much more detailed than the ODNR – Division of Geological Survey map of the top of the Berea Sandstone structure that covers all of eastern Ohio (Gray, 1981).

The yellow lines on Figure 3-11 (Attachment 4) represent contours of equal elevation of the top of the Berea Sandstone (bottom of the Cuyahoga Shale). The interval between contour lines is five feet of elevation. The contour lines show that the top of the Berea Sandstone is undulatory and has more than 50 feet of relief. The highest area on the surface lies beneath homes in the middle part of English Drive (> 915 feet), whereas the lowest area on the surface occurs to the west along Geauga Lake Road (< 860 feet). The surface contains a "saddle," a local low area that extends north-south beneath Kenston Lake Drive (Figure 3-11). West of the saddle the Berea Sandstone top rises to the high area beneath English Drive, whereas east of the saddle the Berea Sandstone top rises toward Chillicothe Road. Thus, the saddle separates two high areas in the surface. As demonstrated in Chapter 3, the saddle is an important factor in the eastern part of the investigation area where it controls migration of gas in the Berea Sandstone and the subsequent leakage of gas upward into joints in the Cuyahoga Shale. As viewed from gas rising upward from the poorly permeable Ohio Shale into the highly permeable Berea Sandstone, the configuration of the top of the sandstone represents the top of the surface (look up at the ceiling) to which gas (think red balloon) can rise before being impeded by the poorly permeable Cuyahoga Shale (think attic insulation above the ceiling).

Local Oil and Gas Plays

Many well-known and well-documented oil and gas "plays" occur in northwestern Pennsylvania and northeastern Ohio. Information concerning the geologic characteristics of local oil and gas fields helped the expert panel visualize how gas migrated from the overpressurized surface-production casing annulus in the English #1 gas well through different geologic units into residential water wells in the Berea Sandstone and Cuyahoga Shale. A play consists of four components that together enable oil and/or gas to accumulate in rocks. These components are (1) a hydrocarbon source rock, (2) a reservoir rock that enables lateral migration and storage of hydrocarbons, (3) a caprock to prevent hydrocarbons from further vertical migration, and (4) a trap to allow the migrating hydrocarbons to accumulate in the reservoir rock (Figure 3-13).

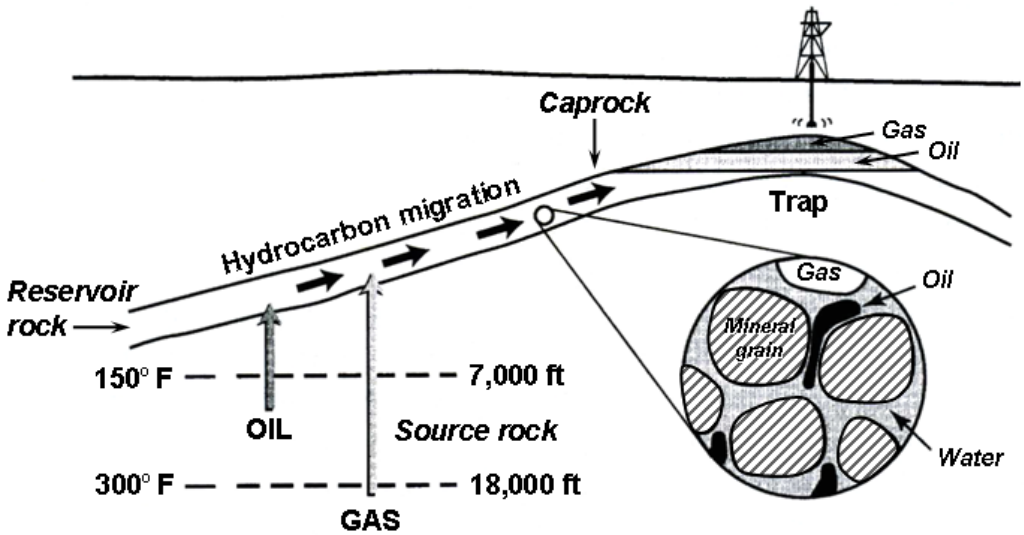

Figure 3-13. Generation, flow, and accumulation of oil and gas within a "play" (modified from Hyne, 2001).

The most detailed and up-to-date descriptions of historic and current commercial oil gas fields in northeast Ohio and northwestern Pennsylvania are in "The Atlas of Major Appalachian Gas Plays," or simply the "Gas Atlas." It is a 1996 report prepared by the West Virginia Geologic and Economic Survey for the U.S. Department of Energy and the Gas Research Institute. The 200 page, large format report contains individual chapters on 30 plays in the Appalachian Basin, which includes all or parts of New York, Pennsylvania, Ohio, West Virginia, Maryland, Virginia, Kentucky, and Tennessee, and citations to more than 900 technical papers and reports. Several chapters are written by experts in the divisions of Geological Survey and Mineral Resources Management within the Ohio Department of Natural Resources. The three chapters dealing with plays in the Berea Sandstone and Devonian Shales (Ohio Shale) are relevant to the tasks of the expert panel. This section presents pertinent information gleaned from the Gas Atlas and from other technical papers.

Plays in the Fractured Ohio Shale

The shale and siltstone layers that comprise the Ohio and Bedford shale in Ohio are called by different names in other parts of the Appalachian Basin. The general term petroleum geologists use to refer to these rocks is Devonian shales and siltstones. (Devonian refers to the part of the geologic time scale during which these rocks formed.) The Gas Atlas devotes two chapters to the plays in these rocks. The first of these chapters describes natural gas production from plays in organic-rich, radioactive shales in parts of Ohio, Kentucky, and West Virginia (Boswell, 1996). The first major gas production in this play was drilled in eastern Kentucky in 1921. Subsequent drilling in the area proved the shale to be consistently productive and by the 1930s the play had expanded into West Virginia and southern Ohio (Boswell, 1996). The Gateway Field in Lawrence County, Ohio, first produced gas in this play in the 1930s. The field remains active today, producing gas from 59 wells drilled into fractured Ohio Shale. After the discovery of the Gateway Field, several other fields in this play were discovered in Ohio including ones in Meigs, Athens, Noble, Washington, Muskingum, Licking, Knox, Coshocton, and Summit counties. According to Boswell (1996),

> *"The uniqueness of the black shale as a reservoir became evident early in the development of the play. Unlike the established sandstone reservoirs in the eastern half of the [Appalachian] basin, the distribution of good and poor shale wells seemed disconnected to either stratigraphic changes in reservoir character or to local structure. Also, the stratigraphic location of shows within the shale sequence was erratic… Although the idea had been discussed earlier, it was not until the 1950s that the unique characteristics of shale gas production were widely attributed to natural fracturing in the reservoir (Hunter and Young, 1953)."*

