Wapanucka Formation (Morrowan): Facies and Fractures, Frontal Ouachita Mountains

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INTRODUCTION

Gas discoveries in the frontal Ouachita Mountains are attributable to structural and stratigraphic relationships within the overthrust belt. Although most gas production has been from the Spiro sandstone, the Wapanucka limestone (Morrowan) has locally proven to be a gas reservoir.

Fractures in Wapanucka limestones are commonly related to the lithology and are important factors for gas production. For example, the Amoco no. 1 Zipperer had a production test of 48.8 MMcfgd (million cubic feet of gas per day) from fractured Wapanucka limestone. Commingling gas from the Wapanucka and the Spiro, this well has produced 21.7 Bcfg (billion cubic feet of gas) from August 1988 to February 1992. Also, portions of the Pittsburg field produce from fractured micritic limestone (Montgomery, 1989).

Three Wapanucka facies are potential hydrocarbon reservoirs. These are those shallow shelf deposits that contain: oolites, phylloid algae, and in situ sponges with scattered sponge spicules. The oolitic and phylloid-algal facies might contain primary or diagenetic porosity, whereas the sponge boundstone and spiculitic-limestone facies could develop significant fracture porosity in certain structural configurations. Thus, mapping the surface extent of the fractures and facies is significant because well control and seismic data do not provide this kind of information.

STRATIGRAPHY

The Arkoma basin was depositionally part of a broad, stable shelf, the Arkoma shelf, along a passive continental margin. Depositional patterns on this shelf varied greatly during the Chesterian, Morrowan, and early Atokan time (Sutherland, 1988). The Wapanucka Formation is the only predominantly shallow-marine unit exposed in the now-deformed Ouachita mobile belt.

The Wapanucka Formation is underlain by a thick shale section that presumably spans the Mississippian/Pennsylvanian boundary in the frontal Ouachitas. The upper part of this shale is informally called "Springer" and is lithologically indistinguishable from thick shale intervals within the lower Wapanucka Formation (Grayson, 1980). The Wapanucka Formation is overlain by the Atoka Formation, which is predominantly shale with some sandstone lenses in the frontal Ouachitas. According to Grayson (1980), the Wapanucka Formation in the frontal Ouachitas consists of four members (one of which is formally named): an upper sandstone-limestone member, a middle shale member, a lower limestone member, and the Chickachoc Chert which is laterally equivalent, in part, to the lower limestone member. The upper sandstone-limestone member at the surface is considered to be equivalent to the Spiro sandstone in the Arkoma basin subsurface, although some workers consider the Spiro sandstone to be the basal sandstone of the Atoka Formation (Lumsden and others, 1971; Grayson, 1980). This paper uses the informal subsurface nomenclature: Wapanucka or Wapanucka limestone refers to the lower limestone member and/or Chickachoc Chert; sub-Spiro shale refers to the middle shale member; and Spiro, Spiro sandstone, and Spiro limestone refer to the upper sandstone-limestone member.

Thick successions of repetitive subtidal-carbonate sequences that include platform, platform-margin, and shelf-slope facies characterize the Wapanucka Formation in outcrop. Shelf-margin deposits (Fig. 1) consist of bioclastic shelf bars capped by oolites and local intertidal-beach deposits. Upper-shelf facies are demosponge boundstones with local foram-peloid packstones, and mounds of phylloid algae. Upper shelf-slope deposits are mostly tubular-algal (*Donezella*) boundstones (Mauldin, 1995). The lower shelf slope is represented by the Chickachoc Chert. The Chickachoc is generally highly frac-

