the Bouscaren uplift includes only rocks of Cambrian (?), Ordovician, Middle to Late Pennsylvanian, and Permian ages. Rocks missing by erosion on the Bouscaren uplift consist of the Morrow, Barnett, Mississippian, Woodford, Thirtyone formation (Devonian chert), Silurian, Fusselman, Montoya, and upper Simpson Group (Bromide, Tulip Creek, and McLish members). At the apex of the Bouscaren uplift the oldest subcrop below the mid-Pennsylvanian unconformity consists of Oil Creek Shale of Middle Ordovician age (Figure 1).

Crater Discovery

Discovery of the probable Bouscaren meteor crater started with mapping of a seismic horizon associated with the basement. The Cambrian horizon was selected by the persistent appearance of a weak seismic trough present at about 1.1 to 1.3 seconds in time depth, and found about 0.120 to 0.140 seconds below a strong positive seismic horizon that was associated with the top of the Ellenburger Group at about 8200 ft depth (Figure 3). It is likely that this seismic trough represents rocks of lower impedances, such as those found in Cambrian sandstone and granite wash. Mapping of the weak seismic trough on the workstation was aided by using black-white seismic color scale with a condensed horizontal scale. Figure 3 shows the common appearance of undisturbed Cambrian horizon that exhibits little local relief. Here the Ellenburger is about 130 ms in time-thickness, and assuming the formation velocity at about 20,700 ft/sec, its thickness is about 1346 ft. When a seismic line was selected where an unusual Cambrian feature was detected, the black-white display took on an unusual display (Figure 4). Following completion of Cambrian horizon mapping (Figure 5), the crater-shaped feature was recognized as a probable simple meteorite impact structure (Figure 6). Elongated along a northeast-to-southwest axis, its oval shape appears to be about 2150 ft long x 1550 ft wide and is about 450 ft deep. Additional horizon mapping immediately above the Cambrian confirmed the impact crater concept. Location of this probable meteor impact crater resulted in naming this feature 'Bouscaren.'

Figure 7 shows the seismic amplitude map of the positive seismic horizon immediately above the mapped Cambrian trough (Red horizon in Figure 4). This horizon appears to be related to meteorite impact breccia and ejecta. High seismic amplitudes outline the crater location (Red to Yellow). These high amplitude distributions suggest formation of a simple meteorite impact crater that contains significant volumes of fractured breccia distributed along its crater floor and rim, which are similar to circular magnetic anomalies often associated with impact craters (Hawke, 2003). The crater dips to the south, with the highest point of the crater rim located on its north side. Lower amplitudes (Blue to Green colors) found outside the rim are likely associated with ejecta. The seismic horizon associated with a trough above this seismic peak horizon (White horizon in Figure 4) shows a more subdued image of the crater and represents possibly an early phase of burial by strata associated with Lower Ellenburger Group of Early Ordovician age (Figure 8).

Figure 9 shows the time-depth map of the Oil Creek Shale seismic horizon, located about 190 feet above the Ellenburger (Figures 3 and 4) and about 1500 ft above the crater. Note that this seismic horizon exhibits little to no relief associated with the Bouscaren impact crater. Rocks that occur above the impact crater are composed primarily of carbonate-dominated Ellenburger, which is estimated to be between about 1300 feet in thickness. Several wells penetrate the Ellenburger on the Bouscaren uplift, but none was drilled any deeper than 350 feet into it. Wells drilled nearest the impact crater drilled no deeper than 206 feet into the Ellenburger.

Transgression of the Sauk Sea began in Late Cambrian time and extended into Early Ordovician when rising highstands marked the deposition of the Ellenburger. Near the end of Early Ordovician the Tippecanoe Sequence began during which a worldwide eustatic lowstand occurred, whose length of exposure covered several million years (Loucks, 2006). Throughout the United States an extensive karst terrain formed on the Ellenburger carbonates (Kerans, 1988, 1989, 1990). The standard section for the Ellenburger in West Texas is found in Loffland Brothers, Tubb #3, Sec. 9, Block B-27, Crane County, approximately 54 miles to the NW of Bouscaren uplift. Here the Ellenburger is about 1325 ft thick and is designated the type section of West Texas (Cole, 1942). Within a twenty-mile radius of the Bouscaren crater, there are only nine wells that have penetrated the entire thickness of the Ellenburger. Thickness values range from about 1500 to 920 feet. Low thickness values appear to be associated with sites on eroded fault-block uplifts. The Ellenburger is divided into Upper and Lower units. The Lower Ellenburger varies in thickness from 740 to 960 ft, wheas the Upper Ellenburger is highly variable in thickness, from 10 to 620 ft. The wide thickness variations of the Upper Ellenburger are due to karsting and erosion that occurred during the early stages of the Tippecanoe Sequence. The Ellenburger is fairly uniform in lithology, composed mostly of very finely crystalline cherty dolomite and some thin shale. Because of uniformity of lithology internal correlations within the Ellenburger have been difficult. However, rock correlation is often accomplished by insoluble residue data that are dominated by varieties of chert and shale (Cole, 1942, Barnes and Dixon, 1959). Insoluble residue horizons have been reported in proprietary reports issued by the Insoluble Residue Research Institute.

Cambrian rocks 13 to 20 miles south of the impact crater are composed of 180 to 240 ft of dolomite, sandstone and granite wash. Some 7.5 miles north of the crater, the Cambrian section is about 133 feet in thickness. It appears that some Cambrian rocks and granite wash were present on the Bouscaren block prior to the meteorite collision. The crater retains a sharp morphology, suggestive that it was buried quickly by rocks of the onlapping Sauk transgression of Late Cambrian - Early Ordovician age. An impact older than the Cambrian-Ordovician boundary could have been subject to a long period of erosion and would have lost its sharp morphological features before burial. These geologic observations suggest the age of impact occurred around the Cambrian-Ordovician boundary, which is dated at 488 Ma.

It is possible that the Bouscaren impact crater filled with shale prior to its burial during Early Ordovician time, similar to the Ames Crater, where capping shale within the crater were deposited under anoxic conditions and became a local petroleum source rock (Curtiss and Wavrek, 1995; Lindsay and Koskelin, 1993; Donofrio, 2007).

Petroleum System

The geologic setting of the Bouscaren meteorite crater provides significant petroleum potential. While the Bouscaren crater is small and lacks any central uplift that commonly accompanies larger impacts, it did form a potentially large reservoir of brecciated rock. Fracturing and brecciation of autochthonous basement rock and allochthonous breccias and ejecta can produce a good quality reservoir. While crystalline rocks are not normally considered a target for petroleum exploration, formation of shock deformation caused by impact would make a significant and productive reservoir if filled with hydrocarbons (Donofrio, 1981).

The meteorite crater found across the Bouscaren uplift is bordered on the north by one to two significant high-angle dip-slip faults that contain some strike-slip movement. The most important unconformity in the geologic column occurred between mid-Mississippian and mid-Pennsylvanian time. During this time petroleum trap development was closely associated with collisional-event-related faults that formed many faulted anticlines in Midland Basin, one of which was the Bouscaren uplift. Petroleum was discovered on the Bouscaren uplift in 1974. The principal hydrocarbon trap includes channel sandstones and pinchouts associated with basal Strawn Detrital (Atoka?) Formation (5 wells: Oil accumulation: 833,433 BO). Figure 10 exhibits the most recent completion (yr. 2008) on the Bouscaren uplift. The well history indicates that oil production was obtained from basal Strawn Detrital Sandstone, similar to nearby older wells. Note, the location of the pre-Pennsylvanian unconformity. Here it rests on the Simpson Group. Over 3000 feet of rock is missing by erosion at that contact. In addition, some petroleum production has been established at the top of the Ellenburger (2 wells: Oil accumulation: 22,719 BO), and Wolfcamp limestone (1 well: Oil accumulation: 84,370 BO).

Figure 11A shows the position of the Bouscaren rock column at the beginning of mid-Pennsylvanian time; when Strawn Detrital and Atoka rocks were deposited across the uplift. At that time Oil Creek shale was adjacent to Bouscaren impact crater breccias across the nearest normal fault. Note the removal of a significant section of rock from the uplift, which includes formations from Ordovician, Silurian, Devonian, Mississippian and Early Pennsylvanian periods. Continued subsidence (Figure 11B) continued to the end of the Permian (251 Ma) and emplaced Oil Creek shale source rock at depths a few hundred feet deeper than the meteorite impact breccia located across the faults. Burial and thermal reconstructions indicate that the oil from the Simpson Group source rocks were generated and expelled when located in the main oil window between 255 and 35 Ma (Katz, et al., 1994). Migration of oils from Oil Creek Shale could have succeeded in reaching the meteorite impact breccias by migrating across the normal faults that bound the north side of the uplift. It is likely that oils found below the Wolfcamp limestone originated from Simpson Group source rocks, but, as of yet, no genetic relationship has been reported between source rocks and reservoirs on the Bouscaren uplift.

