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Preferential jointing of Upper Devonian black shale, Appalachian Plateau, USA: evidence supporting hydrocarbon generation as a joint-driving mechanism

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Abstract: The Catskill Delta Complex of western New York State contains fractured Upper Devonian black shales throughout a 300 km-transect from the more distal, somewhat shallower, deposits of the western region of the state eastward to more proximal and more deeply buried deposits. Each black shale unit grades upward into organically lean grey shale and abruptly overlies another grey shale unit. Within each black shale–grey shale sequence, ENE-trending vertical joints, interpreted to be hydraulic fractures, are best developed (i.e. more closely and uniformly spaced) in the organic-rich shale. Moreover, the density of ENE joints diminishes up-section through each black shale unit, as does the total organic carbon (TOC) content. While ENE joints are less well developed outside the black shale intervals, joints that formed during the Alleghanian orogeny (NW-trending) are found throughout the Upper Devonian shale sequence. Both sets are best developed in black shales in the distal delta sequence, whereas in more proximal deposits the Alleghanian joint sets are best developed in grey shales. Moreover, the density of ENE joints within each stratigraphic level of the black shale exceeds that of Alleghanian joints at the same level, except in the deepest black shale where Alleghanian joints are locally best developed at the top of the black shale interval. The preferential jointing of black shale units in the Appalachian Plateau reflects an extended hydrocarbon generation history. In the distal delta, hydrocarbon generation began when black shale was close to or at maximum burial depth (*c*. 2.3 km) during the Alleghanian orogeny with the propagation of a NW joint set and continued through post-Alleghanian uplift of the Appalachian Plateau when the ENE joints propagated. In the proximal delta deposits ENE joints propagated before the onset of Alleghanian deformation suggesting that the base of the Upper Devonian section was buried to thermal maturity by progradation of the Catskill Delta Complex before the advent of Alleghanian sedimentation.

Joints can enhance the bulk permeability of hydrocarbon source rocks, particularly black shales, because their aperture is significantly larger than matrix pore throat diameters (Tissot & Welte 1984). If joints remain confined within source rocks they may serve as a reservoir within the source rock. Those joints that have propagated to the boundaries of the source rock are efficient drains that can enhance secondary migration of hydrocarbons. Yet, even if individual joints do not propagate across the entire bed or unit, a network of smaller joints that become interconnected during growth can serve as an effective drain. Hence, an understanding of the orientation and density of joints (i.e. the joint pattern) and timing of joint propagation in Devonian black shales of North America is important to the natural gas industry in predicting whether Devonian source rocks are also reservoir rocks. In this chapter we examine the connection of joint development to burial history and organic carbon content in Devonian black shales of the northern Appalachian Basin. It is these organic-rich shales that serve as reservoir rocks within the more central portions of the basin.

We studied joint development in Devonian black shales of the Catskill Delta Complex along a 300 km-transect across the Southern Tier of New York State from the more proximal and deeply buried deposits of the Sonyea and Genesee groups in the vicinity of the Finger Lakes District to the more distal and somewhat shallower strata of the Canadaway and West Falls groups of the Lake Erie District (Figs 1 and 2). Our transect trends obliquely across very low-amplitude folds (<30 m) of the outer Appalachian Plateau in the Finger Lakes District to the unfolded foreland of the Lake Erie District. In sampling for joint development in the more distal portions of the Catskill Delta Complex, we hoped to generate a control data set that could be used to further our understanding of joint development in the more deeply buried black shales of the folded Appalachian Plateau.

