Smoluchowski's Dilemma Revisited: A Note on the Fluid Pressure History of the Central Appalachian Fold-Thrust Belt

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ABSTRACT

Cross-fold joints in the Central Appalachian fold-thrust belt propagated during periods of abnormally high fluid pressure prior to tectonic compaction and the development of first-order Alleghanian structures in the valley and ridge. These early joints, found in both the valley and ridge province and the plateau province, are organized in sets forming patterns that correlate across the Allegheny Front. Examples of early joints are found in the Devonian Brallier and Trimmers Rock Formations of the Pennsylvania Valley and Ridge and in the Genesee Group of the Appalachian Plateau. One interpretation is that high fluid pressures were generated by topographically driven flow across the Appalachian Basin as a consequence of uplift of the core of the Appalachians early in the Alleghanian Orogeny. The high fluid pressures accompanying this topographically-driven flow system later facilitated the development of first-order structures in the valley and ridge. Later joint sets that do not correlate across the Allegheny Front are more likely to be a consequence of fluid pressure pulses developed during local tectonic compaction and the development of first-order Alleghanian structures. These later joint sets vary in number and orientation from location to location.

INTRODUCTION

Smoluchowski's (1909) famous dilemma is that thrust sheets are too wide for emplacement by "dry" frictional sliding. Theoretically, the back end of wide thrust sheets should collapse under the large tectonic stress necessary to push the entire thrust sheet against frictional resistance. The most popular solution to Smoluchowski's dilemma was presented by Hubbert and Rubey (1959) and Rubey and Hubbert (1959), who pointed out that the theoretical width of thrust sheets is greatly increased by an increase in fluid pressure and concomitant reduction in effective normal stress across the basal décollement. Because frictional resistance is directly proportional to effective normal stress, a reduction in effective normal stress has the net effect of reducing the push (i.e., tectonic stress) necessary for emplacement of wide thrust sheets. Lower tectonic stress reduces the tendency for fracture and thickening at the back end of the thrust sheet (Davis *et al.*, 1983).

A reduction in effective normal stress occurs if the base of the thrust sheet cuts through a stratigraphic section containing abnormally high fluid pressures. How this high fluid pressure evolves is still subject to debate. Two mechanisms for generating high fluid pressures as mentioned by Hubbert and Rubey (1959) are artesian flow and mechanical compaction of water-filled pores. In their companion paper Rubey and Hubbert (1959) focus on the generation of abnormally high fluid pressures by three mechanisms: (1) the uplift of sealed sand lenses, (2) tectonic compaction, and (3) compaction by overburden weight. They gave no further consideration to artesian flow. There are, of course, other mechanisms such as aquathermal pressuring (Barker, 1972), diagenetic dewatering of clays (Schmidt, 1973), and generation of CO_2 and CH_4 during the breakdown of hydrocarbons (Spencer, 1987).

Rubey and Hubbert (1959) do not examine artesian flow as a mechanism for generation of abnormal fluid pressures in foreland fold-thrust belts. By implication they consider it less important than tectonic compaction as a source for abnormal fluid pressures in overthrust terrain. The problem is that tectonic compaction occurs well after the initiation of thrusting. The development of overthrust terrain would be greatly facilitated if high fluid pressures developed before the onset of thrusting. Artesian flow may permit such a buildup in fluid pressure. Furthermore, experience in the Alberta Basin suggests that it should be taken seriously as a model for generating high fluid pressures in foreland basins (Tôth, 1980).

Artesian flow is commonly understood to be groundwater flow from a topographically high recharge area to a topographically low discharge area. This type of flow, also called topographically driven flow, is modeled by Tôth (1962, 1980) using a flow net first illustrated by Hubbert (1940). One consequence of topographically driven flow is that the discharge area is subject to pore water pressures in excess of hydrostatic developed because the mechanical energy per unit volume of pore fluid is highest in the recharge area and lowest in the discharge area. A fortuitous combination of aquitards and topography can lead to near-lithostatic fluid pressures in the discharge area (Engelder and Bethke, 1985). A topographically driven flow system is steady state; leakage is balanced by recharge. This is in direct contrast to compaction-driven flow, where fluid pressure gradually returns to hydrostatic once compaction stops.

Are there geological structures that enable the geologist to distinguish topographically driven flow from other mechanisms including tectonic compaction that might have been the source of high fluid pressures in a foreland fold-thrust belt? In principle, regional joint sets could serve as such structures. This paper presents further evidence supporting the regional correlation of cross-fold joint sets (joints with normals subparallel to regional fold axes) in the Appalachian foreland fold-thrust belt and then deals with the geological consequences of regionally developed cross-fold joint sets in terms of a mechanism for generating the necessary pore-fluid pressure.