Other Impact Structures, Including Petroleum History

Because of poor understanding of impact structures by petroleum geoscientists and engineers the petroleum potential of meteorite impact structures has been overlooked. Meteorite impacts can create large reservoirs through fracturing and brecciation (Donofrio, 1981). Shock deformation can even produce reservoirs in crystalline rocks that are normally not considered a target for petroleum exploration. Hydrocarbons have been found at a number of impact structures and provide good guidelines for expecting oil production from the probable Bouscaren impact structure (Barton, et al; 2009, Brenan, 1975; Donofrio, 1981, 1997, 1998, 2007; Forsman et al., 1996; Friedman, 2009; Grieve, 2005; Kirschner et al., 1992; Koeberl, et al., 1996; Pickard, 1994; Sawatzky, 1977). Discovered in 1972, Red Wing Creek field in North Dakota is an Early Jurassic meteorite impact crater (Brenan, et al., 1975) that has produced more than 18 million barrels of oil and more that 25 Bcf gas from 26 wells. One well drilled in 1974 has produced about 3.5 million barrels of oil. Some wells could produce thousands of barrels of oil per day but are restricted because of mechanical constraints (RMOJ, 2011).

Meteorite impact craters of similar age to the Bouscaren structure include the Ames structure, Oklahoma (470 +/- 30 Ma.) and Kärdla meteorite crater in Estonia (~455 Ma) (Figure 12). The Ames structure (Figure 13) is a complex impact structure about 14 km in diameter, with a central uplift, an annular trough, and a slightly elevated trough at a depth of about 3 km (Carpenter and Carlson, 1995; Grieve, 2005). Oil was discovered in impacted rocks during the course of normal oil operations, and the structure has produced as much as 145 million barrels of oil. Due to impact-induced fracturing and karsting the Arbuckle dolomite in the rim of Ames structure has considerable economic potential. Also, wells drilled in the center failed to encounter the Arbuckle, but produced considerable oil from granite-dolomite breccias. The famous Gregory #1-20 produced more than

100,000 barrels of oil in a year from a section about 80 m thick (Grieve, 2006). The prolific oil production may also have been related to the Middle Ordovician Oil Creek Shale that covers and seals the entire structure (Curtiss and Wavrek, 1997).

Located on Hiiumaa Island in western Estonia, the buried and well preserved circular Kärdla impact structure is about 4 km wide and 500 m deep of Middle Ordovician age (~ 455 Ma) (Puura and Suuroja, 1992). The meteorite, approximately 200 m in diameter, struck a shallow sea bed and involved Middle and Lower Ordovician and Cambrian sedimentary rocks (140 m thick) overlying crystalline basement. Covered by Quaternary glacial deposits, the Kärdla crater is barely visible on the present topography, but it has been explored by more than 300 core holes, which provide a multitude of geological and geophysical data that supports its meteorite impact crater origin (Puura and Suuroja, 1992; Plado, et al., 1996). Figure 14 shows the geologic cross section of the crater. Brecciation and fracturing of the crystalline basement and impact material are apparent. The well preserved composite subsurface geology includes 1) post-impact cover of Ordovician sedimentary rocks (15-100 m thick), 2) allochtonous breccias filling the lower part of the crater and beds of fall-out breccias, conglomerates, sandstone, and sandy limestone debris composed of pre-impact rocks, and 3) autochthonous breccias forming the bottom and central peak of the crater (Puura and Suuroja, 1992).

Conclusions

It is not often that a meteorite impact crater that involves fractured rock is positioned ideally for its petroleum potential, but the Bouscaren impact feature appears to be well placed to have received migrated hydrocarbons. Primarily, the Bouscaren crater is located inside the petroleum-rich Permian basin. Trap formation was closely associated with collisional events related with E-W-trending normal and SW-NE trending strike-slip faults that formed many faulted anticlines in Midland Basin during Late Mississippian - Early Pennsylvanian time. Generation of petroleum probably occurred from Simpson Group shale of Middle Ordovician age, one of the basin's premier petroleum source rocks. Petroleum migration into the shattered and brecciated impact rock of Late Cambrian - Early Ordovician age on the Bouscaren uplift could have been accomplished by fluid movement across large-displacement normal faults that bound the north side of the uplift. Petroleum does occur at the Ellenburger formation level at about 8200 ft, indicating that these deep rocks did receive a hydrocarbon charge. Depth to the brecciated and fractured rock is very reasonable (9200 to 9700 ft) for the Permian Basin, suggesting that the Bouscaren impact crater can be tested at an acceptable cost.

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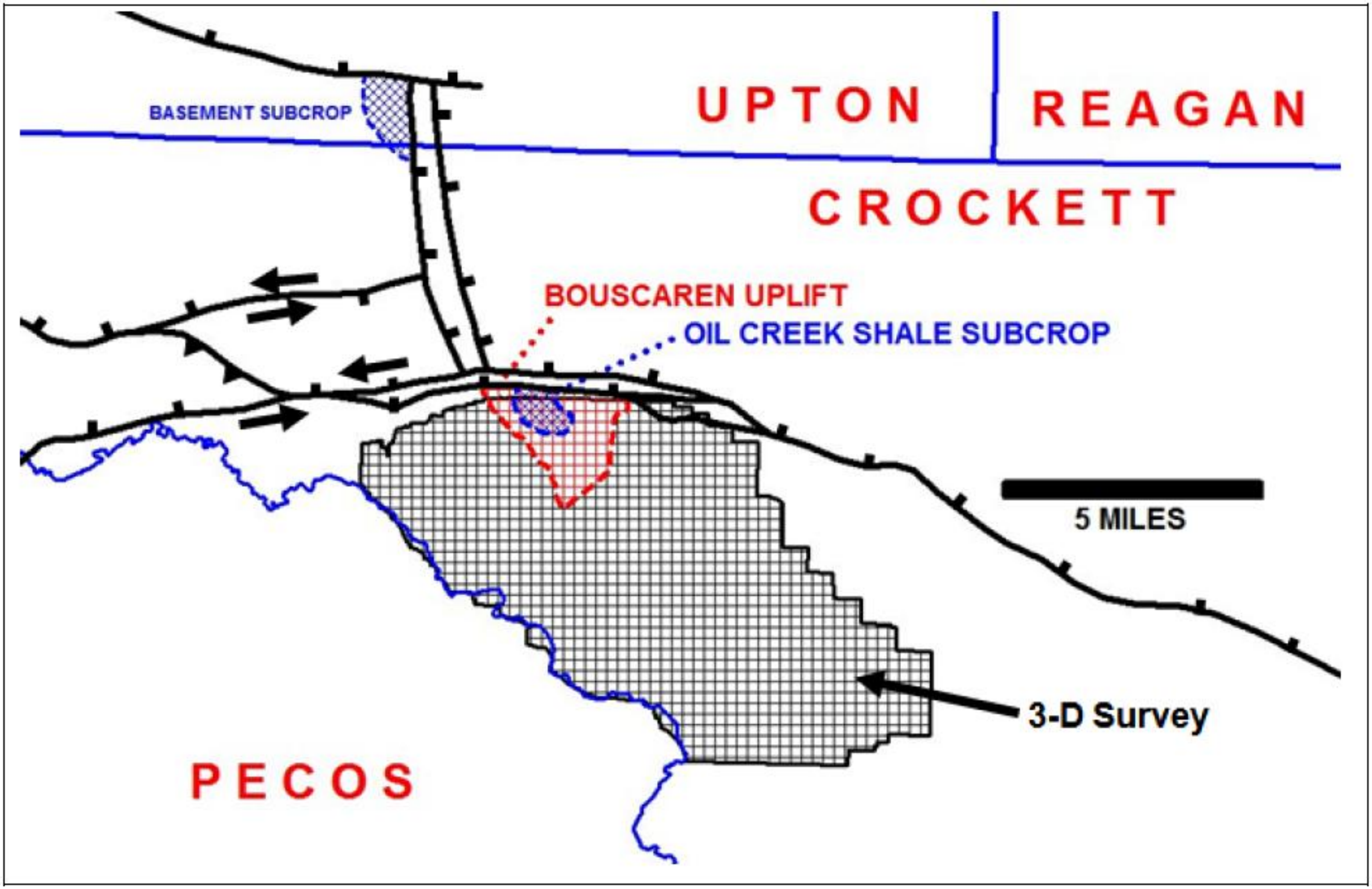

Figure 1. Location map of the 3-D survey in Crockett county, Texas, used in this study (cross hachure). Location of the Bouscaren uplift is shown in a red cross hachure. Subcrop of the oil Creek shale Member of the Simpson formation in shown in a blue cross hachure.