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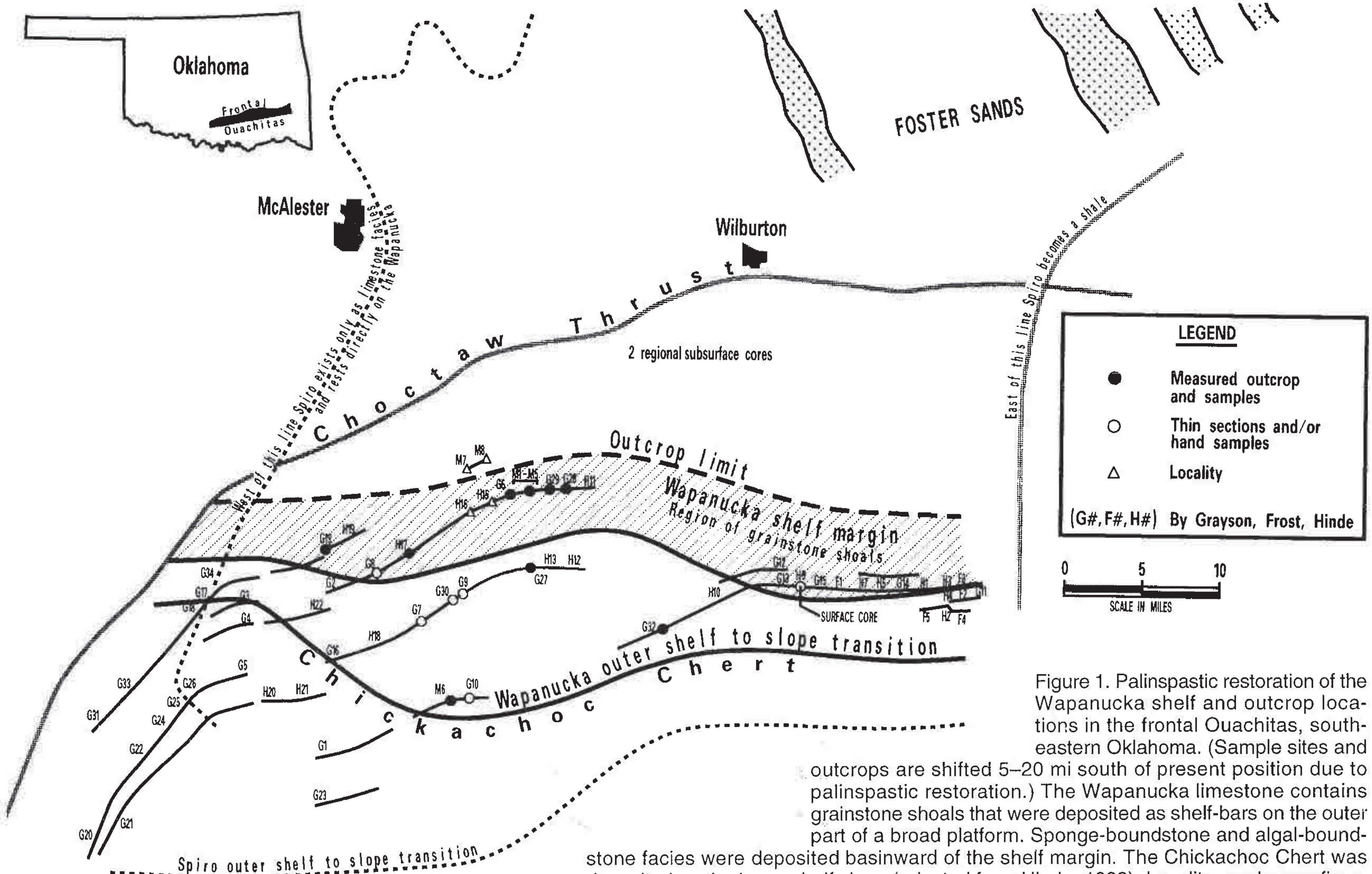

Figure 1. Palinspastic restoration of the Wapanucka shelf and outcrop locations in the frontal Ouachitas, southeastern Oklahoma. (Sample sites and outcrops are shifted 5–20 mi south of present position due to palinspastic restoration.) The Wapanucka limestone contains grainstone shoals that were deposited as shelf-bars on the outer part of a broad platform. Sponge-boundstone and algal-boundstone facies were deposited basinward of the shelf margin. The Chickachoc Chert was deposited on the lower shelf slope (adapted from Hinde, 1992). Locality number prefixes: M-numbers denote localities described in this study. H-numbers are from Hinde (1992); F-numbers are from Frost (1981); G-numbers are from Grayson (1980).

tured where shale is not abundant; the chert may therefore have some reservoir potential. The Chickachoc Chert consists mostly of spiculite (alternating layers of shale and transported spicules).

The Wapanucka limestone is overlain by an extensive shale called the middle shale in outcrop (Grayson, 1980) and usually referred to as the sub-Spiro shale by subsurface workers. This shale represents a fine-clastic influx that choked out carbonate production in the Ouachita region. The Spiro sandstone represents renewed shallow-shelf conditions in which sand and sandy limestones accumulated as shelf-bar deposits (Hinde, 1992). However, some Spiro facies are very similar to those that occur in the Wapanucka. The Wapanucka and Spiro sandstone are the only rigid rocks that are laterally extensive and, therefore, likely to contain economically significant fractures.

REGIONAL TECTONIC HISTORY

The frontal Ouachita Mountains in southeastern Oklahoma contain several imbricate-thrust outcrops of the Wapanucka limestone and overlying Spiro sandstone. These rocks have numerous fractures and faults created by compressional, thin-skinned deformation as thrust sheets were pushed toward the surface. However, this is only one of the tectonic events that led to fracturing of the Wapanucka in the complexly structured Ouachita thrust belt. Several episodes of stress are recorded by calcite-healed fractures in the Wapanucka that formed at different times. Small cross-cutting fractures have different types of calcite mineralization, and some of these fractures occurred after others, as evidenced by a second generation of calcite cutting across a healed fracture.

Major structures in the frontal Ouachitas and Arkoma basin that could have had an affect on Wapanucka fracturing include: basement-involved high-angle faults (normal and reverse), foreland-style thrusts, and folds (Montgomery, 1989). Normal faults were created by the breakup of the pre-existing North American continent, accompanied by development of a system of rift arms and faults that reached far into the cratonic interior (Arbenz, 1989). These basement faults experienced several minor episodes of rejuvenation before major reactivation in the Early Pennsylvanian (Montgomery, 1989). The Wapanucka and Spiro were deposited on the passive margin at the southern edge of the North American plate (Houseknecht, 1986).

Early and Middle Atokan flexural downwarping of the southern margin of the shelf and down-to-the-south syndepositional normal faults were caused by subduction of the North American plate beneath either an island arc or another continental plate (Houseknecht, 1986; Sutherland, 1988). This continental collision resulted in the formation of a collisional orogenic belt, known as the Ouachita system. An allocthonous belt of older Paleozoic deep-water deposits were thrust northward onto the outer continental shelf. Foreland thrusting occurred in the Late Atokan and Desmoinesian (Houseknecht, 1986). The Ouachita Mountains and Arkoma basin contain a broad zone of compressional surface structures, with narrow upright anticlines separated by broad synclines. The frontal zone of the Ouachita Mountains in southeastern Oklahoma consists of numerous imbricate thrust sheets that repeat the Wapanucka and/or Chickachoc Chert and Spiro sandstone between the Choctaw and Ti Valley thrust faults. These thrust sheets are stacked in multilevel duplexes, and the strata within the thrust sheets are complexly folded (Arbenz, 1989). The continental collision may have also reactivated some of the older normal faults as high-angle reverse faults.