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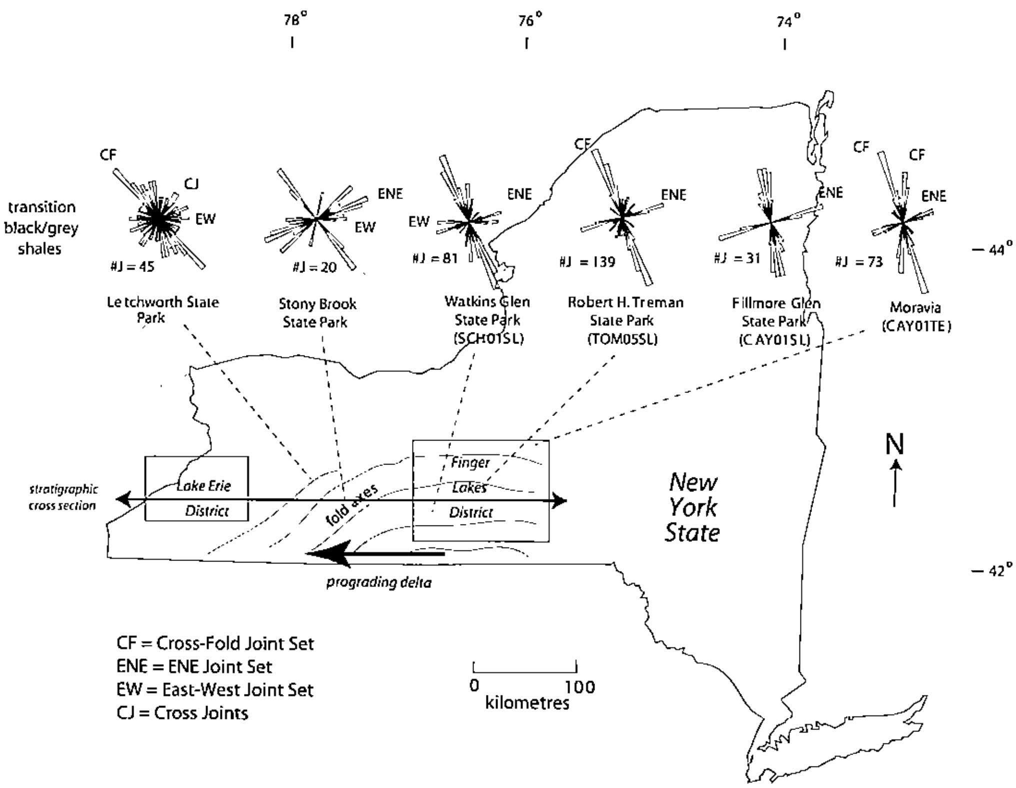

Fig. 1. Location map of the study areas in the Lake Erie and Finger Lakes districts. Approximate direction of progradation of the Catskill Delta location of the stratigraphic cross-section in Figure 4 is shown. Rose diagrams for joints in shales at six locations are superimposed on Alleghanian fold axes. Cross-fold and fold-parallel joints change orientation from east to west to remain roughly orthogonal to Alleghanian folds. Note ENE and E–W joints remain consistent in orientation across the Finger Lakes District.

Our work was stimulated by industry reports from both the Appalachian (e.g. Kubik 1993) and Michigan basins (e.g. Decker *et al.* 1992) that describe a strong relationship between production from Devonian shales and a penetrative fracture permeability that has transformed source rock into reservoir rock. Gas production from Devonian black shales of the Michigan Basin is, in part, a consequence of the desorption of methane from the surface of residual organic material (kerogen and bitumen) and clay minerals (e.g. illite: Schettler & Parmely 1990; Manger & Curtis 1991). However, well logs show that production is principally dependent on a natural joint permeability (Manger & Curtis 1991; Apotria *et al.* 1994). Similarly, there is compelling evidence that organic-rich Devonian shales of the Appalachian Basin have, on average, higher joint densities than interlayered lean grey shales (Soeder 1986; Jochen & Hopkins 1993; Kubik 1993). The robust correlation between joint development and organic carbon content is well defined in Devonian core recovered from the Appalachian Basin as part of the Eastern Gas Shales Project (EGSP; Fig. 3).

Geological setting and stratigraphic framework

Our field area includes a vast stretch of the Catskill Delta Complex extending more than 300 km across the Southern Tier of New York State (Figs 1 and 4). The Catskill Delta Complex thickens towards its source area in the Acadian Highlands of New England (Fig. 4). By the end of the Acadian orogeny (i.e. post-Pocono Group time) the burial depth of the Geneseo black shale in the Finger Lakes District was somewhere between 1.6 and 2.3 km (Lindberg 1985). At the same time, the Dunkirk Shale of the Canadaway Group in the Lake Erie District had roughly 0.6–0.7 km of overburden.