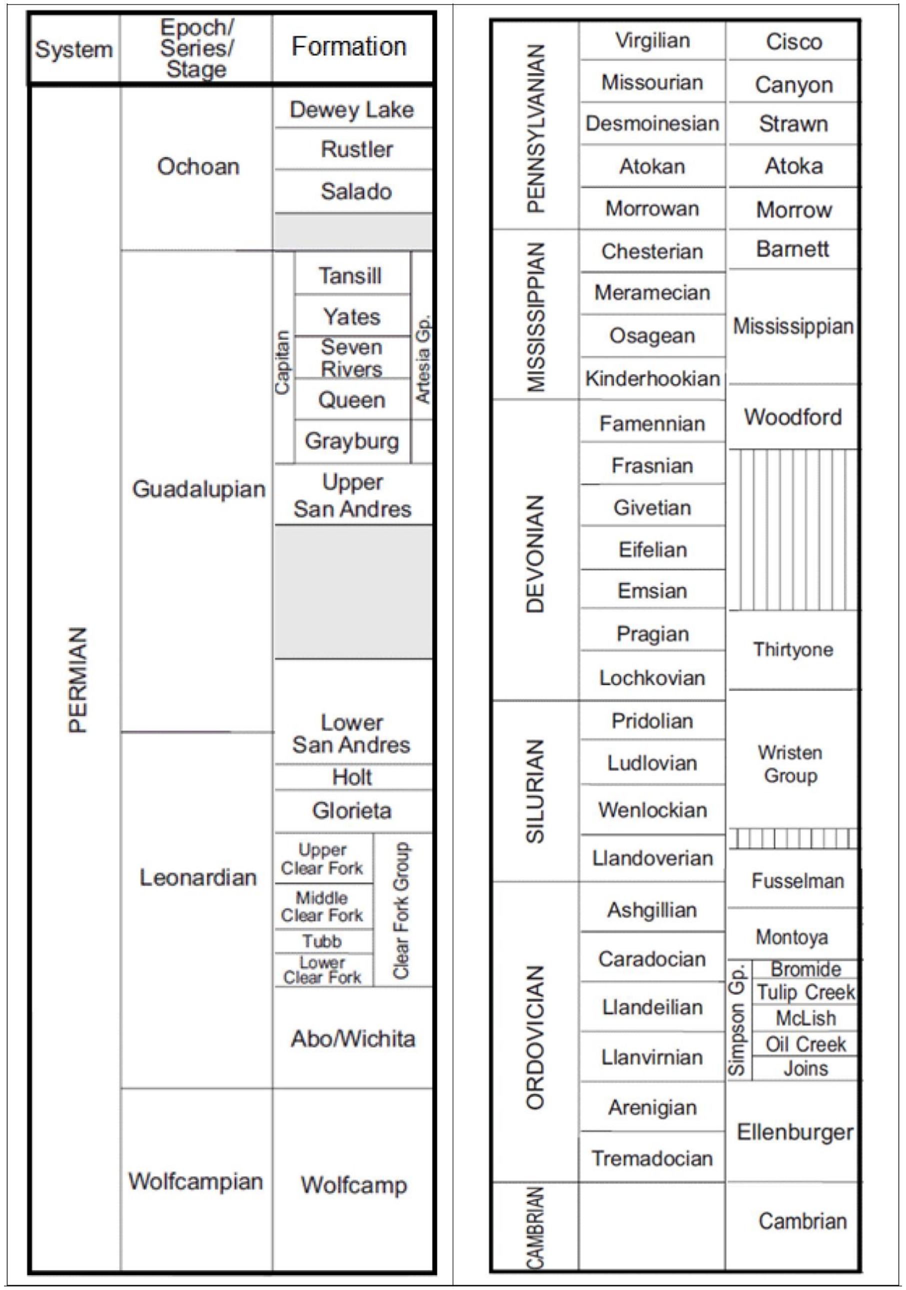

Figure 2. Stratigraphic column of formations present in Permian Basin, West Texas (from Dutton et al., 2004).

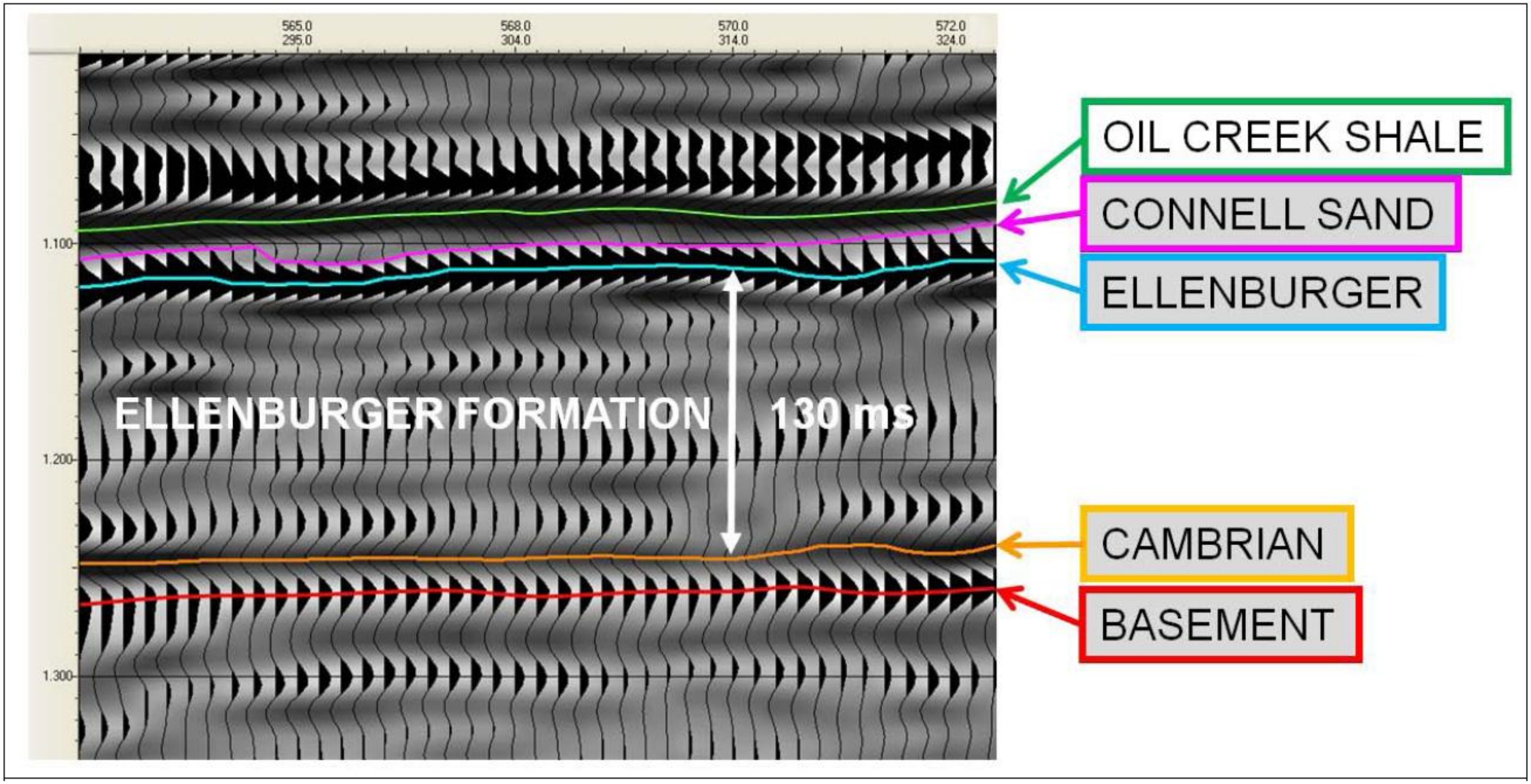

Figure 3. Seismic cross section showing undisturbed Cambrian and basement horizons beyond the effects of the Bouscaren meteorite impact structure. Also shown are the seismic horizons associated with Oil Creek Shale, Connell, and Ellenburger Group. Ellenburger here is about 130 ms in time thickness. At a velocity of 20,700 ft/sec, its thickness is about 1346 ft.

