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Systematic joints in Devonian black shale: A target for horizontal drilling in the Appalachian Basin

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Abstract

The recent application of horizontal drilling as a means of extracting natural gas from black shales of the Appalachian Basin necessitates an enhanced understanding of the origin, orientation, distribution, and permeability of fractures in these source rocks. Some geologists working in the Appalachian Basin maintain that regional fractures hosted by Devonian black shales were generated by glacial loading of seemingly stiff units, yet such notions are contrary to outcrop and core observations that support a Late Paleozoic origin of these targets of horizontal drilling. Black shales carry two regional joint sets (J_1 and J_2) that formed close to or at peak burial depth as natural hydraulic fractures induced by abnormal fluid pressures generated during thermal maturation of organic matter. ENE-trending (J_1) joints parallel the maximum compressive normal stress of the contemporary tectonic stress field (S_H) and are crosscut by NW-trending (J_2) joints. Horizontal drilling should target J_1 by drilling to the NNW to take advantage of a permeability anisotropy arising from the more densely developed J_1 set that is subject to a lower normal stress (i.e, S_h of the contemporary tectonic stress field) than J_2.

Introduction

Recent trends in the price of natural gas have promoted the exploration of unconventional reservoirs of the Appalachian Basin. Devonian black shales constitute one class of unconventional reservoir from which production is optimized when horizontal drilling penetrates a well developed fracture set. However, the increasing use of horizontal drilling requires an improved understanding of those mechanisms that control the origin, orientation and permeability of natural fractures. Further, it is important for industry to recognize that other mechanisms, while they seem reasonable, are *faux amis* (i.e., false friends). One example of a *faux amis* explains fracturing as a consequence of glacial loading and unloading (e.g., Clark, 1982; Evans, 1989). Another *faux amis* holds that systematic fracturing of black shale is a consequence of the brittle nature of these rocks. Both notions are linked in the sense that a flexural bulge accompanying glacial loading may generate a tensile stress in the elastically stiffest rocks entrained above the neutral fiber of the bulge (Lash and Engelder, 2007). However, neither notion is consistent with the regional distribution of systematic fractures in Devonian black shale of the Appalachian Basin. This paper dispels both notions by briefly describing the strongest evidence that speaks against both the stiffness hypothesis and the hypothesized role of glacial loading and unloading in the preferential fracturing of black shales of the Appalachian Basin.

Rock fracture occurs either by rupture in shear or rupture in tension. Rupture in shear yields faults (Handin and Hager, 1957) whereas rupture in tension leads to the propagation of joints (Pollard and Aydin, 1988). Faults are rarely systematic and are invariably concentrated in local zones associated with a master fault or fold (Aydin and

Johnson, 1978) whereas joints are frequently systematic, occurring as sets over regions of more than 1500 km^2 (Engelder and Whitaker, 2006). In gas provinces such as eastern Kentucky, the success of a regional natural gas play employing horizontal completion techniques is heavily dependent upon on the presence of systematic joint sets.

The origin, orientation, and distribution of fractures in Devonian black shales

The Devonian succession of the Appalachian Basin is characterized by several bed-normal joint sets of which two (J_1 and J_2) constitute a basin-wide pattern (Sheldon, 1912; Parker, 1942; Engelder and Geiser, 1980; Lash and Engelder, 2007). Toward the northern end of the basin, the earlier joint set (J_1) formed preferentially in black shale. Joints of the J_1 set, designated as set III in the earlier literature (i.e., Parker, 1942), consistently strike ENE from Virginia to New York and correlate with a strong ENE-trending coal cleat in Morrowan and Desmonian coal deposits scattered from Alabama to Pennsylvania (Engelder and Whitaker, 2006). These early joints, where exposed in folded rocks of the Valley and Ridge, rotated with the tilted layers leaving no doubt that J_1 predates Alleghanian folding (Engelder 2004). The second suite of systematic joints (J_2), which is more common to gray shale deposits (Lash et al., 2004), comprises several subsets disposed approximately normal to fold axes along the orocline bend in both the central and southern Appalachians (Nickelsen and Hough, 1967; Engelder and Geiser, 1980). These subsets are collectively designated as set I in the earlier literature (i.e., Parker, 1942). Subsets overlap from region to region so that individual beds may host more than one subset distinguished by differences in strike of 10º or more (Younes and Engelder, 1999). J_2 retained its vertical orientation during folding as a consequence of its cross-fold orientation (Engelder, 2004). Where J_1 and J_2 joints are observed in the same black shale they generally crosscut (Fig. 1).