The Upper Devonian sequence of western New York grades upwards from a base of marine shales and scattered turbidite siltstones into shallow-

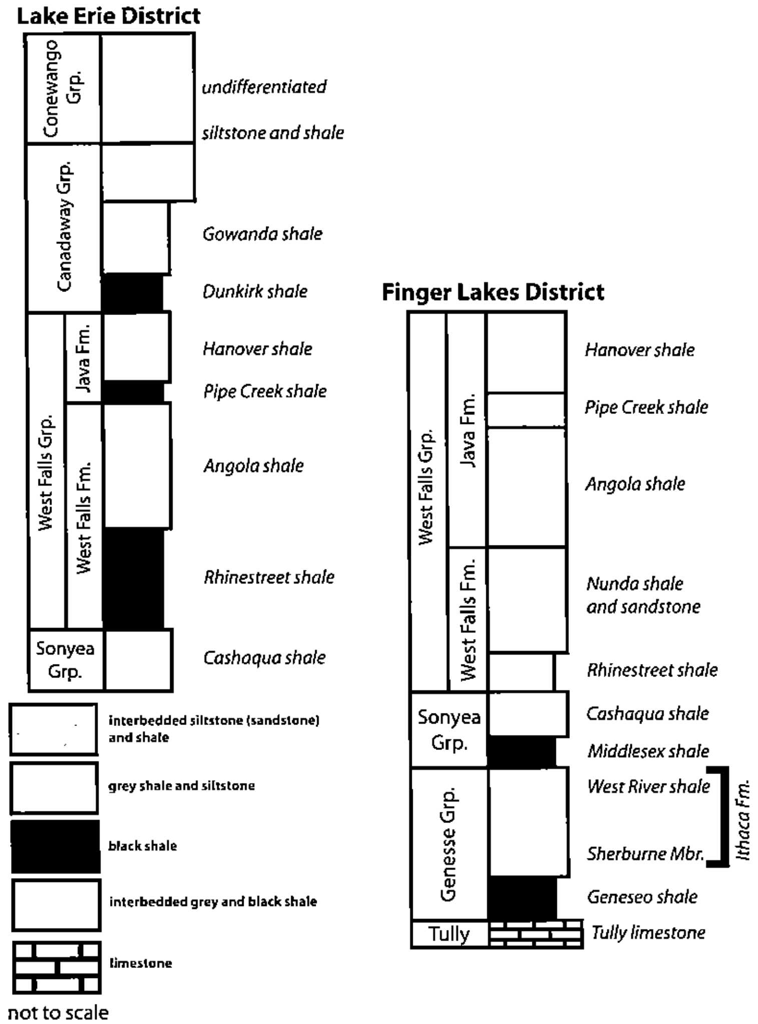

Fig. 2. Generalized Upper Devonian stratigraphic columns of the Lake Erie and Finger Lakes districts.

marine or brackish-water deposits (Baird & Lash 1990), thus recording progradation of the Catskill Delta across the Acadian foreland basin (Faill 1985; Ettensohn 1992). Marine deposits of the Catskill Delta Complex in the northern Appalachian Plateau are arranged in several cycles, each one defined by a basal unit of uniformly laminated fissile black shale that passes upwards through a transition zone of alternating black and grey shale beds into strata dominated by poorly bedded (poorly fissile) grey shale and occasional turbidite siltstone and thin black shale beds (Fig. 2). We documented joint development in four of these black shale cycles within the Genesee, Sonyea, West Falls and Canadaway groups (Figs 2 and 4). The basal black shale unit of each cycle has been interpreted as a record of rapid cratonward movement of the Acadian fold and thrust load followed by deposition of coarser grey shale and occasional silt turbidites (Ettensohn 1985, 1992). Each phase of thrust-sheet imbrication was accompanied by rapid subsidence of the basin and deposition of clastic-starved, organic-rich black shales. Overlying shales and siltstones reflect tectonic relaxation, establishment of terrestrial drainage systems and delta progradation (Ettensohn 1985, 1992). However, Ettensohn's tectonostratigraphic explanation for the cyclic deposition of black shales in the Appalachian Basin has been challenged by models that involve eustatic oscillations and/or fluctuations in productivity of marine organic matter (Johnson *et al.* 1985; Werne *et al.* 2002).