CORRELATION OF CROSS-FOLD JOINTING ACROSS THE CENTRAL APPALACHIAN FORELAND FOLD-THRUST BELT

Cross-fold joints are very prominent in Upper Devonian outcrops along the edges of the Finger Lakes of New York State (Figure 9.1). By the first decade of the twentieth century geologists recognized that these cross-fold joints were organized into more than one set (Sheldon, 1912). While tracing these cross-fold joints along strike of the New York Plateau for more than 200 km, Parker (1942) recognized that they maintained an orientation normal to fold axes despite a 30° change in strike of the fold axes. Parker made no judgment about whether cross-fold joints on either end of the map area are part of the same joint set. Nickelsen and Hough (1967) were the first to map joints as systematic sets in the Central Appalachians. They identified five cross-fold joint sets in sandstones of the Appalachian Plateau in Pennsylvania. By extrapolating to New York State, they identified three joint sets in Parker's map area. On mapping in the Appalachian Valley and Ridge, Nickelsen (1979) and Orkan and Voight (1985) attempted to correlate joint sets between the valley and ridge and plateau of Pennsylvania. Orkan and Voight (1985) identified six cross-fold joint sets in the valley and ridge (Figure 9.2).

Nickelsen and Hough's (1967) and Orkan and Voight's (1985) technique for correlation of joints along strike depends largely on the orientation of joints. Their assumption is that joints of one set have similar orientations over large regions. If a suite of joints at an outcrop is misoriented by, say, 15° from an established joint set, this suite belongs to another joint set regardless of its orientation with respect to local structures. As is illustrated in Figure 9.2, the consequence of this assumption is that members of a joint set do not change orientation even as fold axes swing through the Central Appalachians. On a regional basis the change in strike of fold axes is accommodated by the overlap of joint sets of different orientations. The notion for overlapping joint sets is supported by outcrops containing more than one joint set. Nickelsen