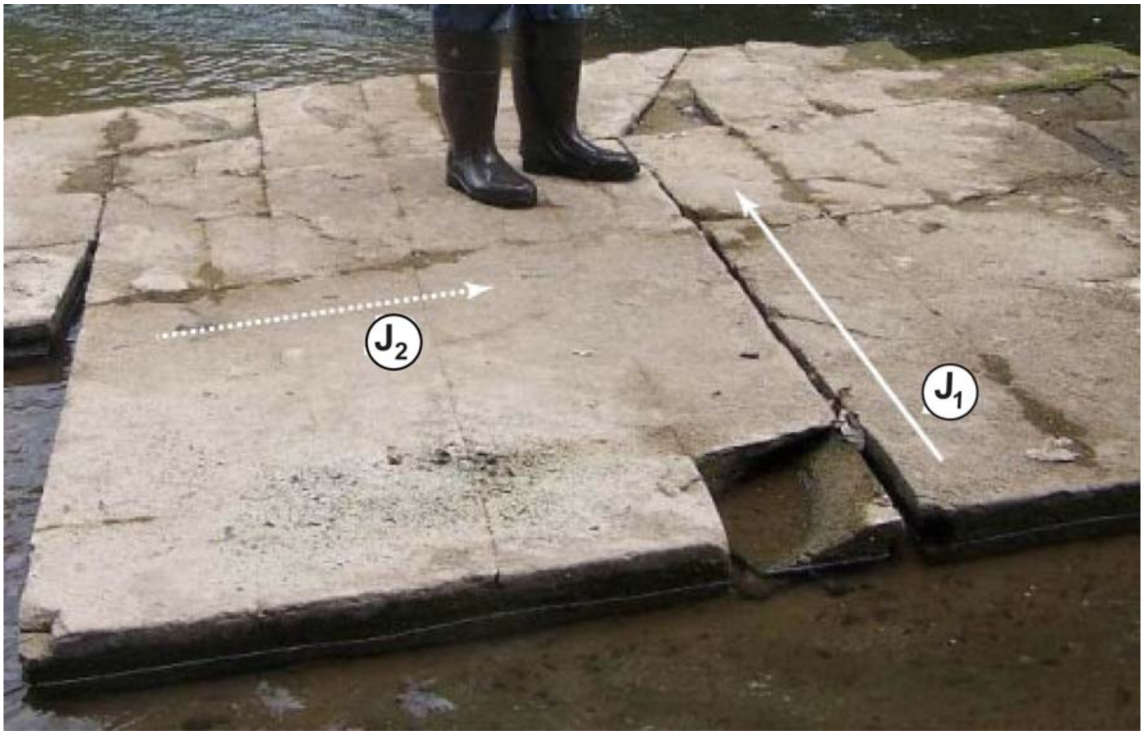

Figure 1. Crosscutting J_1 and J_2 joints in the Marcellus black shale exposed in Oatka Creek, Leroy, NY.

Principal natural gas reservoirs in the Devonian section of the Appalachian Basin include the Lower Huron Member of the Ohio shale and the Marcellus shale (Curtis and Faure, 1997; Curtis, 2002). Other black shale units also yield natural gas, and it is common for industry to allow gas from the various black shale intervals to co-mingle, particularly in vertical completions. The presence of J_1 and J_2 joints in core recovered during the Eastern Gas Shales Project (EGSP) assures that in some portions of the Appalachian Basin, joints of both sets were generated at depths in excess of 2 km (Cliff Minerals, 1982). Further, J_1 and J_2 joints appear together with a greater frequency in black shale intervals, including the Marcellus (i.e., PA-1) and the Dunkirk/Lower Huron black shale (i.e., WVA-5), of EGSP cores. However, the most recurring joint distribution pattern observed in core is one in whichJ_1 favors black shale and J_2 is found preferentially in gray shale. J_1 is particularly well developed in the black shale of the Dunkirk/Lower Huron in a region extending from western New York south to eastern Kentucky (Fig. 2). Mineralized joints are found in deeper core from the central portion of the basin with J_2 most likely to carry a mineral filling (Evans, 1995).