Boswell (1996) states that the newly discovered major gas fields in the Devonian shales and siltstones in Ohio, Pennsylvania, New York, West Virginia, and Kentucky are all related to the migration and storage of natural gas in naturally-occurring fractures. The other chapter in the Gas Atlas describing gas fields in the Ohio Shale is titled the "Upper Devonian Fractured Black and Gray Shales and Siltstones Play" (Milici, 1996). He describes both the major new gas fields developed in the Appalachian Basin in this play as well as the older fields where the occurrence of natural fractures in the thick sequence of Devonian shales first led to commercial production. The play is defined by shale gas reservoirs that consist of fractured black shale source rocks interbedded with gas-producing gray shales and siltstones (Milici, 1996). Many of the original gas fields developed in this play paralleled the southern shore of Lake Erie (Figure 3-14). The

first large gas well in this play was drilled in the 1860s in Fredonia, New York. It supplied gas for street lights and lighting and heat for public buildings. Soon after, discoveries in this play spread to Erie, Pennsylvania, then northeastern Ohio, and reached Lorain County, Ohio, in 1880 (Milici, 1996).

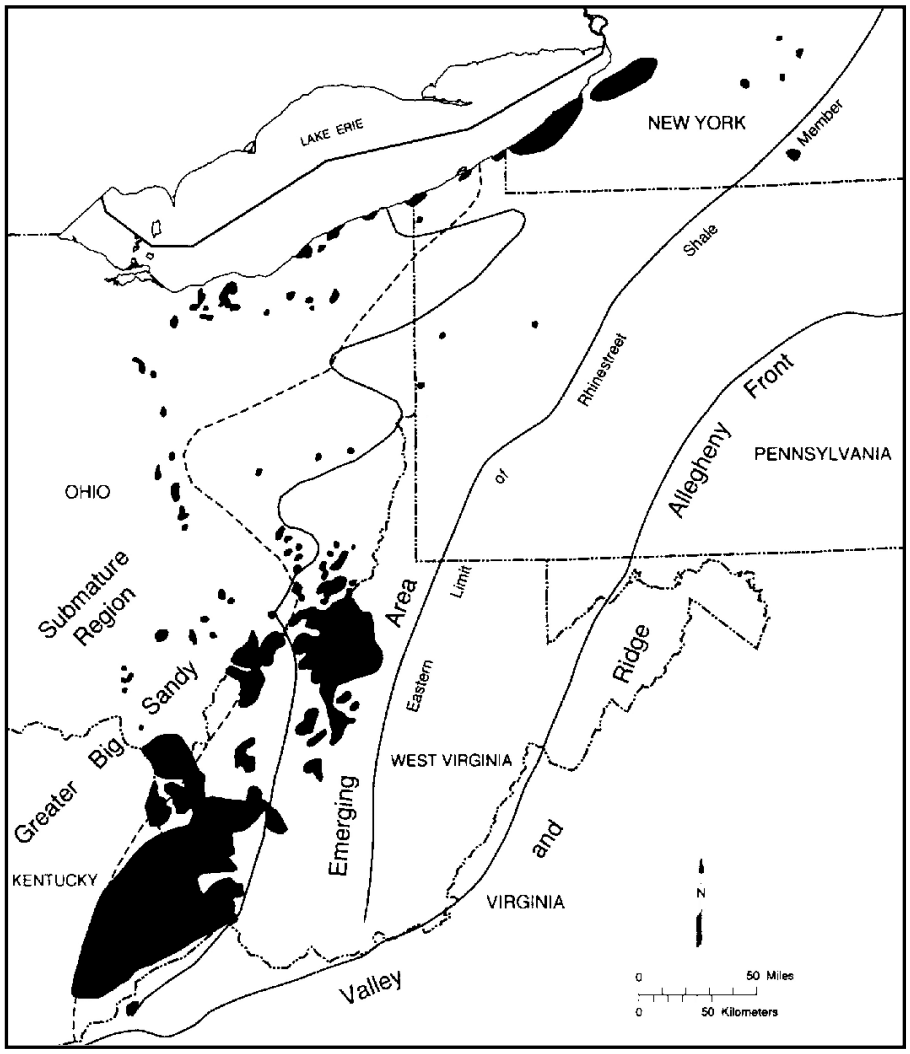

Figure 3-14. Location of fields in the Fractured Black and Gray Shale and Siltstones Play including fields in the Ohio Shale in northeastern Ohio (modified from Milici, 1996).

These older wells typically were low-yielding and low-pressure, but long-lived and capable of providing residential heating and lighting for many years (Janssens and de Witt, 1976). Milici (1996) tabulated reservoir data from 19 commercial gas fields developed in the Upper Devonian Fractured Black and Gray Shales and Siltstones Play. Eight of these fields are in Ohio, including active gas fields in Willoughby, Geneva, and Lowellville, and all eight fields produce gas from the Ohio Shale. The depth to the top of the fractured shale reservoir in these eight fields ranges from 3,860 to 920 feet and averages 2,410 feet. The average pay zone thickness in the Ohio Shale is 210 feet and ranges from 70 to 450 feet. These data indicate that natural fractures in the Ohio Shale are known to occur at depths 1000 feet or more below the bottom of the Ohio Shale in the English #1 gas well.

Figure 3-15 shows production activities at a successful gas well in Geauga County drilled in 1909 into the fractured Ohio Shale reservoir.

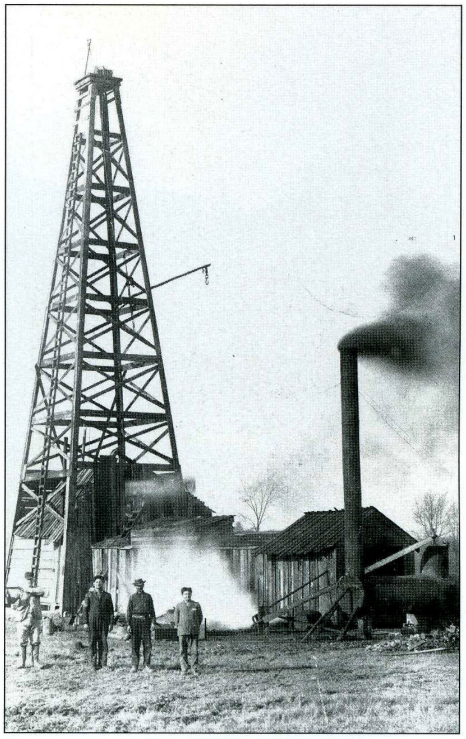

Figure 3-15. Production activities at a 1909 well in Geauga County, Ohio, drilled into fractured Ohio Shale (Spencer and Camp, 2008).