FRACTURE CLASSIFICATION

The AGI *Glossary of Geology* (1980) defines "fracture" as "a general term for any break in a rock, whether or not it causes displacement, due to mechanical failure by stress. Fractures include cracks, joints and faults." Kulander and others (1990) added, "any physical discontinuity in a rock caused by stresses exceeding the rock's strength." Pollard and Aydin (1988) suggested the word "'joint' be restricted to those fractures with field evidence for dominantly opening displacements. Joints are the most common result of brittle fracture of rock . . . and play an important role in the transport of fluids." In Wapanucka exposures, most fractures cannot be definitely classified, owing to the fact that most fracture faces are obscured by weathering, mineralization (mainly calcite), or soil. Because plumose structures are the most common and generally the only texture recognized, most fractures in this study are interpreted as joints. Surface ornamentation such as plumose structure is usually present on regional fractures (Kulander and others, 1979), although it is rarely observed or recognized in some outcrop studies (Lorenz and Finley, 1991).

Smooth, continuous, and planar fracture faces are common in the Wapanucka and are also characteristic of joints (Pollard and Aydin, 1988). Slickensides could be found on most fault planes. Horizontal fractures were not recorded as such unless they had slickensides. Without slickensides they would be hard to differentiate from bedding planes.

OUTCROP FRACTURES AND RESERVOIR POTENTIAL

Fracturing in the frontal Ouachitas can be assessed at surface locations, but comparison to Wapanucka reservoir fractures is difficult because of the lack of subsurface data. The abundance of fractures observed in Wapanucka exposures is evidence of how hydrocarbons could exist in the subsurface. They could be the reservoir, or they could