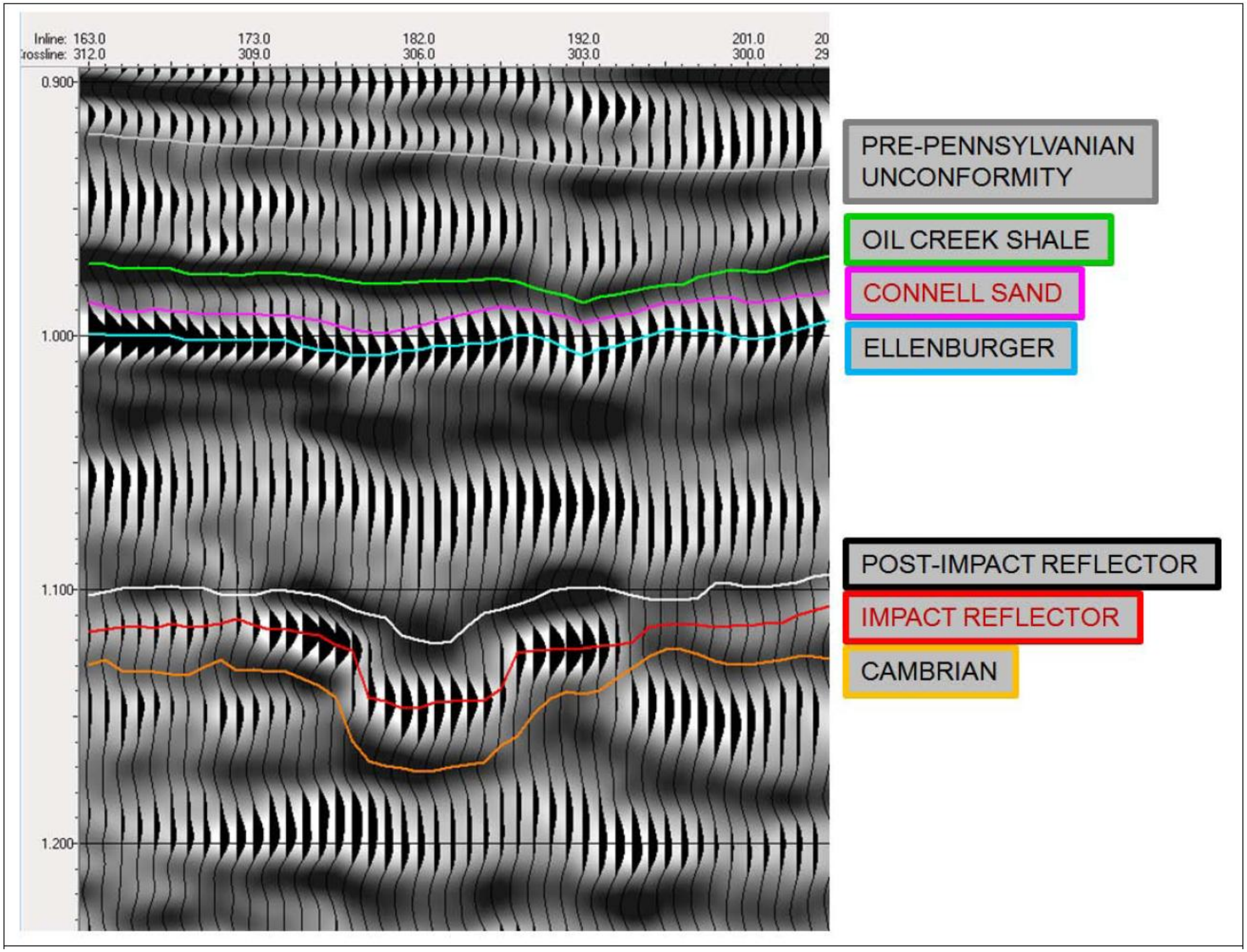

Figure 4. Seismic cross section showing horizons affected by the Bouscaren meteorite impact structure. Note significant downwarp of Cambrian horizon (orange) and high-amplitude seismic horizon associated with the meteorite impact (red). Post-impact seismic horizon (white) exhibits crater-like morphology, but is more subdued. This horizon appears to be associated with the lower part of the Ellenburger. Note the absence of crater morphology on shallower horizons at, and above, the Ellenburger.

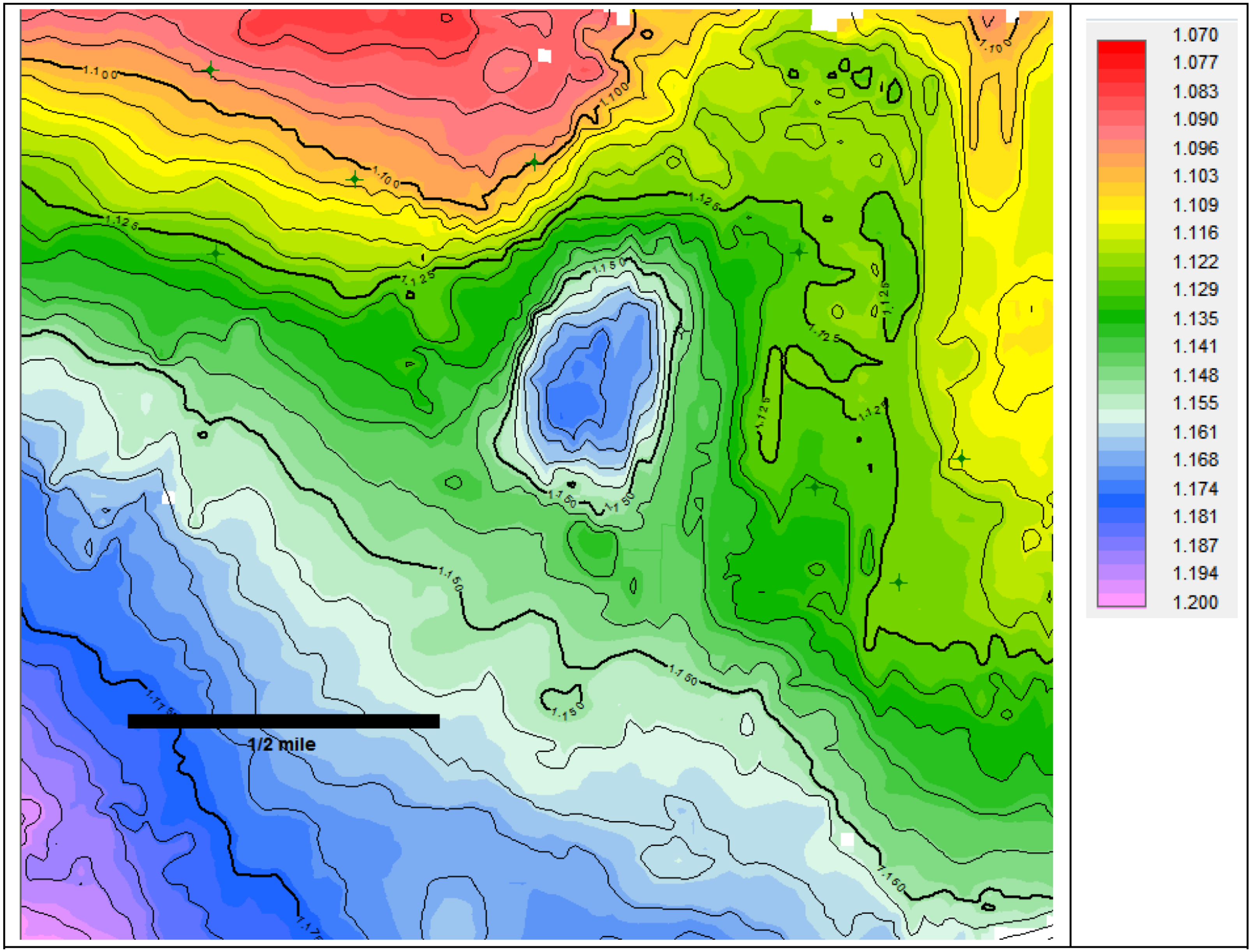

Figure 5. Contoured Cambrian seismic horizon (C.I. = 5 ms). Note the oval-shaped basin formed on the regional Cambrian surface. This feature is interpreted to have been formed by a meteorite strike that traveled along a NE-SW trajectory. Depth of the crater ranges from about 40-50 ms, indicating depths of between 400 and 500 ft. No wells have penetrated this horizon.