Geologic Processes Forming Fractures and Joints

Three different geologic processes are generally accepted for creating the natural fractures in the Devonian shales and siltstones. The first of these processes is called "glacial unloading" and is a well-documented phenomenon in the technical literature in Canada, Scandinavia, and the United States. Its application to the fractured shale and siltstone reservoirs paralleling the southern Lake Erie coast was first suggested by White (1992). He stated that the 4,000 to 6,500 feet of sediment-laden glacial ice that periodically existed in the Lake Erie region during the Pleistocene Epoch of geologic time compressed the near-surface sedimentary rocks. Vertical fractures in these rocks resulted from the isostatic rebound (decompression and re-expansion) of the brittle shales and siltstones. In the past decade this mode of joint creation has gone out of favor as more research into the origin of joints in the Appalachian Plateau of Ohio, Pennsylvania, and New York has been published (Miller, 1996; Engelder, 1993).

A geologic process known to produce natural fractures is called "progressive unroofing" (Figure 3-16). In progressive unroofing, as rock is slowly removed from the land surface over geologic time by weathering, erosion, and sediment removal by streams and rivers, shallow rock units expand vertically and contract horizontally. The stretching and contracting are caused by cooling from temperatures exceeding 200° C at depth, to land surface temperatures between 10° to 25° C. Vertical fractures form in the shallow rocks in response to the removal of overburden, the change in lithostatic pressure, and the change in temperature. In the context of progressive roofing, "shallow" is within half a kilometer (1600 feet) of the land surface (Engelder, 1993, p. 56). The 1,725 foot thick section of Ohio Shale at the English $^{\#}$1 gas well occurs at depths between 220 to 1,950 feet below the land surface.

The rocks in northeastern Ohio have been above sea level and subjected to weathering and erosion for the past 250 million years, including the past 2 million years when continental ice sheets periodically covered the area. Through geologic time, a continuous cycle of simultaneous joint creation and destruction develops. This cycle continues to operate today as overburden (rock and sediment) is removed as the land surface by weathering and erosion as shallow rocks form vertical joints as they rise toward the land surface. Continued weathering and erosion slowly remove the "new" overburden as it is replaced by formerly deeper rocks that develop "new" vertical joints as they slowly rise toward the land surface. Thus, the vertical joints we see today in the Ohio Shale and the rock units overlying it will be weathered and eroded away in the next many million years and replaced by formerly deeper rocks containing vertical fractures created during their pilgrimage to the land surface.

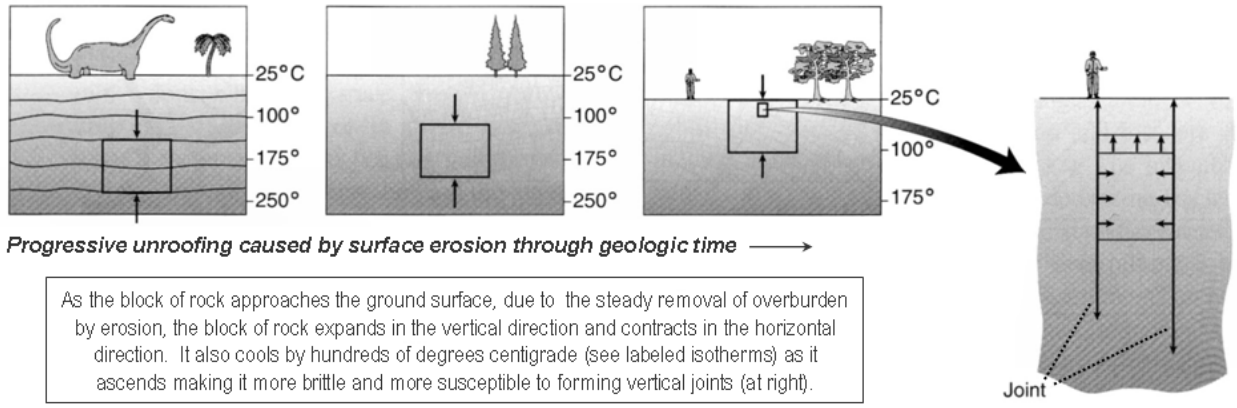

Figure 3-16. Formation of vertical joints from progressive unroofing of overburden (modified from Marshak and Mitra, 2006).

The bearing (azimuth) of this type of joint formed by progressive unroofing is imprinted at depth and is parallel to the axis of principal plane of stress, which in Ohio has been to the east-northeast for the past tens of millions of years (Figure 3-17), subsequent to major tectonic stresses during the Alleghanian Orogeny more than 300 million years ago (Engelder, 1993).

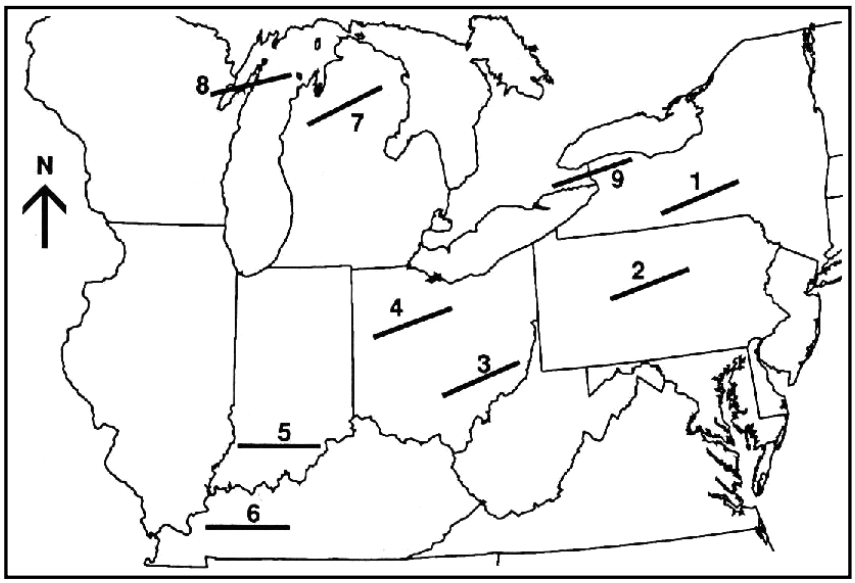

Figure 3-17. Orientation of neotectonic joints in the northeastern United States (modified from Engelder, 1993).