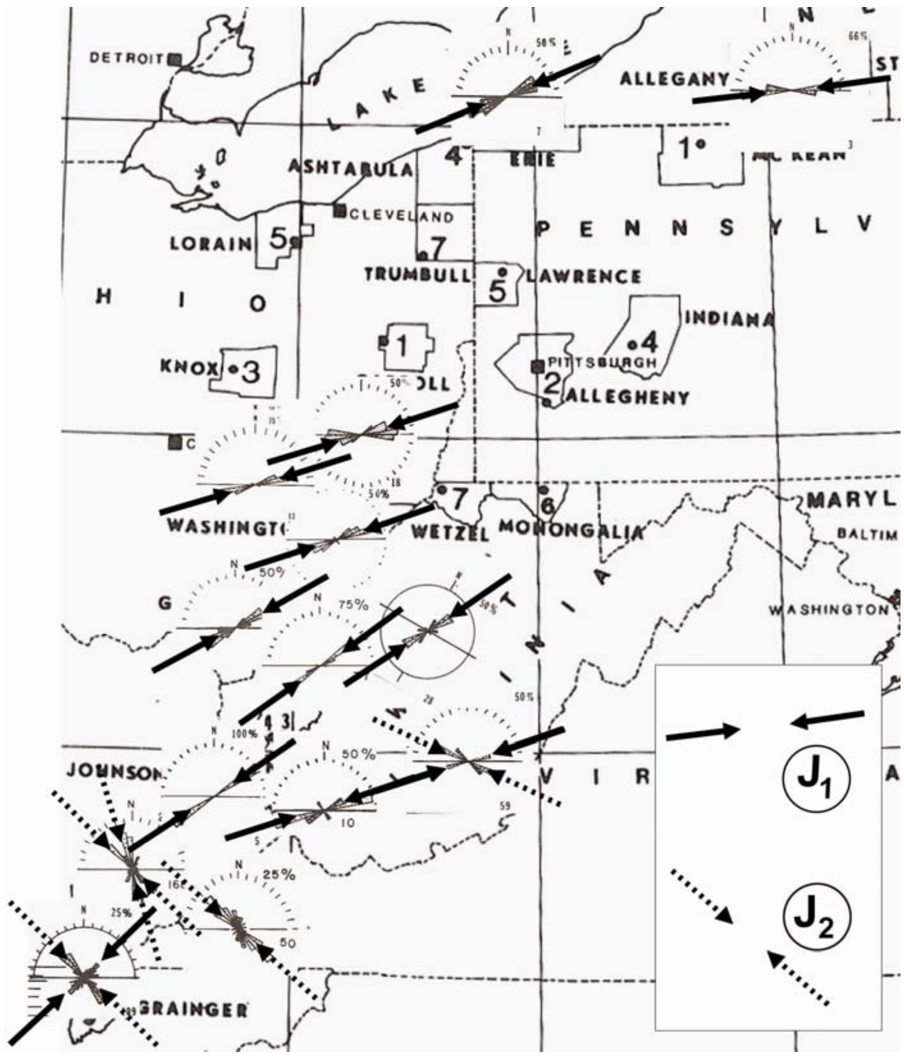

Figure 2. Joints in the Dunkirk/Middle Huron section of cores recovered during the EGSP project (adapted from Cliff Minerals, 1982).

Black shale units, including the Marcellus, the Geneseo, and the Middlesex, commonly carry crosscutting J_1 and J_2 (Fig. 1). Crosscutting joints are best observed in the northwestern region of the basin in NY, yet they also appear where Devonian shale is brought to the surface in the folded Valley and Ridge of PA. At the Allegheny Front where the Marcellus shale is upturned to slightly overturned, J_1 dips steeply to the east whereas J_2 is vertical and in the cross fold orientation (Fig. 3). Here, the acute angle between J_1 and J_2 is less than in western NY, largely because J_2 changes strike along the oroclinal bend of the Central and Southern Appalachians whereas ENE-trending J_1 joints retain a consistent orientation along the length of the mountain chain (Engelder and Whitaker, 2006). Moreover, the crosscutting joint pattern documented from the NW and SE edges of the Appalachian Basin of PA and NY makes its way into the deepest reaches of the subsurface of the Central Appalachian Basin as indicated by two joint sets found in some but not all EGSP cores.