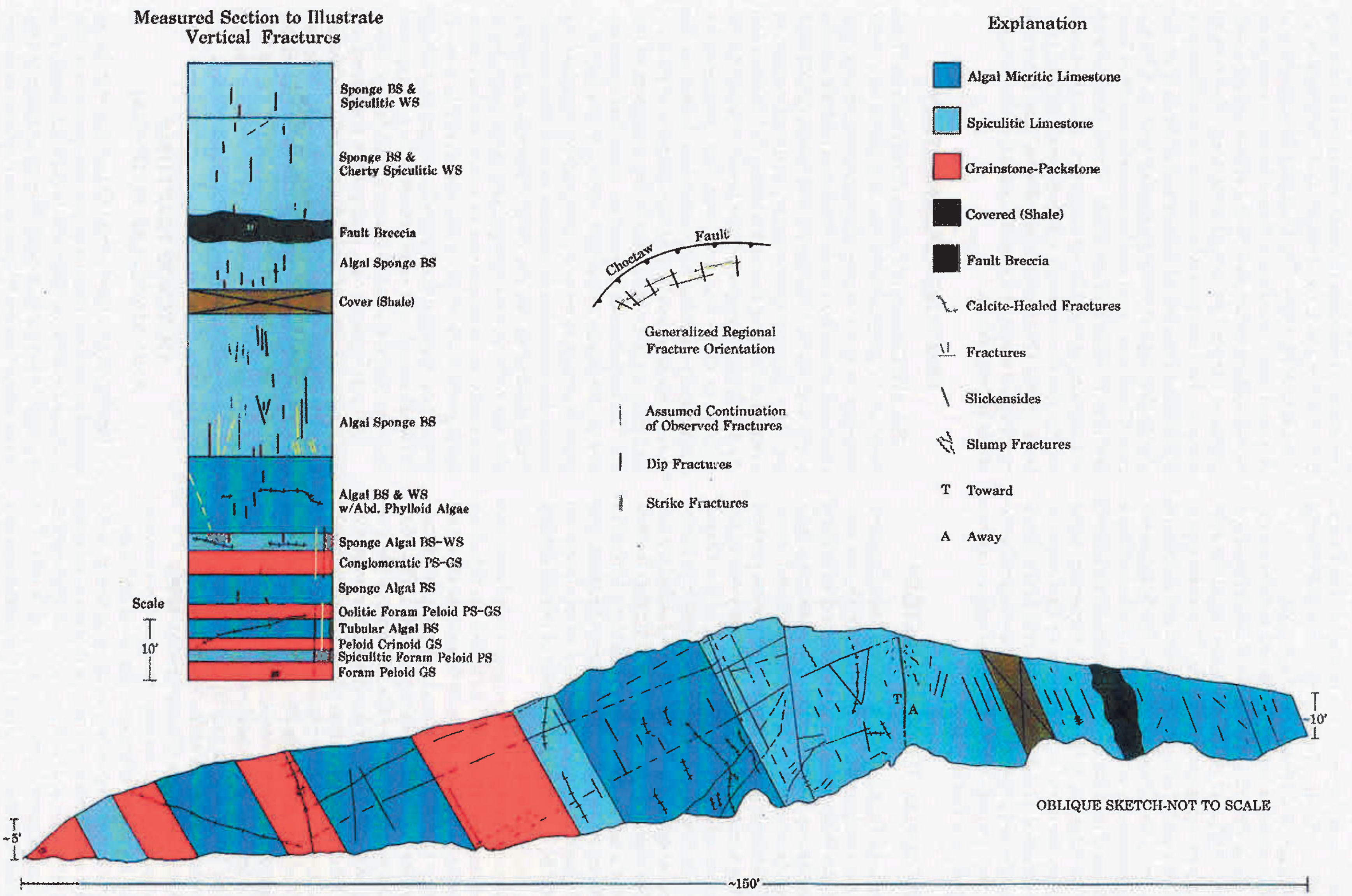

Figure 2. Typical outcrop of the Wapanucka limestone along Limestone Ridge (locality G28), with numerous fractures, including two identified as faults. Most fractures are perpendicular to bedding, but because of the orientation of the outcrop, the dip fractures could not be illustrated cutting through the beds; however, this is shown in the stratigraphic column.

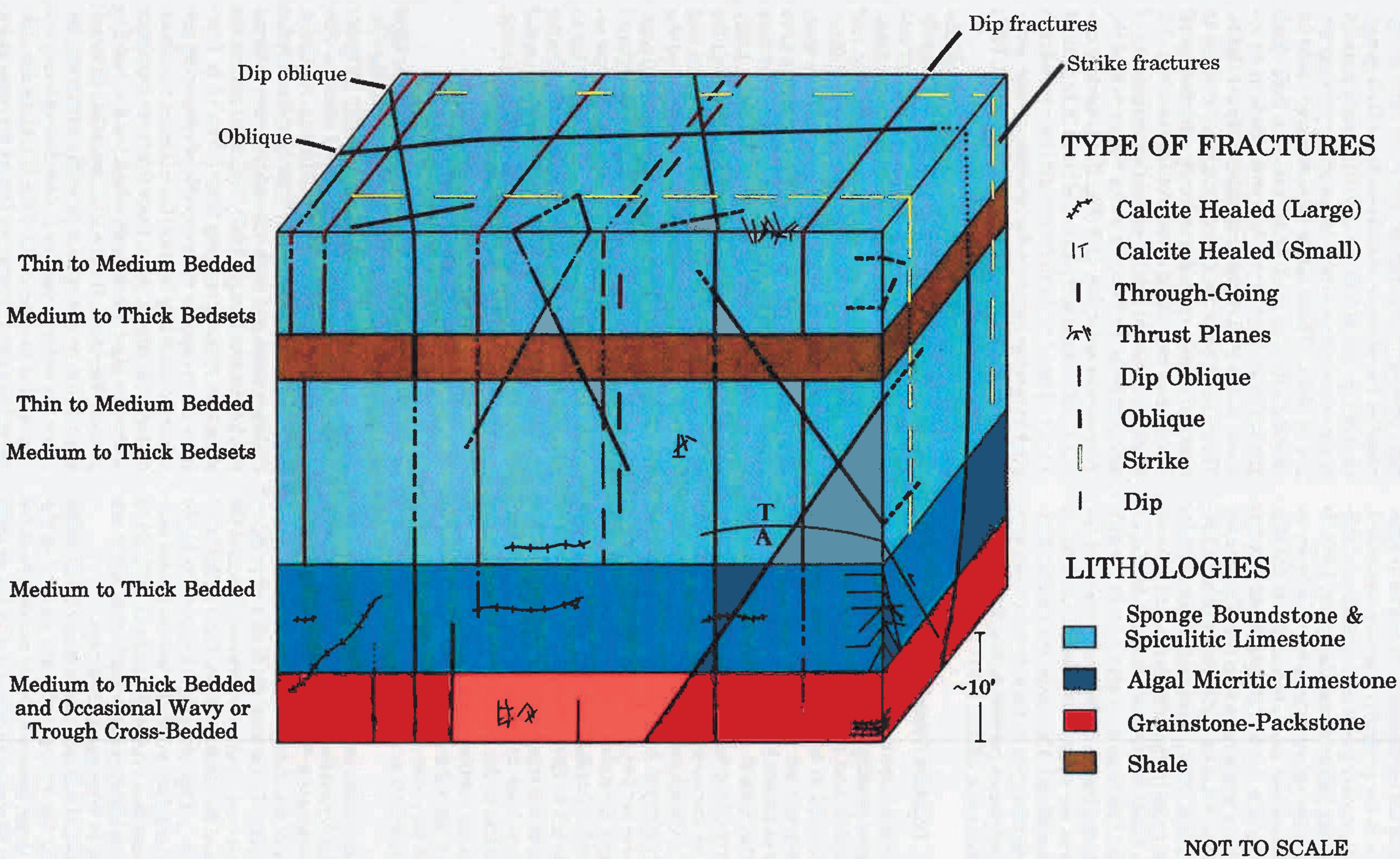

Figure 3. A schematic representation of lithology, bedding, and fractures in the Wapanucka limestone. Most fractures in the frontal Ouachitas are dip and strike fractures that cut perpendicular to bedding. Some regions contain numerous fractures oriented oblique to dip. Fracture abundance is probably influenced by lithology and/or bed thickness. Fractures are more abundant in the sponge-boundstone and spiculitic-limestone facies, which are generally more thinly bedded than other facies.

greatly enhance the permeability. Wapanucka limestone reservoirs are probably fracture controlled, but vugs and primary pores undoubtedly contribute to production (Suneson and Campbell, 1990). In the Arkoma basin subsurface, where the Spiro or Foster sandstone rest unconformably on the Wapanucka limestone, hydrocarbons could migrate from the porous sandstones into the Wapanucka. Fractures in the Arkoma basin, north of the Choctaw fault (Melton, 1929), have orientations similar to the dip fractures (perpendicular to strike) found in this study. Other fracture orientations developed in the frontal Ouachitas may also exist in the subsurface Arkoma basin. In outcrop, many of the large fractures are open, but most of the smaller ones are mineralized. However, the smaller fractures could remain open in the subsurface, depending on the fluid phases present during the history of the rock (Lorenz and others, 1991).