The joints represented by numbers 3 and 4 on Figure 3-17 were measured by Professor Karl Ver Steeg at the College of Wooster in Wooster, Ohio, and published in Ver Steeg (1942).

Stresses created by the movement of Earth's tectonic plates also create joints. When the Appalachian Mountains formed during the 50 million year collision of the North American tectonic plate with the African tectonic plate during the Alleghanian Orogeny, tectonic joints were created parallel to the plane of maximum stress created by the colliding plates. This 300 million year old set of deeply imprinted joints is preserved in rocks in Ohio, Pennsylvania, and New York. In Ohio, the bearing of these joints is west-northwest (Figure 3-18).

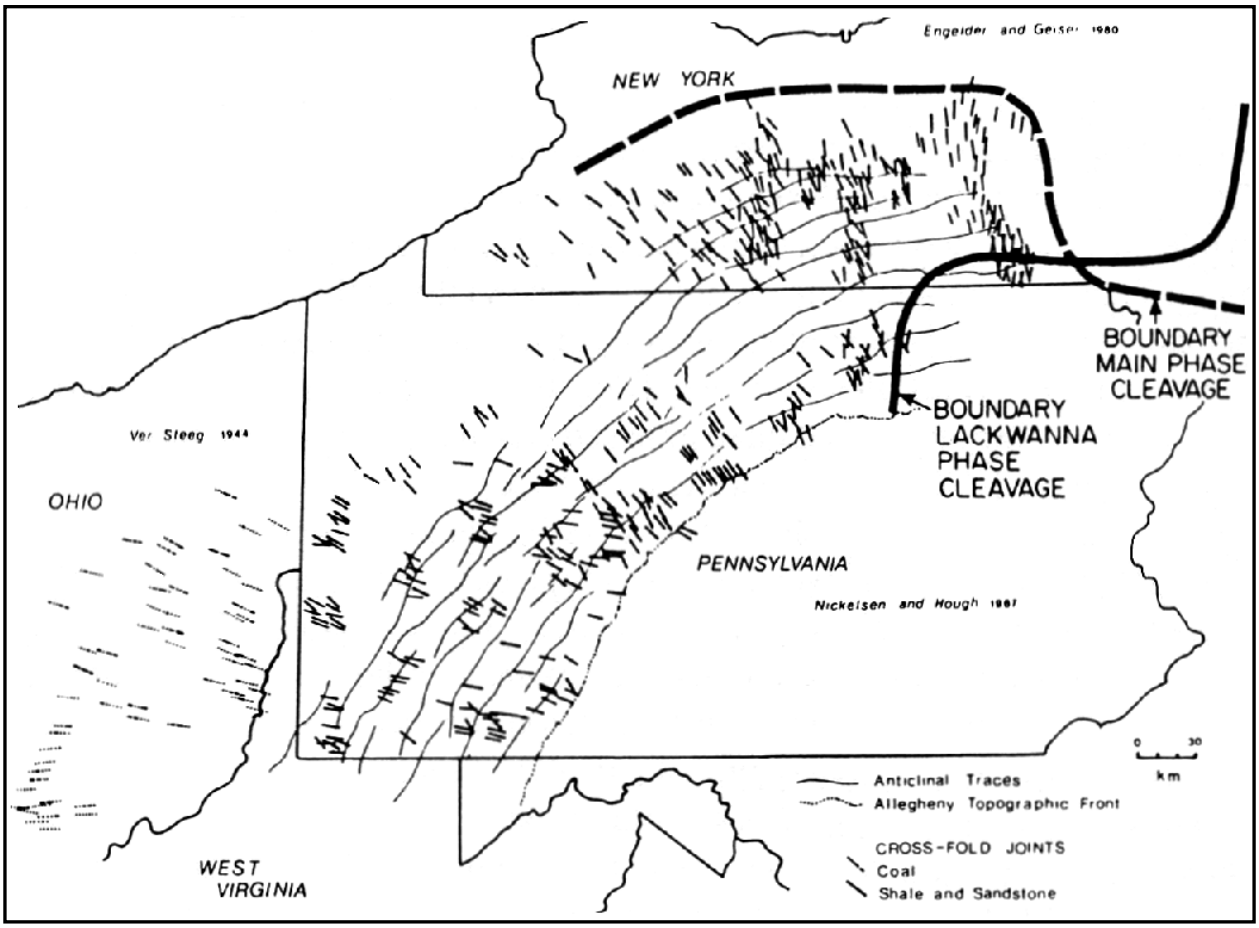

Figure 3-18. Orientation of tectonic joints in Ohio, Pennsylvania, and New York (modified from Engelder, 1993).

A third type of vertical joint found in the rocks in northeastern Ohio is created by the relief of compressive stress as rivers slowly, over millions of years, erode valleys. As shown on Figure 3-19, this process creates compressive stress in the rocks on adjacent upland areas and a resultant tensile stress in the rocks in the valley floor (Wyrick and Borchers, 1981). This type of vertical joint develops parallel to the orientation of ancient river valleys, which in northeast Ohio are parallel to the orientations of buried bedrock valleys filled with glacial materials (Figure 3-2).

The importance of vertical joints, regardless of origin, to the movement of groundwater in rocks with low intergranular permeability has been established in the hydrogeology literature for several decades (Lattman and Parizek, 1964; Wyrick and Borchers, 1981).