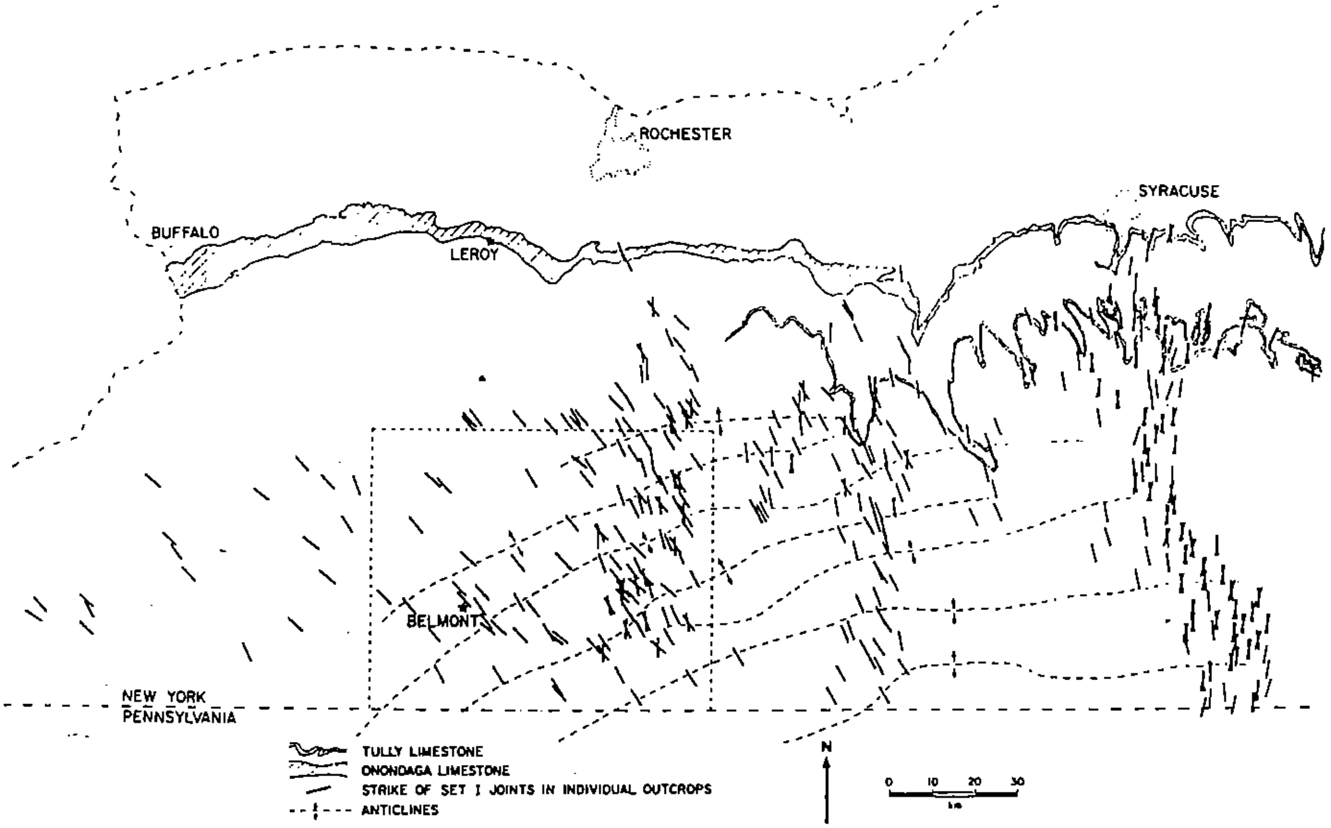

FIGURE 9.1 A map of cross-fold joints in the Middle and Upper Devonian rocks of the Appalachian Plateau of New York State (after Engelder and Geiser, 1980).

and Hough's (1967) correlation strategy was developed in response to the observation that first-order folds in the Pennsylvania Valley and Ridge are kink folds (e.g., Faill, 1973) with straight axes (Nickelsen, 1987, personal communication). Nickelsen's idea is that the valley and ridge developed as overlapping thrust sheets cored with duplexes moving toward the craton with straight-axis kink folds delimiting the thrust duplexes. The curvature of the Central Appalachian Valley and Ridge is accommodated by abrupt changes in the orientation of the first-order folds. Strictly parallel joint sets reflect the kinematics of thrust sheets associated with straight-axis kink folds. Presumably the motion of various sheets is independent, so various joint sets are unrelated in time and space. If these assumptions hold, the use of joint sets to draw stress trajectories over the whole mountain belt is invalid.

While remapping cross-fold joints on the Appalachian Plateau, Engelder and Geiser (1980) took a different approach to the correlation of joints along strike. They assumed that joint sets change orientation gradually to remain roughly perpendicular to local fold axes. Implicit in Engelder and Geiser's (1980) assumption is that stress trajectories associated with an orogenic pulse are curved and regional in extent. In the vicinity of Ithaca and Watkins Glen, New York, the apparent abrupt change in orientation as interpreted by Nickelsen and Hough (1967) is a manifestation of joint sets restricted to particular lithologies where joints in siltstones have a different orientation than joints in shales. An outcrop with two lithologies commonly exhibits two joint sets forming at different angles to the same fold axis. This pattern is not a manifestation of one joint set giving way to another set while moving around an oroclinal bend. Tracing both joint sets in their particular lithologies supports the notion that a single joint set can change orientation along with local fold axes (Engelder, 1985). In an area of the New York Plateau where Nickelsen and Hough (1967) and Orkan and Voight (1985) identified three joint sets, Engelder and Geiser (1980) argue that there are two with joint sets A and D in the western portion of the plateau being equivalent to joint sets D and E, respectively, in the eastern portion. All of this is said to make the point that the regional correlation of joint sets is not trivial.

Although correlation of joints across the Allegheny Front has many of the same difficulties as correlation along strike of the Appalachians, both Nickelsen and Hough (1967) and Orkan and Voight (1985) feel that joints correlate across the Allegheny Front. [The Allegheny Front, which is the boundary between the Appalachian Valley and Ridge and Plateau, is largely controlled by the southeastern edge of the Silurian salt basin where décollement faulting climbed up from the Cambrian shales into the salt beds. Low strength of the salt changed the character of the Appalachian foreland tectonics from duplex structures of the valley and ridge to layer parallel shortening of the Appalachian Plateau (Davis and Engelder, 1987).] A correlation may be based on the common occurrence of a clockwise rotation of joint propagation in both the valley and ridge and the Appalachian Plateau. [Although the clockwise rotation of joint propagation is common throughout the region, Helgeson and Aydin (1989) report that a counter-clockwise rotation is well developed in some outcrops.] At Bear Valley Strip Mine Nickelsen (1979) identified eight stages of deformation with the first three being two phases of jointing followed by layer parallel shortening. These prefolding events witness a prefolding compression that rotates clockwise (Geiser and Engelder, 1983; Engelder, 1985). All along the Allegheny Front from Williamsport to State College, Pennsylvania, early cross-fold jointing shows a sequence indicating a clockwise rotation of compression (Lacazette, The Pennsylvania State University, personal communication). This same sequence is well displayed in the Devonian Brallier Formation at Huntingdon, Pennsylvania.