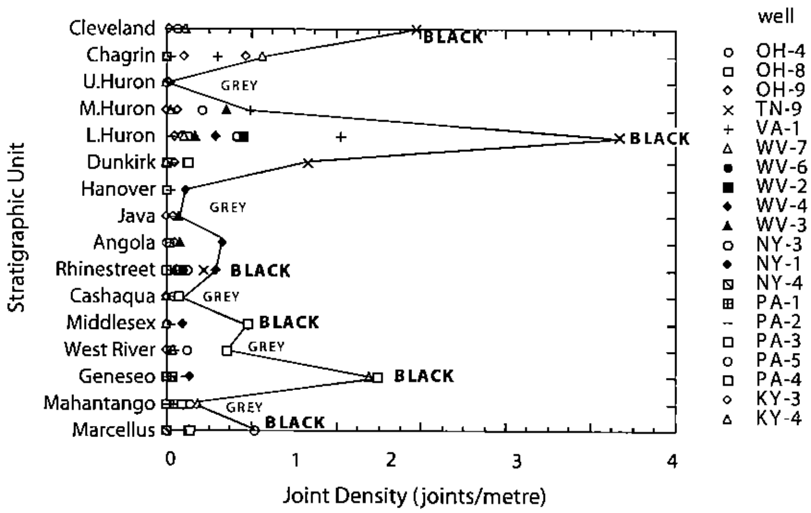

Fig. 3. Plot of joint density (number of joints per unit length of core) within various Devonian formations of the Appalachian Basin (black shale units are shaded). Data are from shale core drilled as part of the Eastern Gas Shales Project (EGSP) and published in a report from Cliffs Minerals, Inc. (1982). The key lists the various EGSP wells. The plot suggests that some black shale sections contain more joints per unit length of core than grey shale. Some unit names apply to the greater Appalachian Basin whereas other unit names are restricted to the New York State portion of the basin. Hence, there is not a one-for-one correlation between the unit names on this plot and stratigraphic terminology employed in the text. The Lower Huron of Ohio and Kentucky is correlated with the Dunkirk Shale of western New York and NW Pennsylvania (de Witt *et al.* 1993). Thus, the single shaded block defining the Dunkirk and Lower Huron black shales does not imply a single very thick unit.

Organic geochemistry of the Catskill Delta Complex

Previous work: the Finger Lakes District

The most complete body of data on the distribution of organic carbon within Devonian shale of the Finger Lakes District of New York State comes from drill cuttings on file with the New York State Geological Survey (Claypool *et al.* 1980). The Catskill Delta Complex in this area of the Appalachian Plateau is dominated by grey shale and siltstone with black shale comprising less than 10% of the section. On average, black shales of the Catskill Delta Complex in the Finger Lakes District contain three–four times the total organic carbon (TOC) of the grey shales (Fig. 5). The organic content of the grey shale serves as a background level against which TOC of the black shale may be compared. The highest TOC in the Catskill Delta Complex of the Finger Lakes District is found in the Middle Devonian Marcellus Formation, which contains almost 10% TOC (Claypool *et al.* 1980). By comparison, the Norwood Member of the Upper Devonian Antrim Formation in the Michigan Basin comprises more than 15% TOC (Loewy 1995).