Fracture Morphology

Abundant fractures in the Wapanucka resulted from a complex postdepositional history of burial, tectonism, uplift, and erosion. The first fractures probably occurred in Atokan time, when regional down-to-the-south normal faults were created by tectonic and sediment loading associated with the advancing Ouachita thrust system (Houseknecht, 1986). Experts disagree on what events have the most effect on fracturing, but fracture orientation in the frontal Ouachitas indicates that fracturing was strongly affected by regional thrusting. Most macrofractures are perpendicular to bedding (Fig. 2, top left) and are either perpendicular (dip fractures) or parallel (strike fractures) to the Choctaw fault (see sketch in the center of Fig. 2). Dip and strike fractures are represented in Figure 3 by the red and yellow lines, respectively. The strike fractures are parallel to the inferred direction of maximum horizontal compression. Strike-fractures can be common in the subsurface despite the absence of flexure, and they are commonly important contributors to reservoir permeability (Lorenz and others, 1991).

In the Hartshorne area, numerous fractures are oblique to dip (green lines in Fig. 3), commonly oriented approximately NNW to NW as a possible consequence of the change of strike of the Choctaw fault in this area. To the east, the fault's orientation is mostly east–west, but near measured section G6 it turns toward the southwest (see Fig. 1 at the "aw" in "Choctaw"). Dip-oblique fractures are likely more abundant than might be inferred from outcrops, because this type of fracture is difficult to detect without bedding plane exposures, which are not common in Wapanucka outcrops.

In the frontal Ouachitas, most major thrust faults that affected the Wapanucka are located in the underlying shale; however, many minor thrusts are visible in the Wapanucka limestone. A few of these have obvious displacement, but most were recognized by the presence of slickensides or fault gouge. In outcrop, faults that are approximately parallel to strike are barely visible as gouge (approximately 2–6 in. thick). These faults resemble and could be mistaken for thin shale beds; however, they climb gradually and cut across limestone beds in an arcuate shape that is characteristic of thrust faults. Thrusts and other faults are commonly evident as zones of closely spaced, randomly oriented, small fractures or brecciated zones. A fault breccia (1–3 ft thick) consists of calcite-cemented fragments of adjacent beds, and occurs in the upper part of the Wapanucka at locality G28 (Fig. 2). (Abundant calcite in subsurface samples could be an indication of a fault.) Thrust faults in the middle shale (sub-Spiro shale) repeat or overturn the Spiro sandstone, independently of the Wapanucka limestone (Frost, 1981; Hinde, 1992).

Literature that addresses the orientation of subsurface Wapanucka fractures confirms that the subsurface fractures strike parallel to the Choctaw fault, analogous to many of the outcrop fractures. The Chitty Scott no. 1-30, in Pittsburg County, had an initial production of 6.7 MMcfd at 540 psi flowing pressure in fractured Wapanucka limestone. A frac-finder log of one of the wells in the area showed 74 ft of fractures and an east-west fracture trend, parallel to the Choctaw fault (Bleakley, 1980). In the Pittsburg field, imbricate thrusts repeat the Wapanucka–Spiro interval five or more times, and each individual imbricate slice (especially of the Wapanucka) is potentially productive (Montgomery, 1989). In this field, many wells have reserves >3 Bcfg. Most wells drilled in the structurally low areas were either dry holes or marginal wells due to the absence of porosity (Richardson, 1987). Greater reservoir enhancement may occur along the crestal portions of the structure due to tectonic fracturing.

Fracture Size, Spacing, and Relation to Lithology

The algal micritic-limestone unit (tubular algal boundstone in Fig. 2) in the middle part of the Wapanucka at locality G28 contains mostly irregular calcite-healed fractures. They have a random, chaotic orientation and are discontinuous. Adjacent, but different, lithologies may have been fractured at different times and with different fracture patterns (Nickelsen and Hough, 1967). This algal micrite has a fracture spacing ranging from 0.5 to 3.0 ft. Fractures do not appear to be capable of enhancing reservoir permeability because the fractures have been sealed with calcite. Also, these fractures terminate within the algal micrite unit, which has few bedding planes; therefore, fluid communication between fractures does not appear possible. However, because the outcrop surface is two-dimensional, it is impossible to determine if the fractures are connected in a third dimension. One of the cores examined for this study had irregular calcite-cemented fractures in micritic limestone and was from a well with excellent production. This core also contained abundant microfractures which, though observed in outcrops, were not recorded. The microfractures in the core are straight, 1–3 in. long, and either perpendicular or parallel to bedding. These microfractures may be the key to the production, because, unlike the larger irregular fractures, the small fractures are not calcite healed. Alternatively, production in this well could be enhanced by open fractures perpendicular to bedding that were poorly represented in the core because they are parallel to the axis of the borehole.