The Devonian Brallier Formation of the central Appalachian Valley and Ridge is equivalent in age and lithologic composition to the Genesee Group of the Appalachian Plateau. Of all the lithologies in the valley and ridge from Cambrian carbonates up through Carboniferous fluvial deposits, none carry joints that more closely resemble those seen on the Devonian section of the Appalachian Plateau. At an outcrop just south of Huntingdon, Pennsylvania, the Brallier dips to the southeast at about 15°. Like joints in the sandstone-shale beds of the Genesee Group on the Appalachian Plateau, two sets of cross-fold joints cut the Brallier, with the finer-grained beds carrying joints striking about 140° and the coarser beds carrying joints striking about 158°. The relative time of propagation of the joint sets may be determined using a joint spacing criterion developed by DeGraff *et al.* (1987) in the Genesee Group at Taughannock Falls, New York. Toward the north end of the Brallier outcrop joints in siltstone beds can be seen propagating upward from joints in shale beds. Based on the spacing criterion, joints in the silty shale

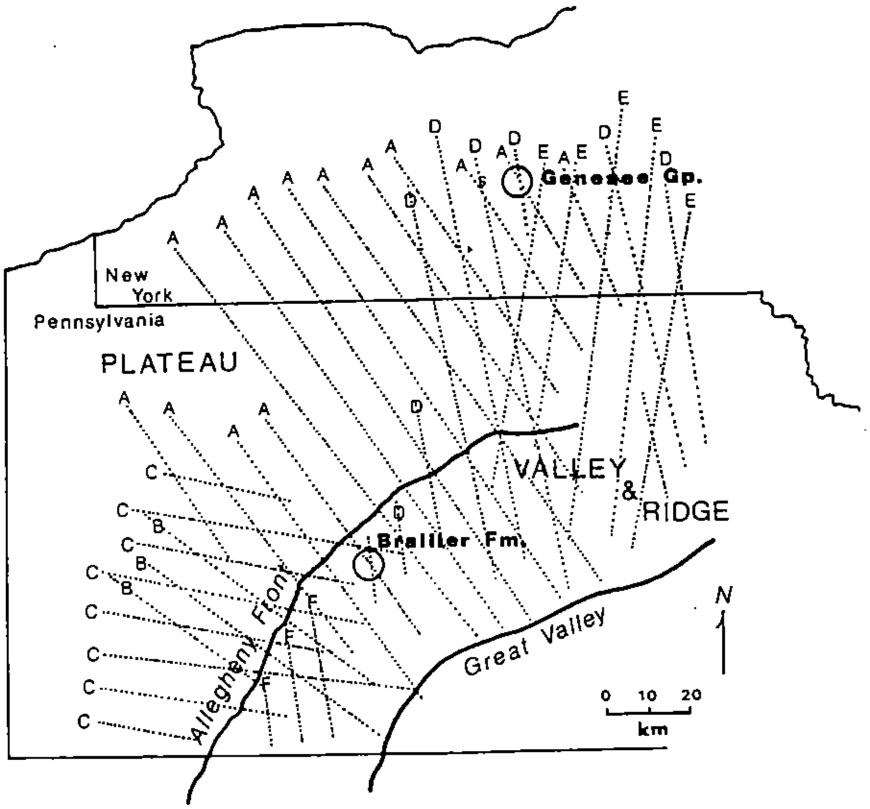

FIGURE 9.2 Orkan and Voight's (1985) map of regional joint sets within the Central Appalachian fold-thrust belt. Sets A through E are those of Nickelsen and Hough (1967). Set F was identified by Orkan and Voight (1985). Regional joint sets are based on the data of Nickelsen and Hough (1967) and Engelder and Geiser (1980).

(140°) propagated prior to those in the sandstone (158°) and, hence, show the same clockwise rotation as seen throughout the Appalachian foreland.

Aside from the fact that these joints look like those found in the flat-lying Devonian rocks of the Appalachian Plateau, two pieces of evidence suggest that the cross-fold joints in the Brallier preceded folding. First, the joints have been rotated to dip between 84° and 87° to the southwest. If the present dip of the Brallier is removed, these joints are vertical, presumably the orientation at which they propagated. Second, some joints in the silty shale beds are decorated with slickensides and fibrous calcite, indicating a left-lateral shear. This is the type of slip expected for the compression responsible for later folding. Furthermore, the orientation of the calcite fibers indicates that slip direction has a shallower plunge than bedding dip. These are some of the same arguments used by Nickelsen (1979) to demonstrate early jointing at Bear Valley.

It is likely that early joint sets propagated prior to the formation of the Allegheny Front. The Allegheny Front became significant only with the development of first-order structures of the valley and ridge, an event that took place long after early joint propagation, as shown by Nickelsen (1979) at Bear Valley. Joints correlate across the Allegheny Front largely because that structural front did not exist at the time the joints formed. The mechanism for early joint propagation must precede and be independent of the development of first-order structures of the Appalachian Valley and Ridge. In summary, the Upper Devonian shales and siltstones of the entire Central Appalachian foreland contain Alleghanian cross-fold joints that predate both major tectonic compaction and the development of first-order folds.