Thermal maturation, mostly burial-related, of black shale in the Finger Lakes District resulted in vitrinite reflectance ($\%R_o$) values of between 1.5 and 2% (Weary *et al.*, 2000). $\%R_o$ of the younger black shales of the Lake Erie District is of the order of 0.5–0.6 (Weary *et al.* 2000, and measurements of this study). Any of three explanations may account for this difference in thermal maturity. First, it may reflect the rapid thickening by sedimentation or tectonics of the Appalachian Basin from the Lake Erie District eastward to the Finger Lakes District at the end of the Alleghanian orogeny (Johnsson 1986). Second, it may be a response to an elevated geothermal flux associated with emplacement of Cretaceous-age ultramafic intrusions in central New York State (Kay *et al.* 1983). Finally, the marked increase in thermal maturity eastward from the Lake Erie District may reflect a regional fluid flow of heated brines from the hinterland (Oliver 1986).

New work: the Lake Erie District

To supplement the Claypool *et al.* (1980) data we measured TOC in shale units of the Lake Erie District from the Cashaqua Shale up-section into the Gowanda Shale (Fig. 2). The Cashaqua Shale, approximately 30 m of light-grey organically lean shale (0.32% < TOC < 0.77%) and sparse thin–thick

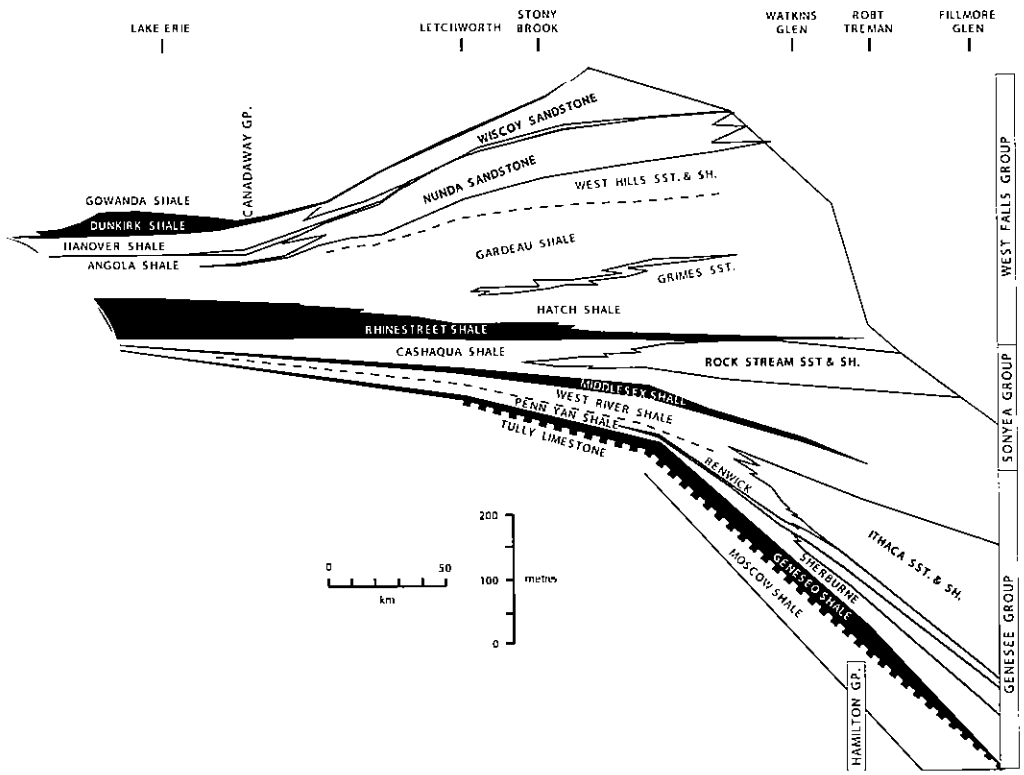

Fig. 4. East–west cross-section through the Catskill Delta Complex showing four phases of black shale deposition defined by the Genesco, Middlesex, Rhinestreet and Dunkirk shales (adapted from Woodrow *et al.* 1988). Because of regional changes in stratigraphy and stratigraphic nomenclature, names of some rock units in the cross-section do not correspond to names of rock units in Figure 2. Figure 1 shows the location and orientation of the cross-section.