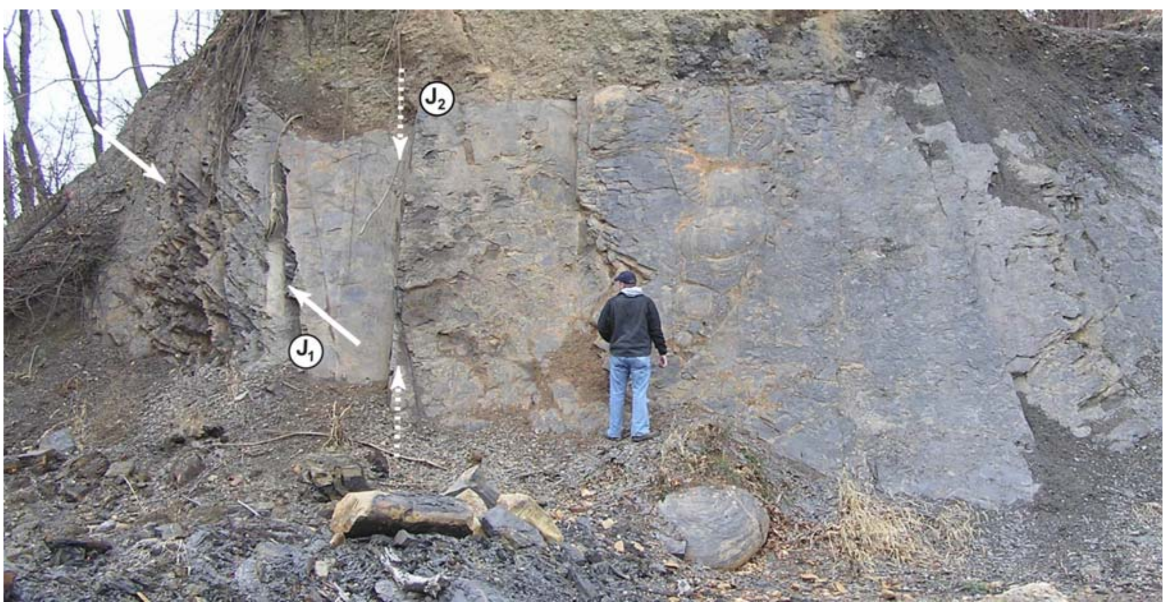

Figure 3. J_1 and J_2 joints in the Marcellus black shale within overturned beds just north of the Allegheny Front at Antis Fort, Pennsylvania. The view is looking north at the underside of bedding.

Timing of J_2 relative to J_1

Resolution of joint chronology in the Devonian shale succession is difficult because J_1 and J_2 joints crosscut (Fig. 1). Dating of J_2 propagation after J_1 propagatoin is based on two self-consistent observations. First, J_1 is normal to bedding throughout the Appalachian Mountains. Second, J_1 joints observed in folded rocks of the Valley and Ridge of both VA and PAwith bedding during 'classic' Alleghanian folding. Regardless of outcrop position along both the Central and Southern Appalachian oroclines, unfolding of bedding invaliably returns J_1 to an ENE strike. Further, J_2 joints parallel the maximum horizontal compression normal to fold axes around which J_1 joints were rotated during folding. Thus folding and J_2 propagation are taken as roughly synchronous whereas J_1 propagation predates folding.

Some J_2 joints in black shale of the Finger Lakes region of the Appalachian Plateau show evidence that they were reactivated in shear during later stages of the Alleghanian orogeny (Engelder et al., 2001). The sense of slip on these joints is consistent with an S_H aligned with the direction of layer-parallel shortening of the Appalachian Plateau thrust sheet (Oertel et al., 1989). Syn-Alleghanian slip of no more than a few cm along J_2 joints is indicated by offset of J_1 joints leading to the conclusion that J_1 predated J_2.