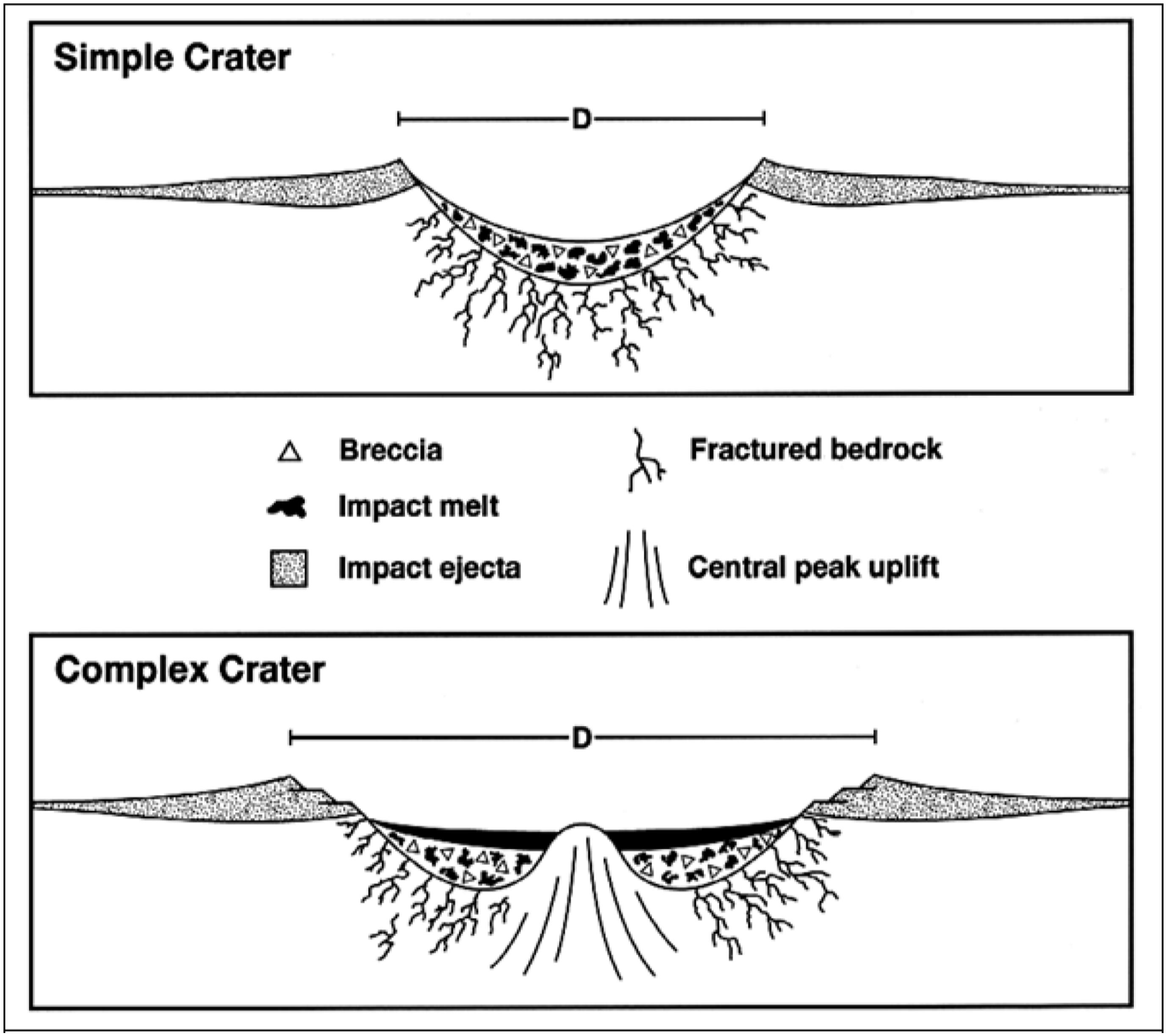

Figure 6. Schematic diagrams of two different types of impact craters. Small impacts form simple craters without any central uplifts. Larger impact craters form complex craters that contain central uplifts. The Bouscaren meteorite impact appears to be a small simple crater without a central uplift.

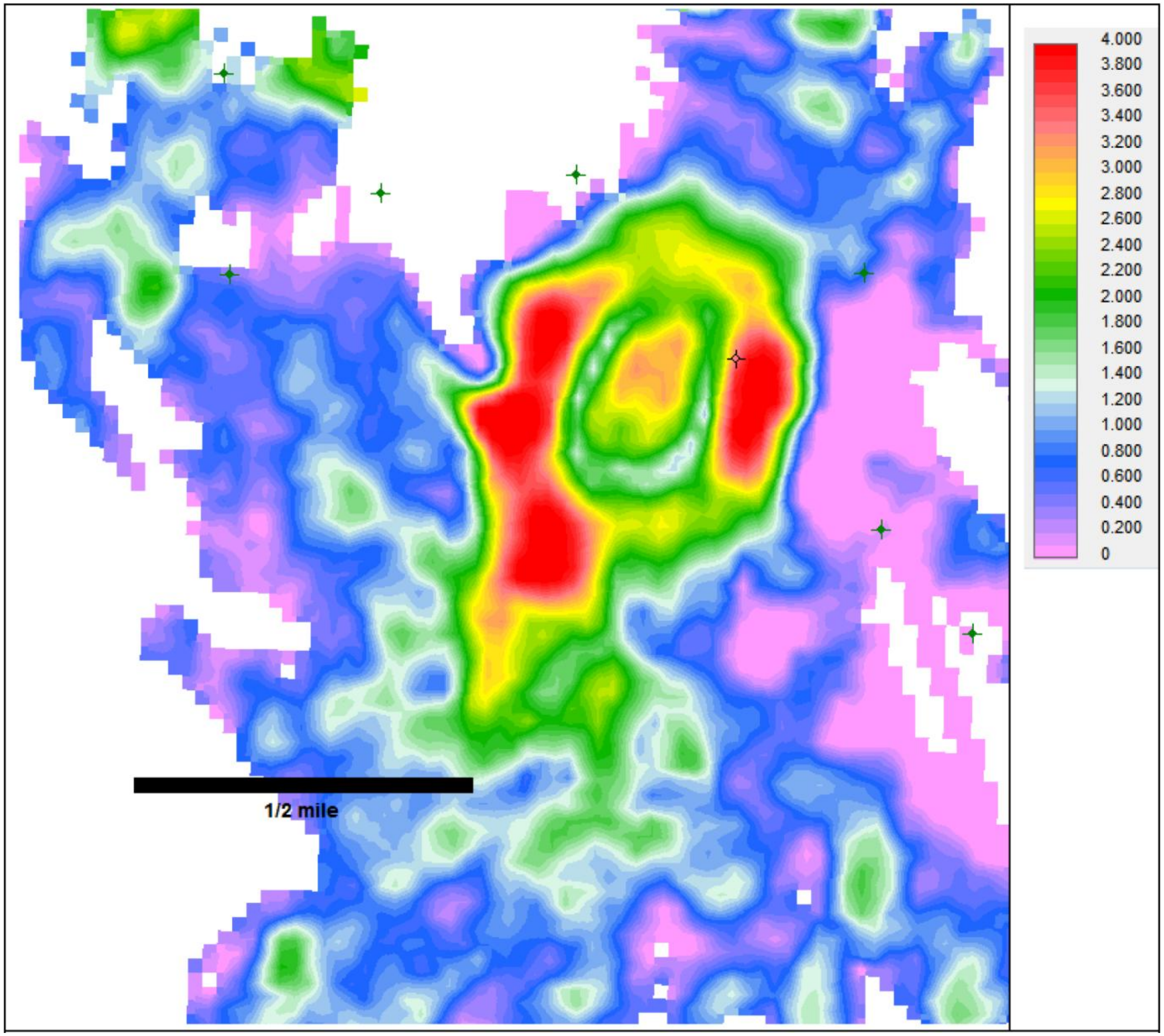

Figure 7. Seismic amplitude map of the seismic horizon that appears to be related to meteorite impact breccia and ejecta (red horizon in Figure 4). High seismic amplitudes outline the crater location (red to yellow). These high seismic amplitudes likely suggest good reservoir development induced by fracturing and brecciation both in the crater floor and rim. Lower amplitudes outside the rim (blue to green) are likely associated with ejecta.

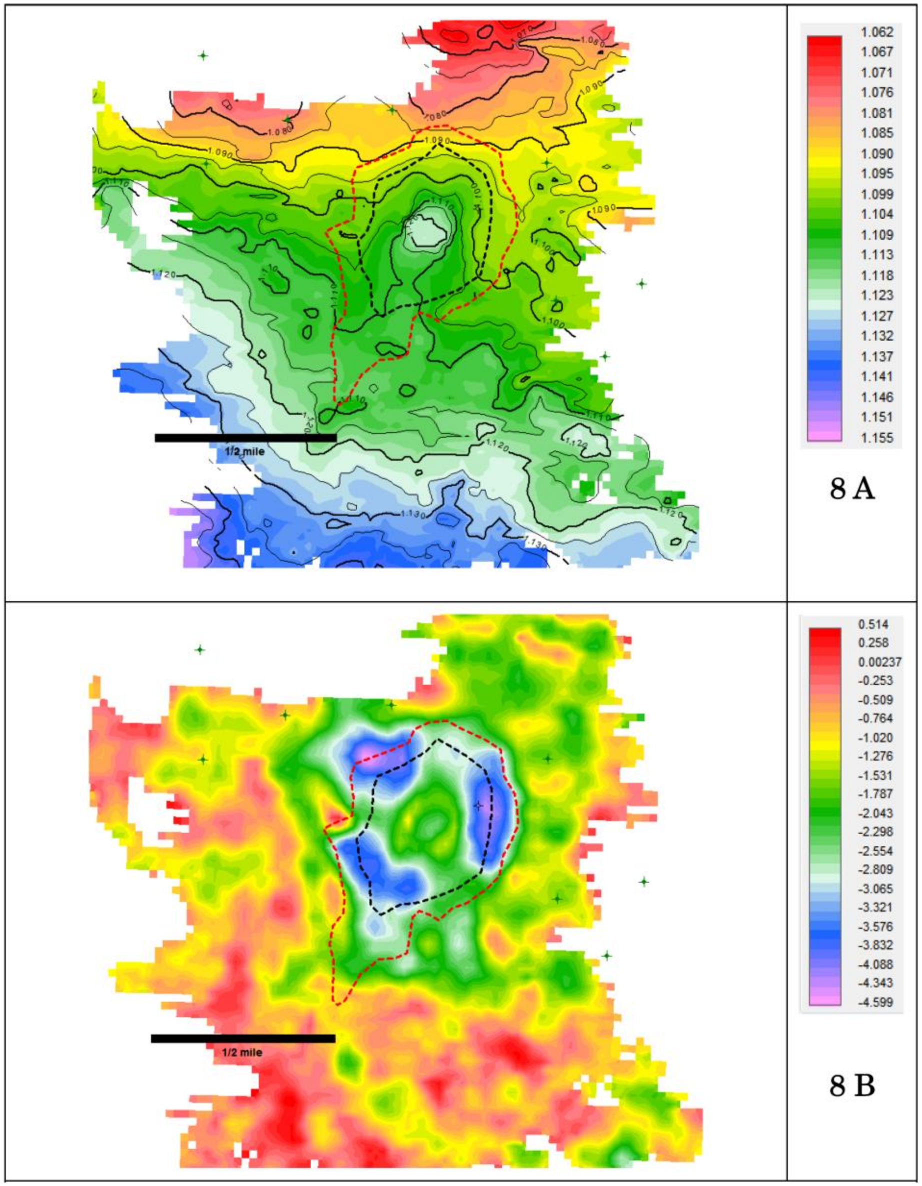

Figure 8. A. Contoured time-depth map of the post-impact seismic horizon (C.I. = 5 ms) (white horizon in Figure 4). B. Contoured seismic amplitude map of the same seismic horizon. Black dashed line follows the crater-rim crest, defined by high seismic amplitude (red horizon), and red dashed line follows the base of the high seismic amplitudes. Note the subdued crater morphology and concentric seismic amplitude pattern. This seismic horizon probably represents rock that initially buried the impact crater (lower Ellenburger?).