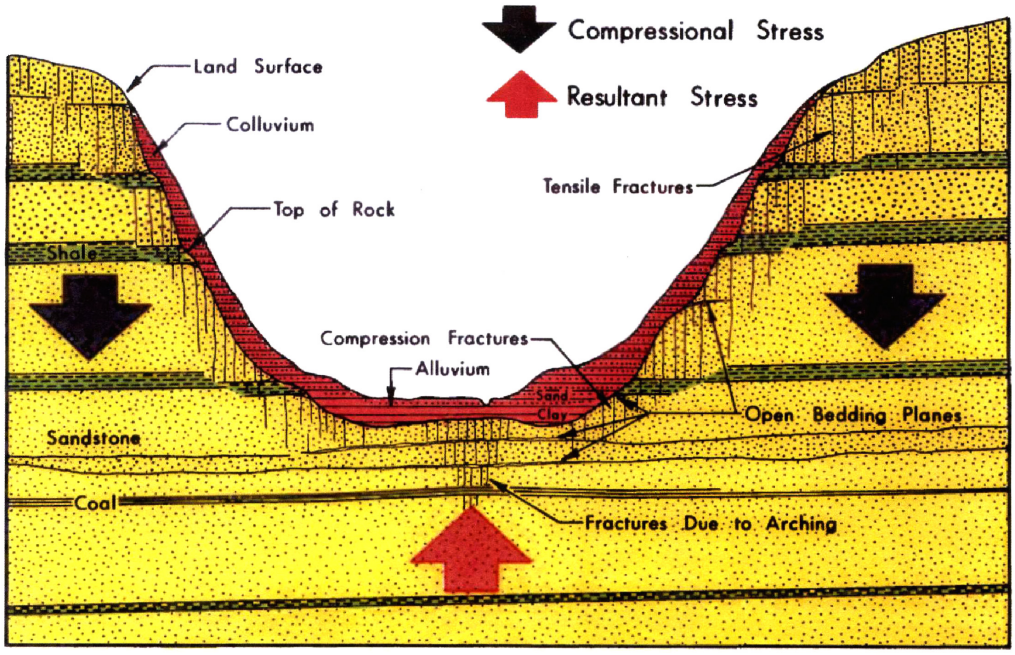

Figure 3-19. Formation of vertical fractures from stress relief (Wyrick and Borchers, 1981).

Gas Migration in Fractured Shales / Formation of Hydrocarbons

Milici (1996), Caramanica (1988), and Claypool and others (1978) present a geologic model describing how gas generated at the molecular level in black organic shale source beds sorbs onto clay minerals (Figure 3-8) and how natural fractures enable gas molecules to migrate from mineral surfaces into porous and permeable siltstone and sandstone beds and ultimately into production wells (Figure 3-20).

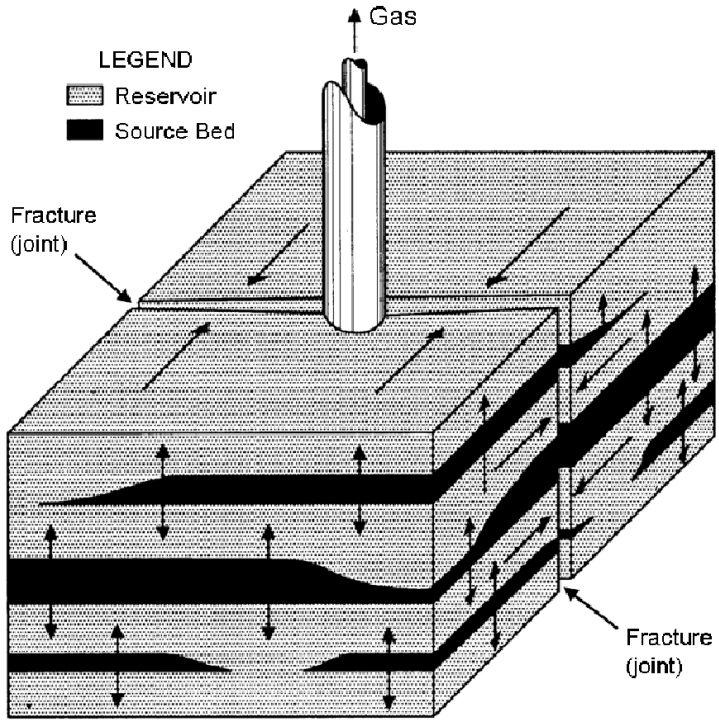

Figure 3-20. Geologic model of gas migration from source beds (modified from Milica, 1996).

The depths below land surface to which oil- and gas-bearing rocks once were buried are critical to the creation of hydrocarbons in source beds. The conversion of organic matter to kerogen and then to hydrocarbon molecules requires prolonged exposure to elevated temperatures and pressures, which can only come from deep burial beneath Earth's surface (Hyne, 2001; Selley, 1997). Oil and gas form within narrow ranges of geothermal temperature and lithostatic pressure. These ranges are known in the petroleum industry as the "oil window" and the "gas window." Kerogen in rocks exposed to temperatures and pressures less than the oil window cannot be converted into oil, instead forming viscous tar (think tar sands in Alberta, Canada). Oil in rocks exposed to temperatures and pressures greater than the oil window convert into natural gas. These well-established concepts are portrayed in Figure 3-13.

The petroleum industry literature indicates that gas fields in the Ohio Shale are due in large part to natural fractures. The oddity about the fractured Devonian shales play (Milici, 1996) is that the same geologic unit is the source rock (black organic shales beds), the reservoir rock (fractured siltstones and fine-grained sandstones), the caprock (less fractured shale beds), and the trap (poorly fractured sections within the thick sequence of shales and siltstones). The existence of gas source beds within the Ohio Shale demonstrates its burial to depths below 18,000 feet (Figure 3-13), where the hydrocarbons were compressed and heated in nature's equivalent of a pressure cooker.

The naturally occurring fractures in the Ohio Shale were created by (1) progressive unroofing of the overburden once overlying the Ohio Shale, (2) tectonic stresses from the Alleghanian Orogeny, and (3) compressive stress-relief during erosion of ancient river valleys. In today's economy, the major commercial fields in the Fractured Devonian Shale and Siltstone Play are found at greater depths farther into the Appalachian Basin using new technologies (horizontal drilling and hydraulic fracturing) never dreamed of when the original fields in this play were discovered along the southern coast of Lake Erie. Nevertheless, the classic fractured Ohio Shale gas fields in northeastern Ohio, Pennsylvania, and New York demonstrate the ability of gas to migrate along naturally occurring vertical fractures and to accumulate in extractable quantities. There is no evidence indicating that the Ohio Shale in Bainbridge Township lacks naturally occurring fractures.

Plays in the Berea Sandstone

Natural gas was first discovered in the Berea Sandstone in East Liverpool, Ohio, in 1860 (Orton, 1888). Since then more than 200 fields have been developed in the Appalachian Basin in this play (Tomastik, 1996). Figure 3-21, taken from the Gas Atlas chapter written by Tom Tomastik (DMRM) shows the locations of fields in the Berea Sandstone and its time equivalent strata.

The primary trapping mechanism in this play is stratigraphic (i.e. changes in lithology within the reservoir rock cause changes in porosity and permeability that negate further movement of hydrocarbons). Gas accumulations in the Berea Sandstone, and its time equivalent sandstone units in other parts of the Appalachian Basin, are derived from the black organic shales within the Ohio Shale and its time equivalents (Harris and Roen, 1984; Nolde and Milici, 1993). The overlying Berea Sandstone drains the buoyant hydrocarbons produced in the underlying organic-rich shale beds through vertical fractures extending from the shales upward into the overlying permeable sandstone layers (Tomastik, 1996).