FLUID PRESSURE AND JOINTING

The regionally developed cross-fold joints of the Appalachian foreland formed at depth in the crust of the Earth, where the propagation of such joints requires the development of effective tensile stresses within the rock (e.g., Nickelsen, 1979; Narr and Currie, 1982). Effective tensile stresses are possible under conditions of cooling (Voight and St. Pierre, 1974), curvature above the neutral fiber of a fold (Price, 1974), or significantly high fluid pressures (Secor, 1965). In the foreland portion of mountain belts where folding would favor the propagation of strike joints (joints striking parallel to fold axes), curvature can be ruled out as a likely driving mechanism for cross-fold joints. At full depth of burial rocks have not cooled appreciably, so thermal cracking can also be ruled out as a driving mechanism. In contrast, a growing body of evidence suggests that high fluid pressure serves as the driving mechanism for joints at depth. Joints filled with such minerals as quartz, calcite, and chlorite are often cited as a manifestation of fluid pressure-driven joint propagation (i.e., hydraulic fracturing; e.g., Beach, 1977). The multiple fracture of crack-seal veins (e.g., Ramsay, 1980) and the repeated arrest of joints during propagation (e.g., Engelder, 1985) are fracture-related structures associated with the cracking of rock under the influence of high fluid pressure.

An understanding of the extent to which joints correlate in both time and space is critical to identifying the mechanisms for generation of high fluid pressures in a mountain belt. Although rapid joint propagation occurs on the scale of outcrops, the timing of joint propagation at different locations across a foreland is less certain. Presently it is not clear whether fluid pressure increases simultaneously everywhere across a foreland or whether high fluid pressure occurs as local pulses affecting only small parts of the mountain range at one time. This, of course, leads to uncertainty about whether joint sets of the same orientation should correlate across distances of tens to hundreds of kilometers. Certainly, based on data discussed above, current dogma for the Appalachians is that early joint sets do correlate over large distances (e.g., Nickelsen and Hough, 1967; Engelder and Geiser, 1980; and Orkan and Voight, 1985).

Figure 9.2 suggests that joint sets, such as "set A," extend from the Great Valley of Pennsylvania to the far reaches of the Appalachian Plateau near Buffalo, New York. This is the Orkan and Voight (1985) interpretation of regional joint sets where joint development cuts across tectonic boundaries such as the Allegheny Front. If a correlation across the Allegheny Front is valid, the evolution of a high pore pressure must have been a foreland-wide event. Not all mechanisms for generation of high pore pressure are regional in extent. Although depositional and diagenetic mechanisms for the generation of high fluid pressure may be regional, they are considered unlikely mechanisms for a regional pore pressure event in the Appalachian fold-thrust belt because the earliest cross-fold joint sets are Alleghanian and, hence, developed long after deposition and diagenesis of the foreland sediments containing the joints. Although tectonic compaction affects an entire foreland, it was not uniform, as indicated by a variation is strain. The upper crust does not have the strength to simultaneously compact across the foreland until the core of the mountain belt has built into a sizable wedge (Davis *et al.*, 1983). Furthermore, strain in forelands is much too low to have been continuously active at plate tectonic rates for the duration of an orogenic event such as the Alleghanian orogeny in the Appalachians. For these reasons tectonic compaction seems unlikely to have contributed to a foreland-wide pore pressure event of the type required for early jointing. The only mechanism for generating a regional pore pressure event that cannot be rejected out of hand is the topographically driven flow system. Therefore, it is assumed to be the most likely source for high fluid pressures causing the simultaneous development of a joint set across the foreland, particularly during early stages of foreland development.

DISCUSSION: OROGENIC PULSES AND THE GENERATION OF ABNORMALLY HIGH FLUID PRESSURE

Early foreland-wide joint sets may be reconciled with topographically driven flow systems. In this case a regional flow system may have formed in response to uplift of mountains to the southeast of the Great Valley. To generate the high pressures for joint propagation, such a topographically driven flow system is, of course, going to require regional aquitards and a significant topographic gradient across the foreland. Because the upper Paleozoic section of the Central Appalachians developed very few through-going thrust faults, it may have served as a regional aquitard. Furthermore, evidence is accumulating that suggests that during the Alleghanian orogeny the Central Appalachians southeast of the Allegheny Front was quite thick (Levine, 1983; Paxton, 1983; Orkan and Voight, 1985). Vitrinite reflectance and fission track data suggest that the Devonian and Carboniferous of New York and Pennsylvania may have been buried to a depth of 6 km (Friedman and Sanders, 1982). Current studies of crustal flexure suggest that external forces were necessary for the magnitude of crustal depression necessary for the depth of burial found in Pennsylvania (Beaumont, 1981). Such crustal loading can be accomplished during continent-continent collisions. The Alleghanian Orogeny was a period during which the continent of Africa collided with North America, producing continental edges having a topography similar to the India-Asia collision. This interpretation of regional joint sets requires that uplift at the core of the mountain belt preceded the development of first-order structures in the foreland. The early development of a regional flow system with elevated pore pressures facilitates later thrusting and the development of first-order structures, particularly in the discharge area of the foreland.