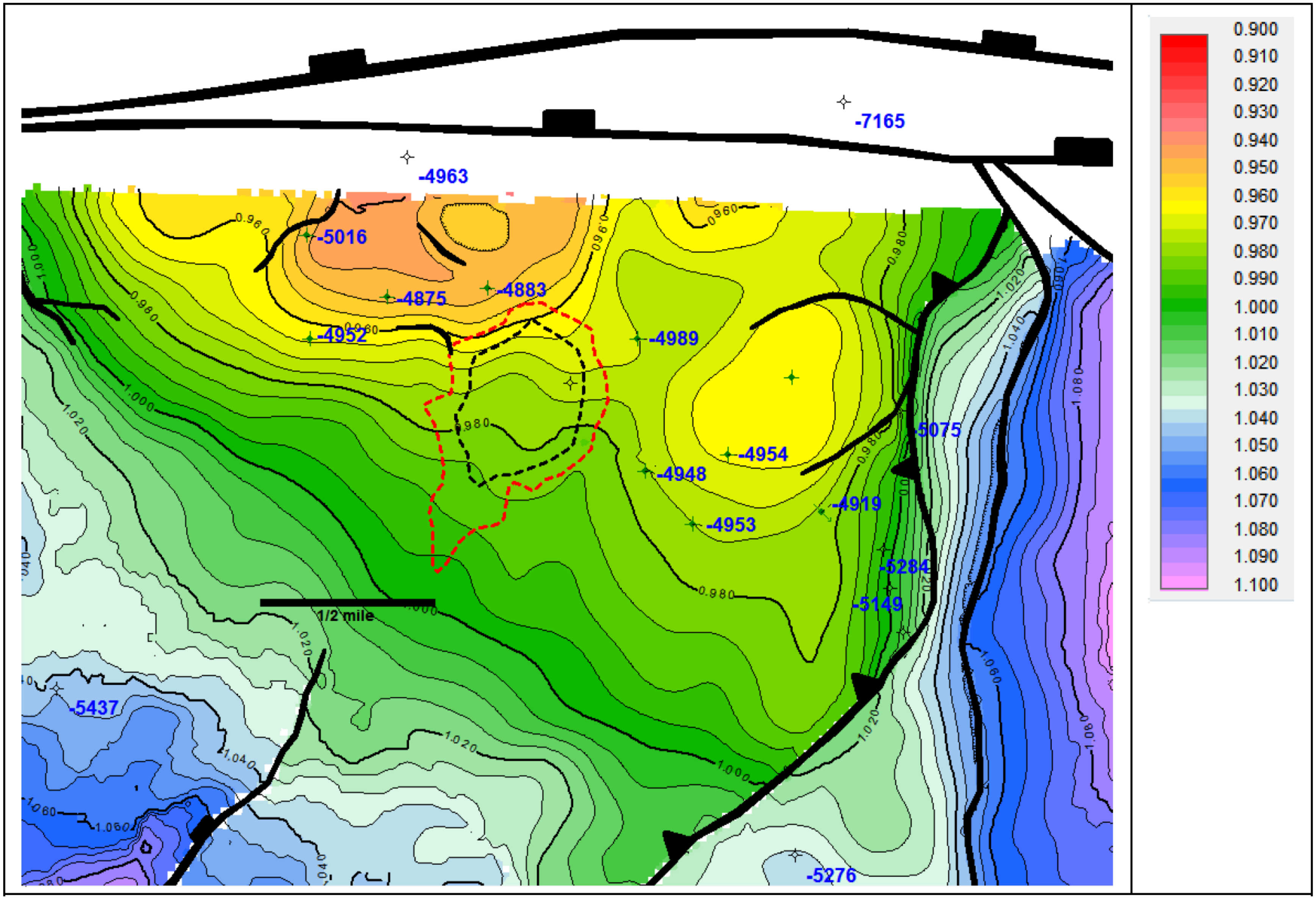

Figure 9. Contoured time-depth map of the Oil Creek Shale seismic horizon (C.I. =6 ms) (green horizon in Figure 3). Subsea depths of Oil Creek Shale are shown in blue figures adjacent to wells. The impact crater is outlined by black and red dashed lines. Black dashed line follows the crater rim crest, defined by high seismic amplitude (red horizon), and red dashed line follows the base of the high seismic amplitudes. Note the absence of any strong structural indication that a meteor crater formed at the base of the Ellenburger Group.

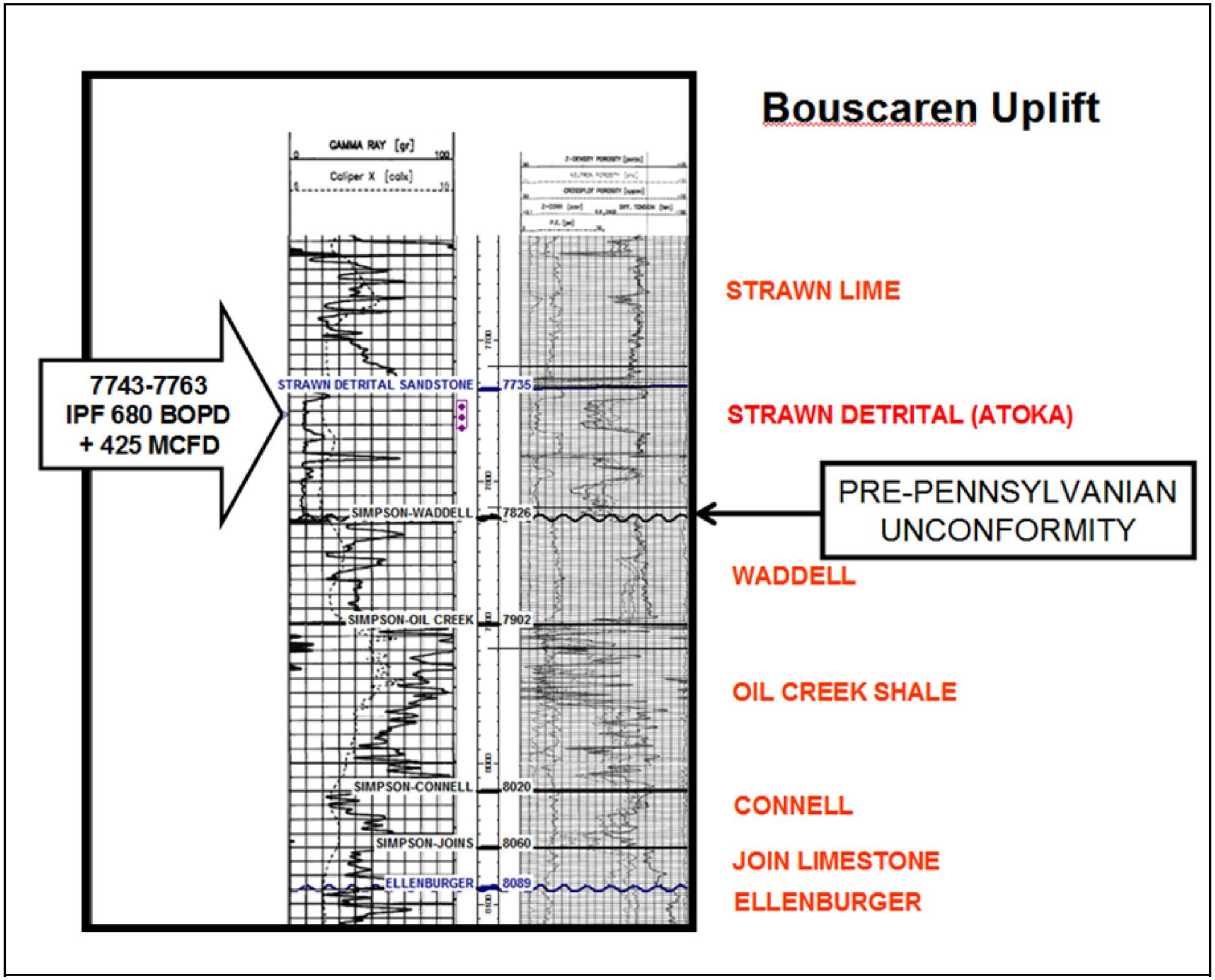

Figure 10. Lower part of log profile of Vera Del State Unit #52-1, located atop the Bouscaren uplift, showing stratigraphic units ranging from Strawn Limestone to Ellenburger Group. At this site over 3000 ft of section is missing at the unconformity when compared to a complete section deposited in this part of the basin. Between depths of 7742 and 7763 ft, this well was completed as an oil well. Its initial daily production rate was 680 BO and 425 MCFG. After producing 14,550 BO and 9412 MCFG in 2 years, the well was abandoned, indicating possibly that this thick, but channelized, sandstone had limited extent.