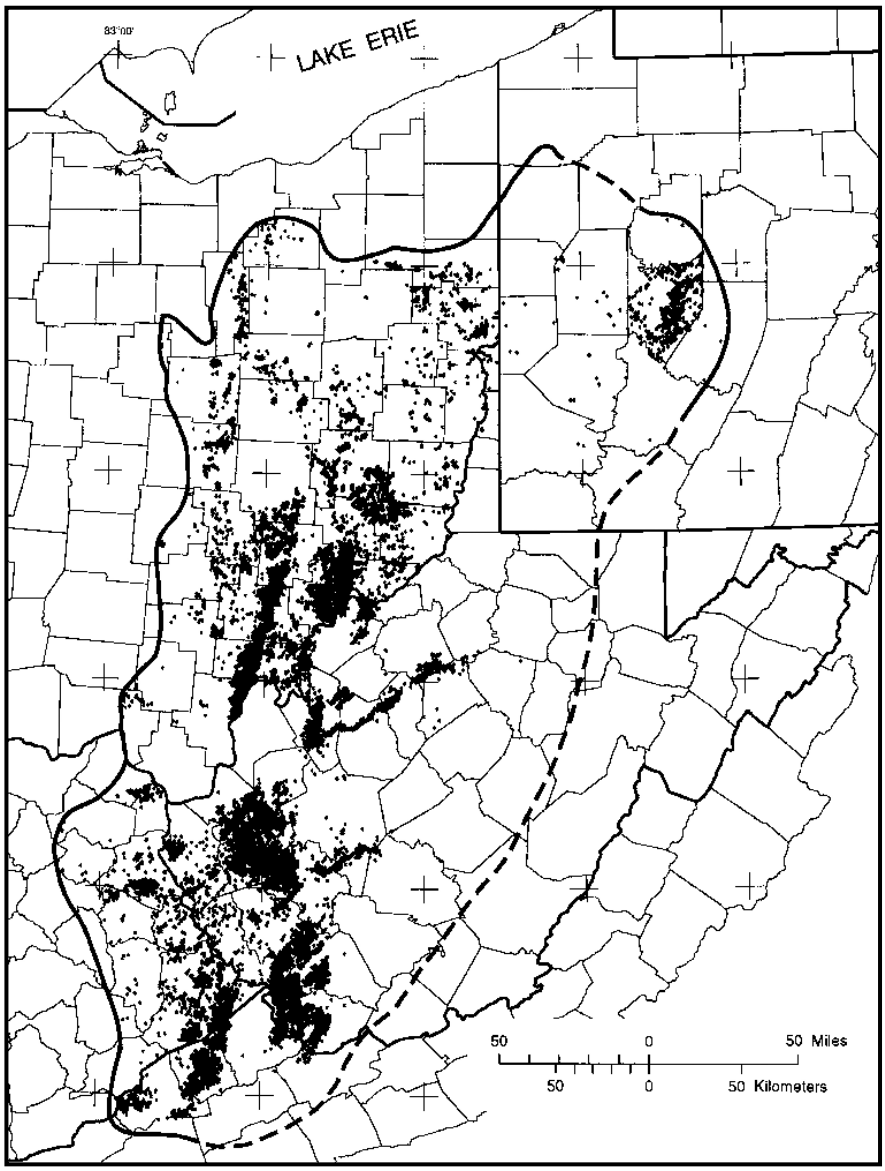

Figure 3-21. Outline of Berea Sandstone plays and locations of gas fields (modified from Tomastik, 1996).

A large amount of information is available regarding the Berea Sandstone because there are so many Berea Sandstone gas fields, although there are none currently active in Geauga County (personal communication, Scott Kell, DMRM). Porosities determined from rock cores and geological logs taken in oil and gas reservoirs in the Berea Sandstone range from 2 to 26 percent, which is consistent with the values from core samples from northeast Ohio measured by Weatherford Labs (Table 3-1). Most of the porosity in the Berea Sandstone is intergranular (Figure 8), although some fracture porosity exists along bedding planes and in vertical fractures. Values of intergranular permeability determined from core samples and geophysical logs in reservoir-quality sandstones range from 0.01 to 480 md, which also is consistent with the core samples analyzed by Weatherford Labs (Table 3-1). Depths to gas-producing zones in the Berea Sandstone and its equivalents range from 178 feet in Medina County, Ohio, to 6,620 feet in Wise County, Virginia. Thicknesses of the pay zone range from 1 to 108 feet (Tomastik, 1996). Figure 3-22 shows the locations of fields in this play in Ohio and other states.