Regardless of their correlation, everyone agrees that some cross-fold joints in the central Appalachian foreland fold-thrust belt propagated early and are organized into discrete sets rather than being distributed randomly or uniformly. The existence of multiple joint sets indicates that the syntectonic stress field changed in orientation during the evolution of the foreland fold-thrust belt. This regional organization of joints leads to the inference that joint propagation took place during punctuated events. Not only did the orientation of the stress field change with time but the magnitude of the effective stress varied. Fluid pressures were not continuously at a level necessary for joint propagation, but rather some poorly understood events caused fluid pressure to fluctuate up and down throughout a region. Such events took place a finite number of times during the development of the foreland portion of the Central Appalachians.

Mountain belts include a complex combination of diachronous structures superimposed over periods as long as 1 billion years ago. During the evolution of foreland fold-thrust belts, deformation is punctuated rather than continuous. Punctuated events called orogenic pulses are identified on the basis of the appearance of an arbitrarily chosen set of structures within the mountain belt. For example, a regionally developed disjunctive cleavage may be attributed to one orogenic pulse, whereas a second cross-cutting cleavage may be attributed to a later orogenic pulse. With few exceptions the duration of an orogenic pulse is extremely difficult to measure.

The intensity of an orogenic pulse is often correlated with the finite strain within rocks or the regional shortening associated with folding and faulting. Orogenic pulses become increasingly hard to discriminate as the finite strain or regional shortening decreases. Although the case may be argued that major structures such as folds are the signature of a single orogenic pulse, multiple joint sets within folds are themselves witness for multiple orogenic pulses prior to the folding event. Regional joints, particularly sensitive indicators of individual orogenic pulses, are commonly found in the unmetamorphosed foreland where more than one set may cross-cut. Cross-fold joints may propagate even during very mild orogenic pulses and in many instances before significant bed rotation. These mild orogenic pulses in the foreland may reflect uplift events in the core of the mountain belt or periods of rapid tectonic compaction. Unlike faults, folds, or finite strain markers of any sort, the propagation of joints is so close to instantaneous that one moment in the history of mountain building is recorded. The convenience of joint sets is that stress trajectories associated with an orogenic pulse can be mapped with reasonable confidence (Ode, 1957).

The development of several joint sets suggests that fluid pressures were not continuously lithostatic throughout the Alleghanian orogeny. If fluid pressures were continuously at lithostatic during realignment of the stress field, then joints should have a uniform distribution of orientations rather than appear as isolated joint sets. Multiple joint sets suggest that fluid pressures rise to lithostatic levels during short-lived events before pore fluids leak off to drop the pressure well below that needed for joint propagation. Fluid pressures rise again once the

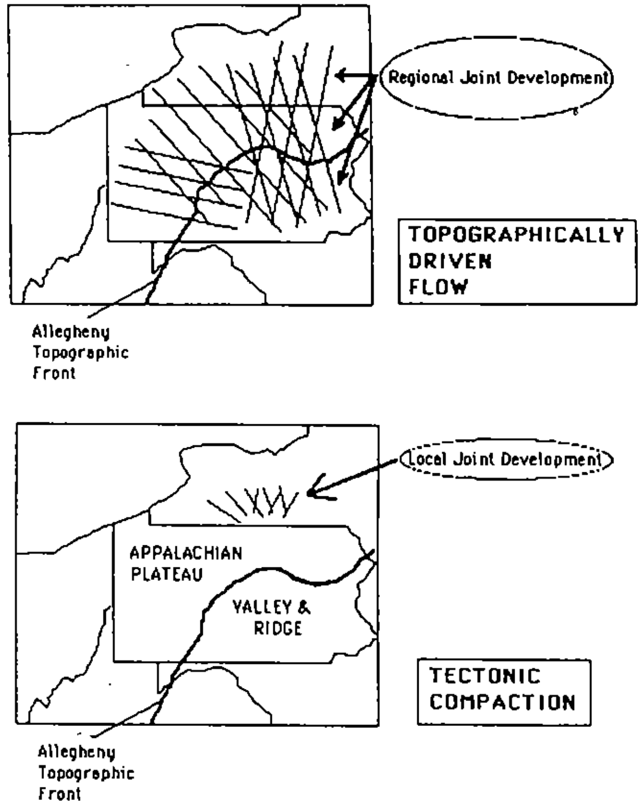

FIGURE 9.3 A schematic drawing illustrating the differences between local and regional joint development.

stress field is realigned. In order for topographically driven flow to account for multiple joint sets, the topography may have bounced up and down several times during the development of the foreland fold-thrust belt. An example of such vertical movements of crust is found in the multiple development of black shale basins in the Appalachian Catskill delta of the Acadian Orogeny (Ettensohn, 1985).