The origin of J_1 and J_2 joints

Because the Earth is a self-gravitating body, vertical stress (S_v) is compressive and increases with depth as a function of integrated density. In the absence of tectonic stress, minimum horizontal stress (S_h) is also compressive and a function of rock properties depending largely on the state of lithification of the rock. Early in the history of a sedimentary basin like the Appalachian Basin, S_h is related to S_v through consolidation (Karig and Hou, 1992). After lithification, however, S_h varies as a function of S_v through elastic rock properties (Narr and Currie, 1982). The extent to which the interior of the Earth remains in compression is witnessed by the fact that tensile stress has never been measured at depth in rock except near the points of extreme stress concentration associated with tunnels, mines, boreholes and other man-made cavities within the Earth (Engelder 1993).

Joint propagation arises from one of the two major driving stresses: absolute tension and effective tension. The latter is achieved when compressive stress at depth is counterbalanced by a fluid pressure within the joint, thus leading to joint propagation by the natural hydraulic fracturing (Engelder and Lacazette, 1990). Absolute tension rarely occurs within a self-gravitating Earth except as a consequence of (1) thermoelastic contraction associated with rapid cooling of igneous rocks (DeGraff and Aydin, 1987) and (2) folding where rocks on the outside of a neutral fiber are brought to tension by bending stresses (Lash and Engelder, 2007). Thermoelastic contraction can be ruled out as a mechanism for generating tensile stress and consequent joints in black shale of the Appalachian Basin. Further, the fact that these rocks are flat-lying to gently folded suggests that bending cannot account for regional joint propagation.

The J_1 joint set is present in organic-rich rocks, including black shale and coal, throughout the Central and Southern Appalachians (Engelder and Whitaker, 2006). In light of the limited mechanisms for generating absolute tensile stress in Devonian shale and Carboniferous coal successions, NHF remains the most likely joint-driving mechanism. Surface morphology on J_1 joints reveals the cyclic rupture expected of a NHF (Lacazette and Engelder, 1992). The NHF driving mechanism is confirmed by joints that propagated through concretion-bearing shale without cleaving the concretions (McConaughy and Engelder, 1999). Moreover, the strong affinity between J_1 and black shale supports the argument that volume-increase reactions during the transformation of organic matter to hydrocarbons creates the high fluid pressures necessary to drive NHFs through these rocks (Lash and Engelder, 2005). In fact, joint propagation by incremental rupture indicates that the driving fluid was CH_4 (Lacazette and Engelder, 1992).

Coal cleat is another type of NHF structure generated in response to the thermal maturation of organic material. The earliest coal cleat in the greater Appalachian Basin from AB to PA strikes parallel to J_1 (Engelder and Whitaker, 2006). Cleat forms as a consequence of pressure generation associated with dewatering as coal enters the oil window (Ting, 1996). Burial curves for Pennsylvanian coals of the Black Warrior Basin of AB and for Devonian black shale of the northern Appalachian Basin show that (1) both deposits entered the oil window at about 300 Ma (Pittman et al., 1997; Lash at al., 2004) and (2) J_1 formed during a 15 Ma window between 305 Ma and 290 Ma (Engelder and Whitaker, 2006).

Key to understanding the origin of fluid driven joints like J_1 is an appreciation that tectonic stress was not responsible for joint propagation. Rather, these joints propagated as a direct result of the burial-related maturation of organic matter. Tectonic stress, by virtue of a consequent horizontal stress anisotropy (i.e., direction of $S_{H)}$, controlled the joint propagation direction but not the timing of propagation. The uniform orientation of J_1 throughout the Appalachian Basin bears witness to the presence of a lithospheric-plate scale stress field (Engelder and Whitaker, 2006) that arose from lithospheric plate boundary tractions (i.e., Nakamara et al., 1977). The formation of J_1 joints records the lithospheric-plate stress field related to the oblique convergence of Gondwana and Laurentia during formation of the Pangean supercontinent (Engelder and Whitaker, 2006).