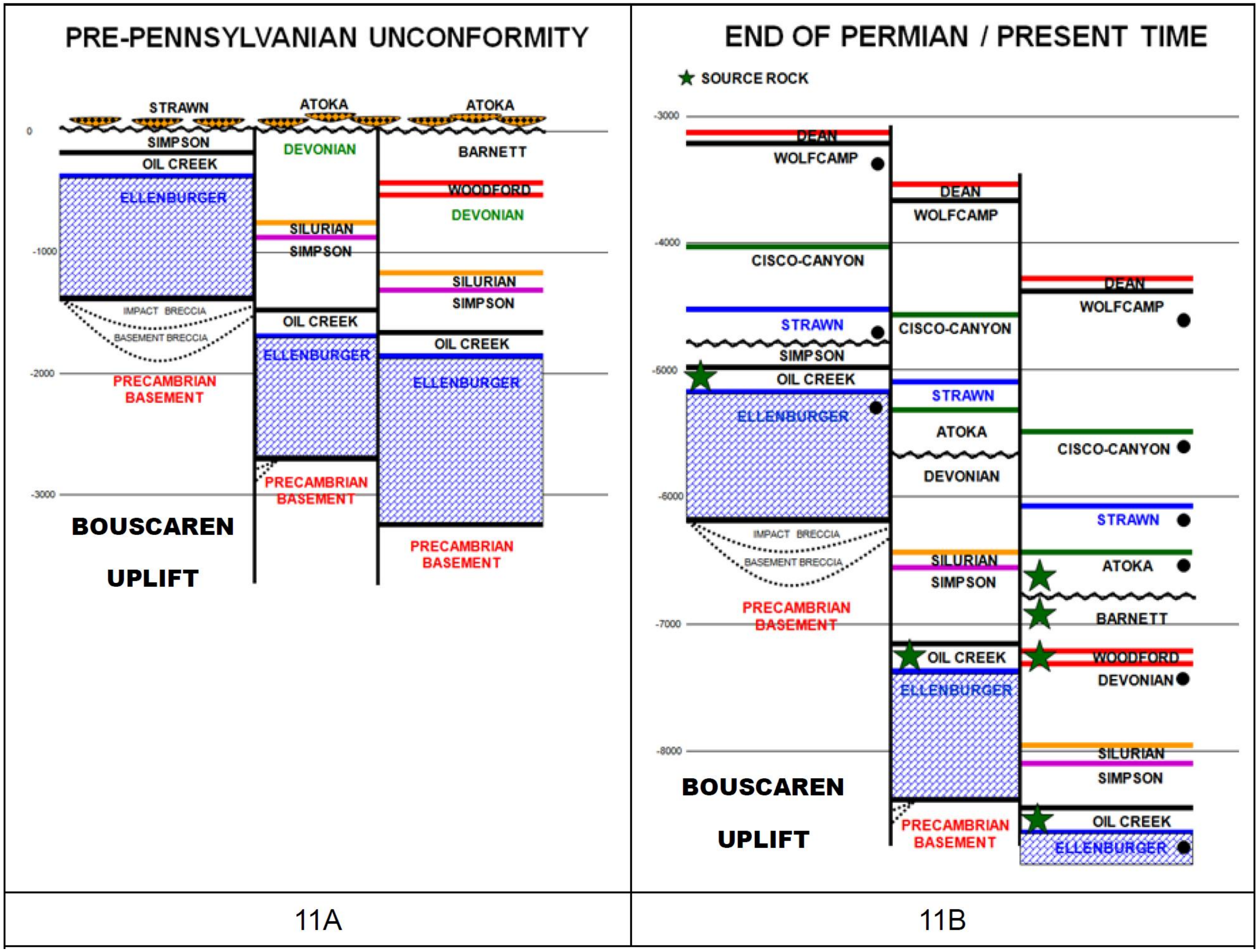

Figure 11. Stratigraphic section at two geologic times across normal faults located north of the Bouscaren uplift. 11A is approximately 310+/- Ma at the beginning of Strawn detrital or Atoka deposition above the regional pre-Pennsylvanian unconformity. 11B represents the end of the Permian (251 Ma). Only minor deformation occurred after that time. Simpson Oil Creek Shale entered the oil window by 255 Ma and was active in the basin until 35 Ma. Note that the Oil Creek Shale at this time is deeper than the impact breccia. Oil generated from the Oil Creek Shale kitchen north of Bouscaren uplift could easily have migrated into basement breccia associated with the impact crater. Other source rocks, such as Barnett and Woodford, could have contributed to this possible hydrocarbon migration.

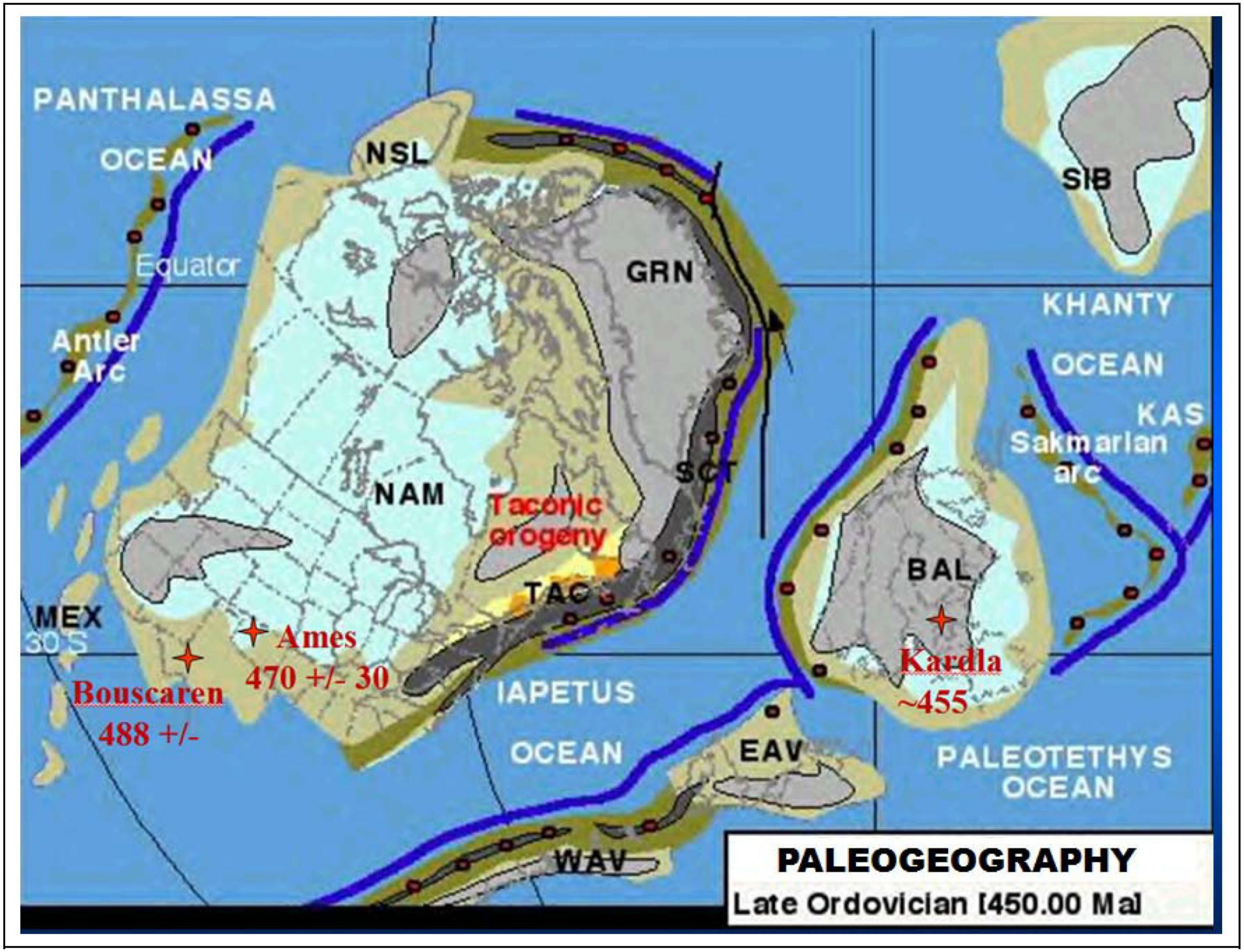

Figure 12. Locations of Late Cambrian to Middle Ordovician impact craters positioned on Late Ordovician paleogeography. Note the locations of Bouscaren, Ames, and Kärdla impact craters. The east-west alignment of these "chain of craters" is impelling evidence of their having formed from a fragmented comet/asteroid/meteorite. However, at this time the ages do not fully support this proposal; yet, later narrowing of the error bars of geological ages could support impacts that originated from a single extraterrestrial event. (Map modified after Blakey, 2005.)