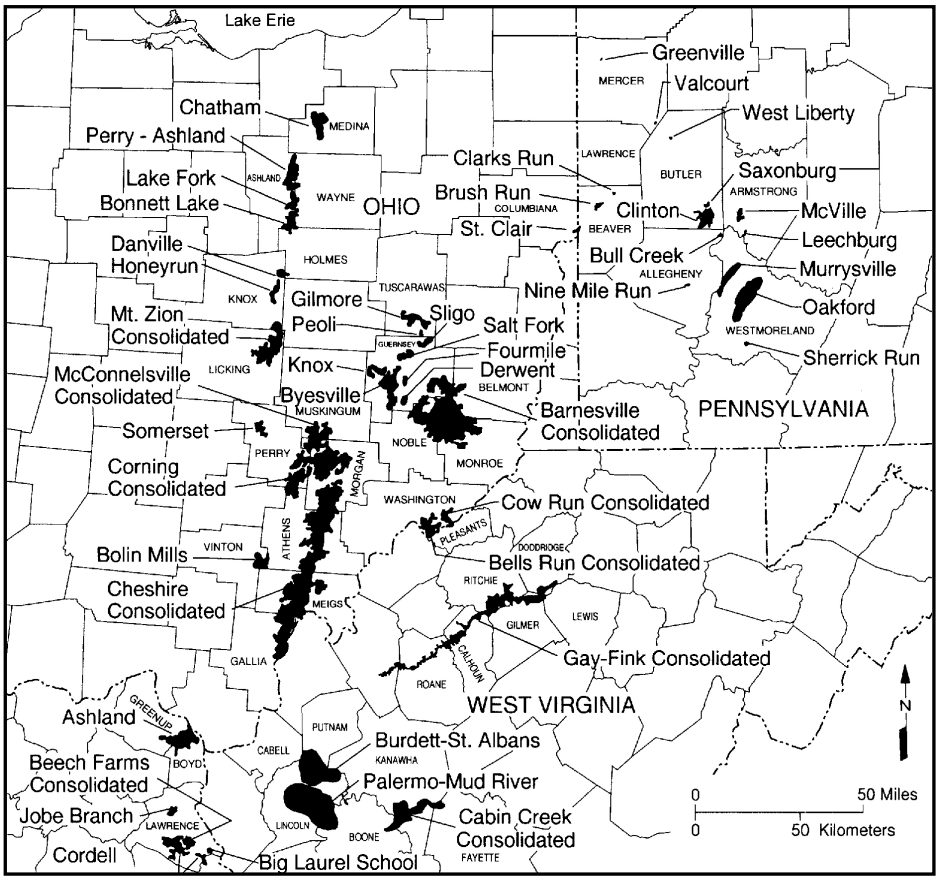

Figure 3-22. Locations of gas fields in the Berea Sandstone and its equivalents (modified from Tomastik, 1996).

Figure 3-22 shows that northeastern Ohio is devoid of Berea Sandstone gas fields even though there are localized areas where hydrocarbons are generated in the underlying Ohio Shale. The geologic reasons for the absence of Berea Sandstone gas fields relate to the four components needed to form a play (Figure 3-13). Because of its nearness to the land surface, it is likely that the Cuyahoga Shale beds overlying the Berea Sandstone are sufficiently fractured that they do not serve as a caprock preventing the upward escape of gas. It is also possible that lithologic variations in the Berea Sandstone are not great enough to create stratigraphic traps, resulting in gas migration upward. The proximity of the Berea Sandstone to the land surface in the region and the numerous outcrops along river valleys suggest that any gas accumulating in the sandstone beds near these areas would escape to the atmosphere. As a consequence of these geologic factors, the Berea Sandstone has not been a good commercial source of hydrocarbon accumulation in northeastern Ohio.

Measurement of Regional Fracture Patterns

The background information from the petroleum geology literature dealing with gas plays in the Ohio Shale highlighted the importance of natural fractures to the migration and accumulation of natural gas deposits and the need for the expert panel to acquire detailed data on fracture orientations and densities in the geologic units involved in the subsurface gas invasions. The panel requested that DMRM personnel take measurements at nearby outcrops and quarries of vertical fracture orientations in the Sharon Sandstone, Cuyahoga Shale, Berea Sandstone, and

the Bedford and Ohio shales. These measurements were made during the summer of 2009 under the field supervision of Dr. Bair. Figures 3-23 and 3-24 illustrate how a Brunton compass is used to make these measurements.

Figure 3-23. The orientation (bearing) of vertical fractures is measured by aligning the sides of the compass along the edge of the fracture and recording its bearing relative to north.

Figure 3-24. During periods of low river flow, fracture bearings can be measured in streambed outcrops like this one in the Chagrin River along Geauga Lake Road.

Although the petroleum industry uses the term "fracture" to refer to linear extensional features in rocks, these features are also referred to as "joints." As described in the textbook by van der Pluijm and Marshak (2003), joints are natural planar or curvilinear fractures in rocks formed by tensile loading (extension) whereby the walls of the joint move apart very slightly during development without any offset of features cutting across the joint. Joints surfaces are not perfectly smooth and opposite sides of a joint touch one another. Joint openings are irregular and more like the openings between your palms when placed together than like two parallel sheets of plate glass. In the flat-lying sedimentary rocks in the Midwest, joint sets are

perpendicular to the ground surface (i.e. vertical) and therefore perpendicular to the largely horizontal layers of rock (van der Pluijm and Marshak, 2003). It is these sets of vertical joints that promote the migration of natural gas in the Fractured Devonian Shales and Siltstones Play described in the preceding section. Table 3-2 lists the location, geologic unit, and bearings of joints measured at the request of the expert panel. A total of 95 measurements were made.

Table 3-2. Bearing Measurements of Joints in Specified Geologic Units

Sharon Sandstone	Cuyahoga Shale	Berea Sandstone	Berea Sandstone	Ohio Shale
Best Sand Quarry	***Chagrin River***	***Samco Quarry***	***Mesenburg Quarry***	***Haydite Quarry***
305	50	54	10	325
320	50	345	20	280
295	60	20	25	300
305	305	279	30	291
280	320	343	35	320
292	318	345	35	299
60	332	340	35	4
56	58	345	55	35
55	280	53	60	52
54	65	275	350	
63	324	55	335	
332	320	35	320	
Route 422 Outcrops	318	333	300	
61	332	53	***Haydite Quarry***	
59	324	35	35	
59	65	305	55	
60	60	303	320	
330	65	15	311	
60	63	53	55	
337	70	55	315	
347	57	330	308	
60	344	320	320	
	279	321	30	
	RMB Quarry	319	85	
	79		86	
	78		34	
	69		311	
	81		312	
	29			
	86			
	83			
	80			
	358			
	355			
	345			
	350			
	345			

All bearings measured in degrees east of North

Analysis of joint bearings typically is done by plotting the bearing data in one or more standardized ways. Rose diagrams display joint bearings about a 360° circle so that the number of joints falling within a specified range of bearings is represented by a pie-slice segment whose radius is proportional to the number of joints within specified range. Figure 3-25 displays Rose diagrams of the data listed in Table 3-2.