While it is true that J_2 joints are present in organic-rich rocks of the Appalachian Basin, including both black shale and coal, they are best developed (i.e., most densely formed) in Devonian siltstone and gray shale successions. Like their predecessors, J_2 joints have characteristics of NHFs (Engelder and Lacazette, 1990; Lash et al., 2004). The orientation of these joints, which appear in the cross-fold orientation relative to the Alleghanian folds of the Central and Southern Appalachians, was controlled by tectonic stress. The J_2 joint set comprises several overlapping subsets indicative of a regional stress field that rotated throughout the time of J_2 propagation (Nickelsen and Hough, 1967; Engelder and Geiser, 1980). In some regions of the Appalachian Basin, the Alleghanian stress field rotated clockwise; elsewhere, the stress field rotation was counterclockwise (Zhao and Jacoby, 1997; Younes and Engelder, 1999).

Some geologists equate the heavily fractured nature of black shale of the Appalachian Basin with a high elastic stiffness. However, organic-rich deposits of the Appalachian Basin are defined by relatively large sonic travel times and low densities indicative of relatively low elastic stiffness (Plumb et al., 1991). They are also subject to relatively high S_h (Evans et al., 1989). The initiation of J_1 within black shale indicates that neither low stress nor high stiffness were critical properties in localizing joint propagation as would be the case for joints driven by absolute tension. This observation further fuels the conclusion that elevated fluid pressure, likely a consequence of catagenesis, enabled these joints to propagate under effective tension.

Glacial loading as a mechanism of joint propagation

Glacial loading related to the establishment of the Laurentine ice cap created a forebulge that advanced southward and then retreated to the north in response to the decay of the ice cap. In such a scenario, joints could have propagated as a consequence of the development of absolute tensile stress above the neutral fiber of the forebulge. Clark (1982) argued for development of a maximum radial tensile stress at 0.9 km depth about 50 km SSE of the glacial limit, which passes from central Ohio through NE Pennsylvania. Induced tensile stress would have reached no more than 150 km SSE of the glacial limit although in the presence of hydrostatic pore pressure an effective tension may have extended somewhat farther to the south. A potential shortcoming of this model is that the difference between overburden compressive stress and horizontal tension would have exceeded the frictional limit for normal faulting within Devonian shale succession of the Appalachian Plateau (Evans, 1989). Still, there is some evidence that local tension can develop in stiff layers without concomitant faulting throughout the section (Lash and Engelder, 2007).

The timing of J_1 at the beginning of the Alleghanian orogeny leaves no doubt that glacial loading did not drive these joints (Engelder and Whitaker, 2006). Moreover, jointing associated with glacial loading would have occurred in the stiffest beds first. Indeed, within the Devonian shale succession, relatively compliant organic-rich shales would have been last to host joints induced by glacialloading. Moreover, glacial loading would have produced one joint set, yet two sets crosscutting at nearly right angles are found within the central basin at depths well in excess of that predicted for the glacial loading model. Crosssutting of joints itself is indicative of relatively high compressive normal stress across the earlier joint, which is inconsistent with establishment of absolute tensile stress predicted by the glacial loading model. Finally, glacial loading might result in slight overpressuring in shale due to compaction disequilibrium but compaction disequilibrium acting alone is not capable to causing NHF largely because S_h increases with increasing compaction-induced pressure.

A geological coincidence

The J_1 joint set and S_H of the contemporary tectonic stress field are parallel in eastern North America (Plumb and Hickman, 1985; Zoback, 1992). This parallelism led to an early interpretation that the orientation of the J_1 joints was controlled by the modern S_H in the North American lithosphere (e.g., Engelder, 1982). Indeed, some J_1 joints have mistakenly been called neotectonic joints (Hancock and Engelder, 1989). We now know that the parallelism of S_H and J_1 is a geological coincidence (Engelder and Whitaker, 2006). In the Late Paleozoic, the modern eastern edge of North America (Laurentia) was oriented about 45º clockwise from its present orientation such that this same edge of Laurentia faced south (modern coordinates). ESE- to WNW-directed convergence of Gondwana (Africa) against Laurentia (North America) set up plate boundary tractions in which S_H paralleled the direction of convergence (Engelder and Whitaker, 2006). At the time of their propagation, J_1 joints were oriented ESE. However, post-Paleozoic continental drift carried these joints into their present orientation parallel to S_H of the contemporary tectonic stress field.