Locality G29 (Fig. 1), an abandoned quarry near Hartshorne, Oklahoma, contains abundant fractures in the thin-bedded sponge-boundstone and spiculitic-limestone unit near the top of the Wapanucka. Some strike-fracture planes (parallel to strike) are spaced as closely as 1–2 ft and are as much as approximately 20 ft by 40 ft in extent. The latter two dimensions might be greater, but some of the fracture plane is covered or has slumped to the quarry floor.

Numerous dip fractures (perpendicular to bedding) also occur in this sponge-rich limestone. Fractures commonly occur in groups. Fractured areas 20–40 ft wide are separated by areas 20–40 ft wide that are relatively fracture free. The fractured areas contain large fractures spaced ~6 ft apart. Many small dip fractures occur between the larger fractures, with an average spacing of ~3 ft and lengths of 1–6 ft. The long fractures normally range from 10 ft long, with terminations at bedding planes, to 40 ft long, where they cut completely through the sponge-boundstone and spiculitic limestone. Typically, at most outcrops, roughly half of the fractures terminate at bedding planes and the other half are longer. The long fractures in this quarry appear to die out in the Middle Shale Member above the sponge facies. Very few extend into the underlying micritic algal boundstone. As fractures frequently terminate at these micritic algal units, these units may be significant permeability barriers in the subsurface.

Throughout the frontal Ouachitas, large fractures (≥15 ft long) cut across several rock types and do not appear to be affected by lithology (Fig. 3). However, some fractures in one facies might not continue through the adjacent rock unit. Three long fractures near the center portion of locality G28 (Fig. 2) cut continuously through the sponge facies, but not through the other facies. Most fractures continue through shales <6 in. thick, but terminate in thicker shales (Fig. 3), especially if the shales are thicker than 3 ft. This might be expected because fracture terminations are common at contacts with more ductile beds (Stearns and Friedman, 1972). Subsurface Wapanucka shales that are 0.5–3 ft thick may not be permeability barriers because of fracturing. However, shales >3 ft thick may be considered permeability barriers because fractures were not observed to cut through them.

The fact that fractures are more abundant in the sponge-boundstone and spiculitic-limestone facies may be attributed to their thin bedding and hardness. Generally, thinner bedded units have more closely spaced fractures (Lorenz and others, 1991), and more brittle lithologies have more abundant fractures (Mallory, 1977). The sponge-boundstone and spiculitic facies appear to be the most brittle, and often contain abundant secondary chert, which is very brittle.

Spacing of dip fractures (perpendicular to strike) was measured at outcrops that haven't been dynamited, localities M6, M7, and M8 (Fig. 1). Locality M6 (Fig. 1) consists almost entirely of micritic tubular algal boundstone deposited on the outer portion of the Wapanucka platform. Fracture spacing was measured over a lateral distance of ~1,500 ft on a mound-shaped limestone outcrop (Fig. 4). It could be an algal (*Donezella*) mud mound, or its shape could have resulted from recent erosion. Because of the lack of bedding in this massive tubular algal boundstone, it is impossible to tell if the morphology is depositional or erosional, or if it is due to the fact that this anticline is plunging eastward. The fractures at this location are mostly grouped in sets ~200 ft across separated by 200-ft intervals that are, for the most part, devoid of large fractures. Most fractures cut entirely through the mound, which is ~20 ft thick. These fracture sets usually contain pairs of dip fractures, whereas the distance between fracture pairs ranges from 15 to 25 ft. The mound tapers to only 6 ft thick in the eastern 300 ft of the outcrop. Here, most dip fracture pairs cut through the entire 6 ft of limestone. Spacing between pairs is about 20–30 ft in the eastern portion, and fractures are approximately 3–6 ft apart in each pair (Fig. 4). In the far western part of this outcrop, where bedding is obvious, few fractures are observed, but more of the outcrop is obscured by soil and vegetation.

Fractures are well exposed ~18 mi west-southwest of Wilburton (Fig. 1) on the north limb of a tightly folded syncline just north of a snakehead anticline along the Choctaw thrust (Fig. 5). In the palinspastic restoration (Fig. 1), localities M7 and M8 are plotted about 7 mi south of the present site of the Choctaw fault. Sixteen dip fractures occur across 70 ft of outcrop (Fig. 6) in a 20-ft-thick exposure of medium-bedded Wapanucka limestone on the north side of the syncline (Fig. 6). Most fractures extend through the entire 20 ft of this fossil-rich limestone. Most of these macrofractures were spaced 6–8 ft apart; a few were spaced ~3 ft apart. Although extensive cover precluded measurement of stratigraphic intervals and definite identification of litho-facies, outcrops measured nearby contain Wapanucka shelf-margin and related deposits