Although rapid uplift and erosion of a Himalayan-like mountain chain may be reasonable, admissible strain rates suggest that tectonic compaction as envisioned by Rubey and Hubbert (1959) may also be a likely mechanism for punctuated events in the fluid pressure history later during the Alleghanian orogeny (Evans *et al.*, 1989). After initial jointing events the Appalachian Plateau was shortened by about 10 percent during the Alleghanian Orogeny, an event that may have lasted more than 50 m.y. (Engelder and Engelder, 1977). Evidence for more than one orogenic pulse suggests that shortening was discontinuous throughout the 50-m.y. period, in which case the strain rate would have exceeded 10^{-16} s^{-1} during individual events. If the porosity reduction rate is on this order, then fluid pressures would build toward lithostatic pressures in shales and well-cemented siltstones within periods less than 1 m.y. (Walder and Nur, 1984). If this is the case, fluid pressure events were not foreland wide, and so there may be little reason to correlate cross-fold joints in the valley and ridge with those of the Appalachian Plateau (Figure 9.3).

Although a judgment is highly subjective, I would attribute set A in Figure 9.2 to a topographically driven flow system. Set A is equivalent to joints cutting siltstones in the Genesee Group (Engelder, 1985). Fluid pressures associated with joint set D, which propagated in the direction of Alleghanian layer-parallel shortening (Engelder and Geiser, 1980), are more likely to have been generated by tectonic compaction. Because I am not familiar with joint sets B, C, and F, I cannot make a judgment concerning them.

CONCLUSIONS

The mechanism responsible for high fluid pressures in the Appalachian foreland may be identified on the basis of the regional correlation of joint sets. The correlation of early regional joint sets across the boundary of structural provinces suggests that topographically driven flow was active prior to the development of first-order structures. This is then the solution to Smoluchowski's dilemma for the Appalachian fold-thrust belt where the high fluid pressures from a topographically driven flow system facilitated the development of first-order structures where such development is highly dependent on the reduction of effective stress. In contrast, some later joint sets developed as a consequence of fluid-pressure pulses during local tectonic compaction.

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REFERENCES

Barker, C. (1972). Aquathermal pressuring: Role of temperature in development of abnormal-pressure zones, *American Association of Petroleum Geologists Bulletin 56*, 2068-2071.

Beach, A. (1977). Vein arrays, hydraulic fractures, and pressure solution structures in a deformed flysch sequence, S.W., England, *Tectonophysics 40*, 201-225.

Beaumont, C. (1981). Foreland basins, *Geophysical Journal 65*, 291-329.

Davis, D. M., and T. Engelder (1987). Thin-skinned deformation over salt, in *Dynamical Geology of Salt and Related*

Structures, I. Lerche and J. J. O'Brien, eds., Academic Press, Orlando, Fla., pp. 301-338.

Davis, D., J. Suppe, and F. A. Dahlen (1983). Mechanics of fold-and-thrust belts and accretionary wedges, *Journal of Geophysical Research 88*, 1153-1172.

DeGraff, J. M., D. E. Helgeson, and A. Aydin (1987). Transient and stabilized spacing of thermal and tectonic joints, *Geological Society of America Abstracts with Programs 19*, 638.

Engelder, T. (1985). Loading paths to joint propagation during a tectonic cycle: An example from the Appalachian Plateau, U.S.A., *Journal of Structural Geology 7*, 459-476.

Engelder, T., and C. Bethke (1986). Reexamination of the Gulf Coast Model used by the Rubey-Hubbert Hypothesis for thrust belt tectonics, *Geological Society of America Abstracts with Programs 10*, 595.

Engelder, T., and R. Engelder (1977). Fossil distortion and décollement tectonics of the Appalachian Plateau, *Geology 5*, 457-460.

Engelder, T., and P. A. Geiser (1980). On the use of regional joint sets as trajectories of paleostress fields during the development of the Appalachian Plateau, New York, *Journal of Geophysical Research 85*, 6319-6341.

Ettensohn, F. R. (1985). The Catskill Delta complex and the Acadian Orogeny: A model, in *The Catskill Delta*, D. L. Woodrow and W. D. Sevon, eds., Special Paper 201, Geological Society of America, Boulder, Colo., pp. 39-49.

Evans, K., G. Oertel, and T. Engelder (1989). Correlated anomalies of in situ stress and compaction in Devonian shales of the Appalachian Plateau: An insight into the nature of Alleghanian deformation, *Journal of Geophysical Research 94*, 7155-7170.

Faill, R. T. (1973). Kink band folding, Valley and Ridge Province, Pennsylvania, *Geological Society of America Bulletin 84*, 1289-1314.