There is, however, a joint set that parallels S_H of the contemporary tectonic stress field and post-dates folding (Hancock and Engelder, 1989). Joints of this set are vertical in regions of the Appalachian Valley and Ridge where beds dip as much as 30º. The Marcellus shale of outcrop in the Valley and Ridge of PA carries both J_1 and 'neotectonic' joints (J_3). J_1 joints rotated in response to folding remaining normal to bedding whereas J_3 joints are perpendicular to the Earth's surface and thus define acute angles with tilted beds (Fig. 4). The Marcellus shale exposed as much as 40 km into the Valley and Ridge from the Allegheny Frontdisplays a well-developed disjunctive cleavage that had started to overprint J_1, a confirmation of the early and deep propagation

Figure 4. J_1, J_2, and J_3 joints in the Marcellus black shale within folded beds just south of Jacksons Corner, Pennsylvania. The view is looking ENE at south-dipping bedding.

of these joints. It is possible that J_3 joints in the Valley and Ridge were induced by glacial loading in the contemporary tectonic stress field, yet J_1 is surely not related to either glacial loading or the contemporary tectonic stress field.

Horizontal v. vertical wells

Although J_1 and J_2 joints in black shale are both NHF and, consequently, virtually identical in terms of aperture and surface roughness, there are two important differences between these joint sets when it comes to engineering and completion techniques necessary to maximize production of natural gas. First, unmineralized joints subject to lower normal stress will be more permeable (Kranz et al., 1979). The least horizontal normal stress in the Appalachian Basin is nearly perpendicular to J_1 meaning that, all things being equal, J_1 is more permeable than are J_2. Second, J_1 joints are the better developed and more closely spaced than J_2 in organic-rich rocks (Loewy, 1995; Lash et al., 2004). Thus, even if J_1 and J_2 have the same permeability, the host black shale will exhibit a bulk anisotropy with a higher permeability in the J_1 direction.

The completion of vertical wells may involve large hydraulic fracture treatments. Propagation of hydraulic fractures will strike ENE-WSW in the direction of S_H of the contemporary tectonic stress field (Evans et al., 1989). Hydraulic fractures propagating in this direction will intersect a J_2 joint and, presumably, continue on across several more. In this case, the major drainage path to the well is first along J_2 and then along the ENE-trending hydraulic fracture. By intersecting J_2 joints, hydraulic fracture treatments in vertical wells are capable of taking advantage of neither the bulk permeability anisotropy of black shale nor the normal-stress induced permeability anisotropy of J_1 vs. J_2 joints.

Because the contemporary tectonic stress controls the propagation of hydraulic fractures across J_2 joints, the only practical means of immediately communicating with the more permeable J_1 joint set is by horizontal drilling in a NNW or SSE direction. In this case, later hydraulic fracturing from the horizontal portion of the well bore will propagate in the direction of S_H which is parallel to J_1. The likely outcome of a hydraulic fracture treatment in a horizontal well drilled to the WNW, for example, is the reopening J_1 rather than fracturing intact black shale. Hence, horizontal drilling in Devonian black shale should be directed to the NNW, perpendicular to S_H of the contemporary tectonic stress field, to benefit from both the bulk permeability anisotropy and the normal-stress induced permeability anisotropy of these rocks.

Conclusions

Successful horizontal drilling of unconventional reservoirs is dependent upon a reliable prediction of the orientation of systematic fractures. J_1 formed preferentially in Devonian black shale throughout the Appalachian Basin early in the Alleghanian tectonic cycle as a consequence of burial-related thermal maturation of kerogen to hydrocarbons. This joint set, the most closely-spaced in black shale, is now oriented parallel to the maximum horizontal stress of the contemporary stress field. Black shale also carries a less well developed younger joint set (J_2) which, by virtue of its orientation, is subject to higher normal stresses in the contemporary tectonic stress field. Hence, a higher joint density and stress-induced permeability anisotropy in Devonian black shale speaks to the advisibility of horizontal drilling toward the NNW or SSE in order to cross the more densely formed J_1 systematic joint set subject to a lower normal stress in the contemporary tectonic stress field.

Acknowledgments

This paper was supported by Penn State's Seal Evaluation Consortium.

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