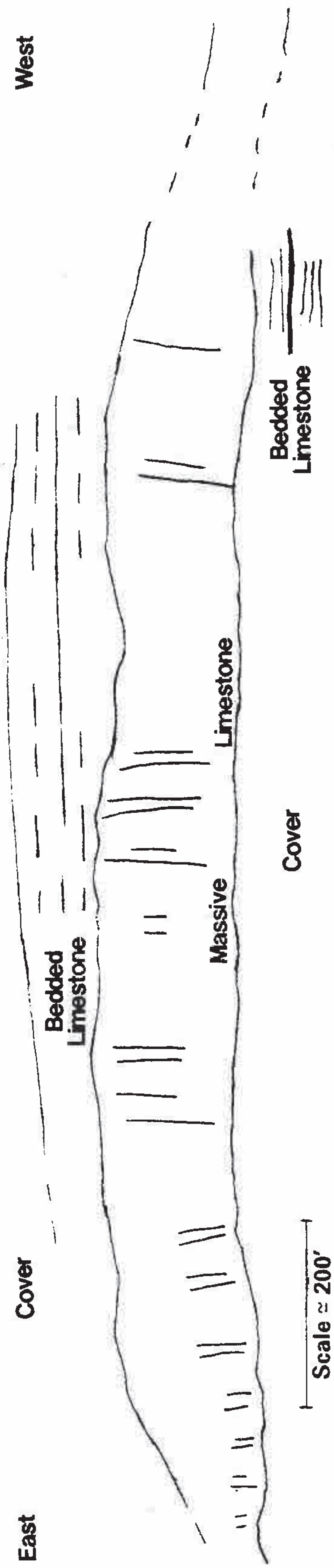

Figure 4. Fracture spacing in outcrop of the Wapanucka limestone. Dip fractures in an algal micritic-limestone (mostly tubular algal boundstone) at locality M6. The mound shape of the outcrop may be (1) depositional (i.e., an algal bioherm), (2) the result of recent erosion, or (3) structural. This outcrop is on the south limb of an anticline that plunges below the surface to the east. (The thickest portion of the massive limestone is ~20 ft.)

(grainstones, packstones, and sponge boundstones). Fractures, with the characteristics observed at this outcrop, could permit hydrocarbon communication between grainstone units in the subsurface.

No detailed measurements of fractures in the Spiro were made; however, based on observations at approximately 30 outcrops, fractures are more abundant in the limestone facies of the Spiro than in the sandstones, and silica- and/or calcite-cemented sandstones generally contain more fractures than the porous, weakly cemented sandstones. As in the Wapanucka, dip fractures and strike fractures are the most abundant fracture types in Spiro limestones. At Hartshorne Lake and localities G34 and G33, ~50% of the observed fractures are dip fractures and 30% are strike fractures. The remaining 20% are evenly divided between oblique fractures (in all facies) and irregular calcite-healed fractures (primarily in micritic limestones). This distribution of fracture types is essentially the same as distribution in Wapanucka limestones.

In contrast to the Spiro limestone which has abundant dip fractures at locality G34, the top of the Wapanucka has sets of orthogonal fractures oriented obliquely to dip and strike. These could be younger fractures related to near-surface phenomena (Lorenz and others, 1991), or may be evidence that dip fractures did not travel through the 48 ft of sub-Spiro shale between the Wapanucka and the Spiro. Due to lack of exposure, it is impossible to determine if the shale is fractured, or if it ever contained fractures that extended from the Wapanucka to the Spiro. In the cores studied, the sub-Spiro shale had some microfractures but no large fractures; perhaps because shales behave plastically (Nolte, 1988), which hinders fracture penetration (Lorenz and others, 1991). The thickness of the sub-Spiro shale could be an important factor for Wapanucka hydrocarbon accumulations. Fracture communication between the Wapanucka and the more-porous Spiro sandstone could possibly enhance the reservoir potential of the Wapanucka. This would be more likely to occur in regions of the subsurface where the sub-Spiro shale is thin or missing.

SUMMARY

Fracturing is believed to be of major importance to reservoir potential of the Wapanucka limestone. Numerous fractures in the frontal Ouachitas cut perpendicular to bedding. Most of these are oriented perpendicular to strike (dip fractures) or parallel to strike (strike fractures) (Fig. 3).

Fractured reservoirs of the Wapanucka Formation might be found in the sponge-boundstone and spiculitic-limestone facies because it has a high fracture density, as does the Chickachoc Chert. The sponge-boundstone and spiculitic-limestone facies was deposited on the upper Wapanucka shelf adjacent to the shelf margin. The Chickachoc Chert is the most basinward Wapanucka shelf deposit and should be recognizable on seismic sections due to its considerable difference in lithology from other Wapanucka facies.

Fracturing might create communication between porous segments of oolitic facies or phylloid-algal mounds. Oolites were formed on the shelf margin, usually capping bioclastic shelf bars. Phylloid-algal facies were deposited as