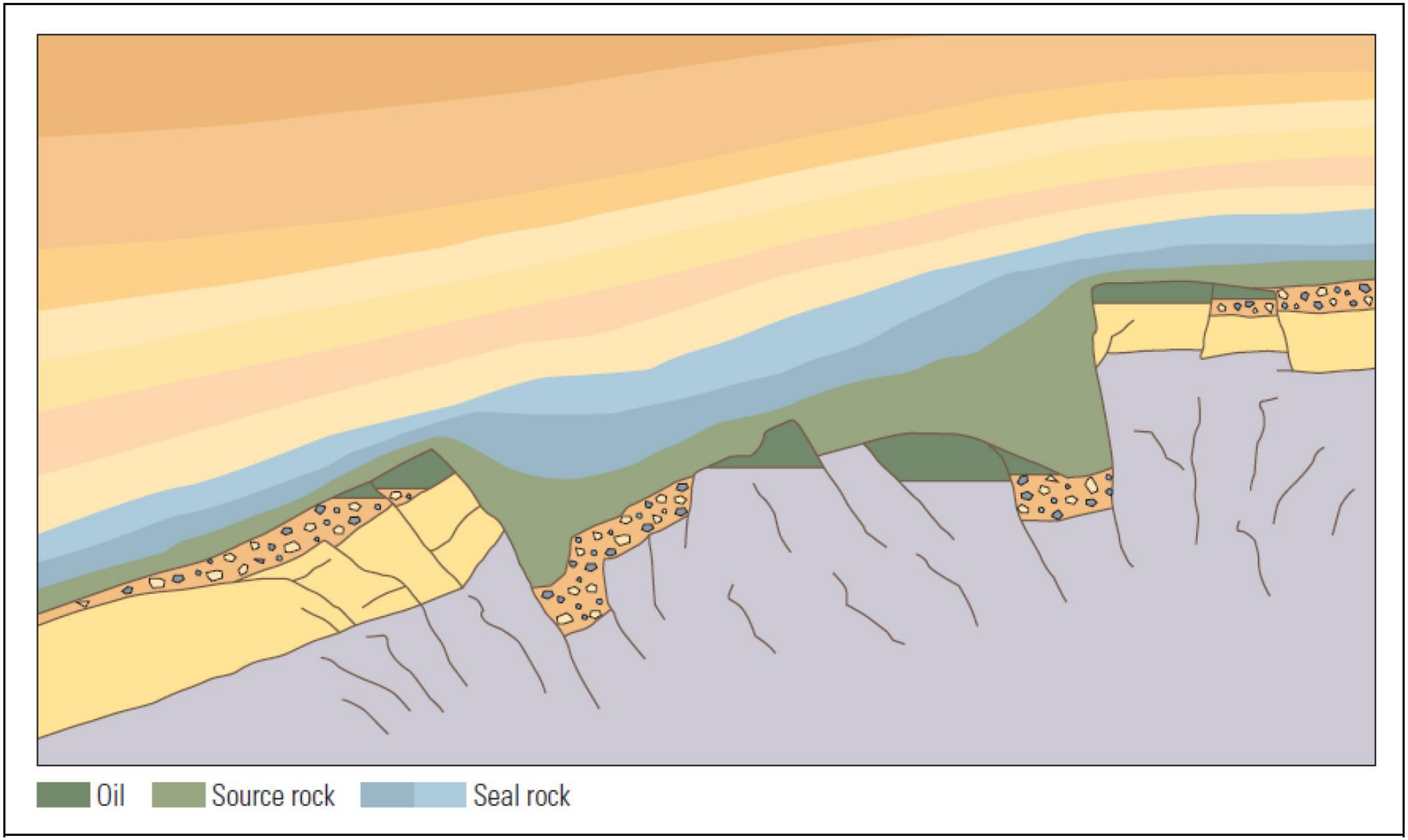

Figure 13. Schematic cross section, Ames meteor impact crater petroleum system. Organic-rich shales that filled the Ames crater became the source rock for reservoirs that formed in the fractured and brecciated granites and dolomites beneath the crater floor. Petroleum migrated into upthrown blocks in the central ring and outer rim. Additionally post-impact shales acted as seals. The section of Devonian and younger beds overlying the structure is about 7000 ft thick. (From Barton et al., 2009.)

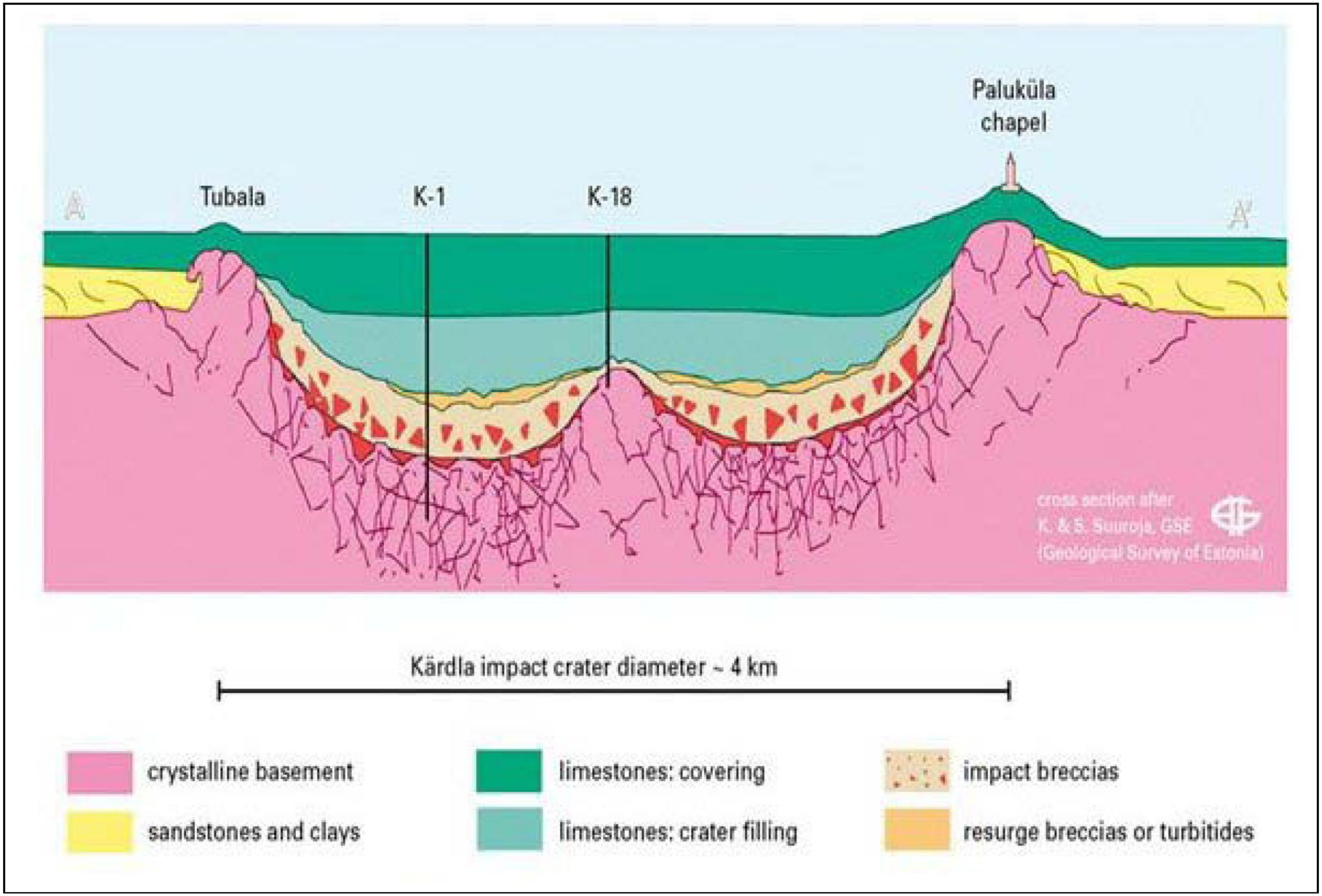

Figure 14. Schematic geological section of the Kärdla meteorite crater showing the location of impact breccia and fractured basement crystalline rocks (from Suuroja, 2002).