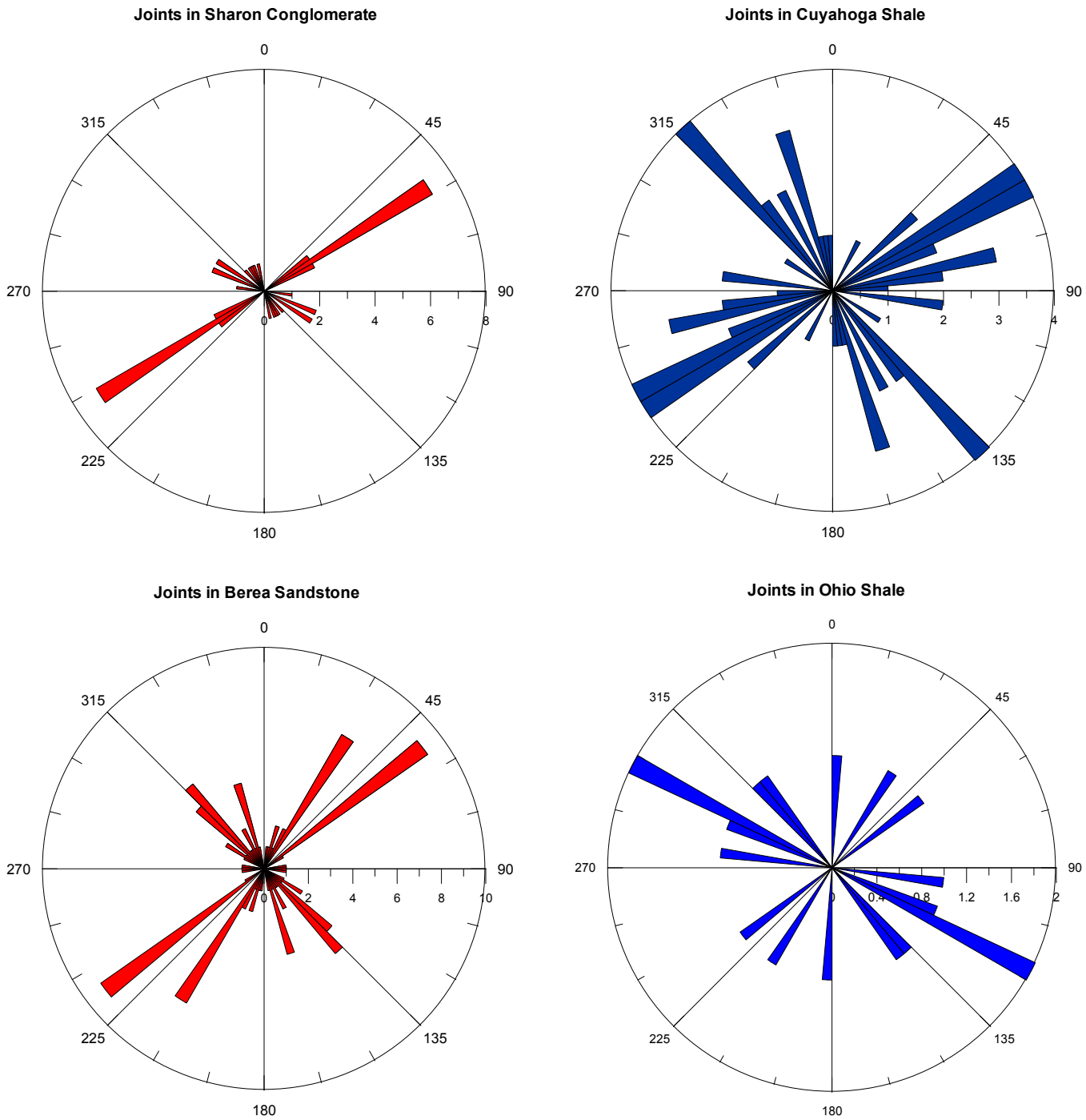

Figure 3-25. Rose diagrams of joint bearings measured in the Sharon Sandstone, Cuyahoga Shale, Berea Sandstone, and Ohio Shale.

The Rose diagrams show that joints in all four geologic units share the same two principal bearings: roughly N 55° E and N 55° W. As shown on Figures 3-17 and 3-18, these bearings correspond to the orientation of joints created by progressive unroofing (neotectonic stress) and tectonic stress, respectively (Engelder, 1993). Thus, in the sedimentary rocks in northeastern Ohio, there are two sets of systematic joints oriented about 110º and 70º from one another (Figure 3-25). A systematic set of joints comprises a series in which all the joints are parallel or subparallel to one another and maintain roughly the same spacing over the region of observation (van der Pluijm and Marshak, 2003). Figures 3-23 and 3-24 show these two sets of systematic joints.

Rose diagrams also can be used to make inferences about differences in joint spacing and joint density. Joint spacing is the average distance between adjacent members of a joint set. Joint density is the number of members of a joint set occurring within a specified distance (Suppe, 1985). Joint spacing and joint density depend on three parameters: bed thickness, bed stiffness, and strain. All other parameters being equal, joints are more closely spaced in thinner beds and more widely spaced in thicker beds. Stiffer beds have smaller joint spacings than do beds that are more plastic, all other parameters being equal. Bed stiffness is a function of lithology. For example, Figure 3-26 shows that beds of dolomite, which are relatively stiff, have a smaller joint spacing (greater joint density) than sandstone beds, which are less stiff.

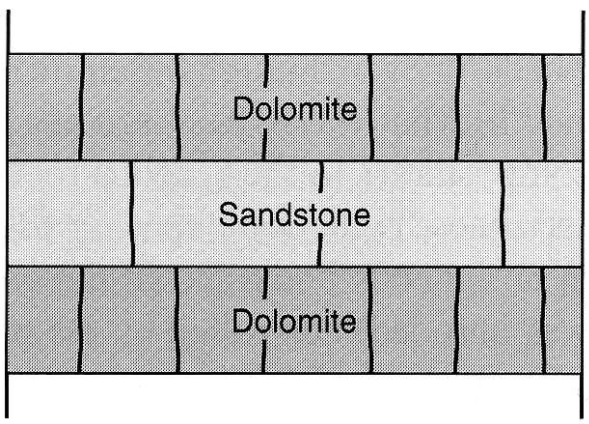

Figure 3-26. Cross-sectional diagram illustrating differences in joint spacing due to differences in stiffness (van der Pluijm and Marshak, 2003).

The Rose diagrams in Figure 3-25 show there were more joints available to be measured in the stiffer Cuyahoga and Ohio shales than in the less stiff Sharon and Berea sandstones. The relationship between joint spacing and bed stiffness is seen in Figures 3-23 and 3-24. The spacing between joints in the shale beds in the Cuyahoga Shale (Figure 3-23) is much smaller than the spacing between joints in the fine-grained sandstone/siltstone bed seen in Figure 3-24.

Figure 3-26 also shows that vertical joints in heterogeneous, layered rocks do not propagate across bedding planes. This is, in part, caused by differences in the lithology and stiffness of adjacent beds. It is also caused by the open spaces that exist along the planar surface of a bedding plane. A propagating joint cannot cross a free surface, like an open bedding plane, because the extensional (tensile) forces separating the rock into two blocks are not transferred across the open space. As a result, new or developing joints cannot propagate across existing joints or bedding planes. This is an important concept when evaluating the idea that a network of new joints, in the shape of an inverted cone, was created by overpressurization of the surface-production casing annulus in the English #1 gas well.