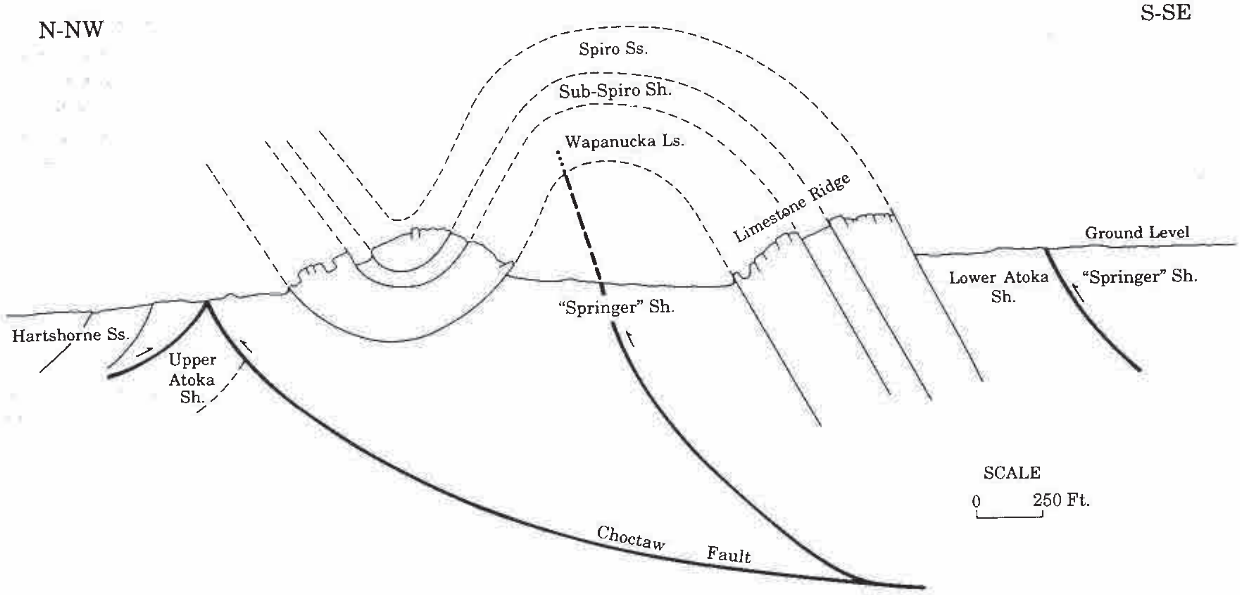

Figure 5. Cross section across Limestone Ridge ~18 mi west-southwest of Wilburton (near the "a" in Choctaw in Fig. 1). The syncline was identified by the presence of south-dipping Wapanucka limestone on the north side of the ridge and north-dipping Wapanucka limestone on the south side of the ridge and by Spiro sandstone and limestone in middle of the ridge.

shoals or boundstone mounds adjacent to the shelf margin, and may contain shelter porosity. The location of oolite and phylloid-algae deposits may be indicated on isopach maps by thick anomalies. Paleotopographic highs on top of the Springer shale, if not obscured by compaction, might also be indications of these favorable Wapanucka facies, because oolites and phylloid algae were probably deposited on local highs.

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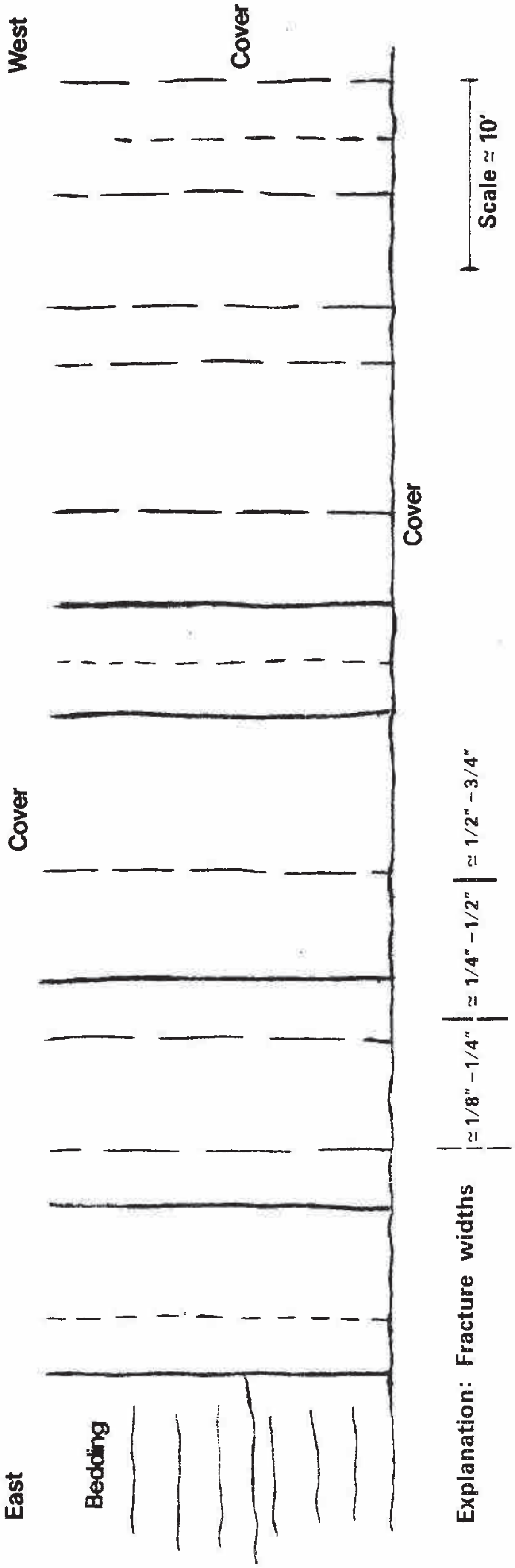

Figure 6. Fracture spacing measured along a strike fracture face (parallel to the Choctaw fault) at locality M8. Most of these are dip fractures (perpendicular to strike), except for a few that are slightly oblique. Runoff, from the slope above, probably has some effect on the fracture widths. All of the fractures are open, except for microfractures which were not recorded. Since the Wapanucka beds are usually tilted in the Ouachitas and southern Arkoma basin, most boreholes should intersect numerous Wapanucka fractures if this type of fracture spacing exists in the subsurface.

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