Friedman, G. M., and J. E. Sanders (1982). Time-temperature burial significance of Devonian anthracite implies former great (6.5 km) depth of burial of Catskill Mountains, *Geology 10*, 93-96.

Geiser, P., and T. Engelder (1983). The distribution of layer parallel shortening fabrics in the Appalachian foreland of New York and Pennsylvania: Evidence for two noncoaxial phases of the Alleghanian orogeny, in *Contributions to the Tectonics and Geophysics of Mountain Chains*, R. D. Hatcher *et al.*, eds., Memoir 158, Geological Society of America, Boulder, Colo., pp. 161-175.

Helgeson, D., and A. Aydin (1989). Use of surface features for interpretation of the propagation, interactiona, and intersection of joints, *Geological Society of America Abstracts with Programs 21*, A64.

Hubbert, M. K. (1940). The theory of groundwater motion, *Journal of Geology 48*, 785-944.

Hubbert, M. K., and W. W. Rubey (1959). Role of fluid pressures in mechanics of overthrust faulting: I. Mechanics of fluid-filled porous solids and its application to overthrust faulting, *Geological Society of America Bulletin 70*, 115-166.

Levine, J. R. (1983). Tectonic history of coal-bearing sediments in eastern Pennsylvania using coal reflectance anisotropy, Ph.D. thesis, Pennsylvania State University, 315 pp.

Narr, W., and J. B. Currie (1982). Origin of fracture porosity: Example from Altamont field, Utah, *American Association of Petroleum Geologists Bulletin 66*, 1231-1247.

Nickelsen R. P. (1979). Sequence of structural stages of the Allegheny orogeny at the Bear Valley Strip Mine, Shamokin, Pennsylvania, *American Journal of Science 279*, 225-271.

Nickelsen, R. P., and V. D. Hough (1967). Jointing in the Appalachian Plateau of Pennsylvania, *Geological Society of America Bulletin 78*, 609-630.

Ode, H. (1957). Mechanical analysis of the dyke pattern of the Spanish Peaks area, Colorado, *Geological Society of America Bulletin 68*, 567-576.

Orkan, N., and B. Voight (1985). Regional joint evolution in the Valley and Ridge Province of Pennsylvania in relation to the Allegheny Orogeny, *Guidebook, 50th Annual Field Conference on Pennsylvanian Geology*, Bureau of Topographic and Geological Survey, Harrisburg, Pa., 144-164.

Parker, J. M. (1942). Regional systematic jointing in slightly deformed sedimentary rocks, *Geological Society of America Bulletin 53*, 381-408.

Paxton, S. T. (1983). Relationships between Pennsylvania-age lithic sandstone and mudrock diagenesis and coal rank in the Central Appalachians, Ph.D. thesis, Pennsylvania State University, 503 pp.

Price, N. J. (1974). The development of stress systems and fracture patterns in undeformed sediments, *Advances in Rock Mechanics, Proceedings 3rd Congress ISRM*, 487-496.

Ramsay, J. G. (1980). The crack-seal mechanism of rock deformation, *Nature 284*, 135-139.

Rubey, W. W., and M. K. Hubbert (1959). Role of fluid pressures in mechanics of overthrust faulting: II. Overthrust belt in geosynclinal area of western Wyoming in light of fluid pressure hypothesis, *Geological Society of America Bulletin 70*, 167-205.

Schmidt, G. W. (1973). Interstitial water composition and geochemistry of deep Gulf Coast shales and sandstones, *American Association of Petroleum Geologists Bulletin 57*, 321-337.

Secor, D. T. (1965). Role of fluid pressure in jointing, *American Journal of Science 263*, 633-646.

Sheldon, P. (1912). Some observations and experiments on joint planes, *Journal of Geology 20*, 53-70.

Smoluchowski, M. (1909). Some remarks on the mechanics of overthrusts, *Geological Magazine 6*.

Spencer, C. W. (1987). Hydrocarbon generation as a mechanism for overpressuring in Rocky Mountain Region, *American Association of Petroleum Geologists Bulletin 71*, 368-388.

Tôth, J. (1962). A theory of groundwater motion in small drainage basins in central Alberta, *Journal of Geophysical Research 67*, 4375-4387.

Tôth, J. (1980). Cross-formational gravity-flow of groundwater: A mechanism of the transport and accumulation of petroleum (the generalized hydraulic theory of petroleum migration), *American Association of Petroleum Geologists Bulletin 64*, 121-167.

Voight, B., and B. H. P. St. Pierre (1974). Stress history and rock stress, *Advances in Rock Mechanics, Proceedings 3rd Congress ISRM*, 580-582.

Walder, J., and A. Nur (1984). Porosity reduction and crustal pore pressure development, *Journal of Geophysical Research 89*, 11,539-11,548.