beds of siltstone and black shale, is abruptly overlain by the Rhinestreet Shale, 60–80 m of black shale containing horizons of very large (>2 m diameter) septarial carbonate concretions. Geochemical analysis of the Rhinestreet Shale reveals it to be organic-rich (1.8%<TOC<8.01%). The Rhinestreet intertongues with increasingly greater proportions of grey shale and siltstone, and thickens to several hundred metres in the Finger Lakes District (Roen 1984; Evans *et al.* 1989; de Witt *et al.* 1993). The Rhinestreet Shale is gradationally overlain by the organically lean (0.18%<TOC<0.98%) Angola Shale in the Lake Erie District, which comprises about 65 m of grey shale and sporadic thin beds of siltstone and black shale. Overlying the Angola Shale is the carbon-rich (4.85%<TOC<7.37%) Pipe Creek Shale, which thickens from 0.6 m along the Lake Erie shoreline near Silver Creek, New York, to more than 5 m east of Hamburg, New York (Fig. 6). The Pipe Creek is overlain by the Hanover Shale, roughly 30 m of organically lean (0.09%<TOC<0.93%) grey shale and occasional turbidite siltstone and thin black shale beds. The poorly bedded character of the grey silty shale is testimony to its highly bioturbated condition (Baird & Lash 1990). The Hanover Shale is abruptly overlain by the Dunkirk Shale, approximately 15 m of laminated fissile greyish-black and black shale, sparse thin siltstone beds and large (1.5 m maximum diameter) septarial carbonate concretions.

The organic carbon content of the Dunkirk Shale varies at two levels. First, TOC diminishes upsection from 4.63% at the base to 2.74% at the top of the unit along the Canadaway Creek section and the Lake Erie shoreline in the vicinity of Dunkirk, New York (Figs 6 and 7). Roughly 70 km to the east (Cazenovia Creek section), however, TOC of the Dunkirk Shale diminishes from 2.2% at its base to 1.1% at the top of the unit (Figs 6 and 7). Rock-Eval parameters provide information regarding the type of organic material within a source rock as well as its level of thermal maturation (Peters 1986). Comparison of the S2 Rock-Eval parameter (a measure of the hydrocarbon generative potential of a source rock) with TOC suggests that organic matter in the Dunkirk is dominantly oil-prone Type II kerogen of marine origin (Langford & Blanc-Valleron 1990),

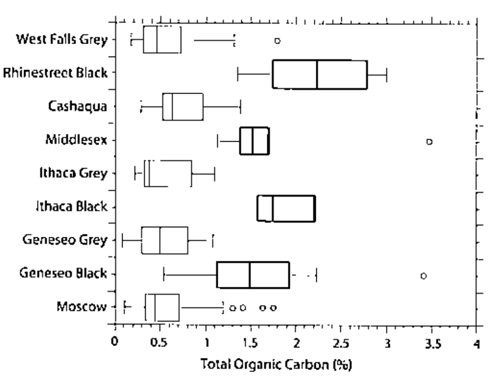

Fig. 5. Percentage of total organic carbon (TOC) averaged for various shales of the Finger Lakes District of the Appalachian Basin. TOC data were taken from cutting samples as reported in Claypool *et al.* (1980).

testimony to the distal location of the Dunkirk Basin. Rock-Eval production index (0.121–0.163) and T_{max} (439–444 °C) parameters place the Dunkirk Shale of the Lake Erie District within the thermal zone of oil generation (Tissot & Welte 1984; Peters 1986; Espitalie 1986). Vitrinite reflectance of the Dunkirk Shale (0.62%) also places this unit within the oil-generating window (Tissot & Welte 1984; Espitalie 1986). Abundant solid bitumen observed in Dunkirk Shale samples (J. Ruffin written comm. 2001) indicates that these rocks generated hydrocarbons (e.g. Momper 1978; Comer & Hinch 1987).

The Dunkirk Shale grades upward through a sequence of interbedded black and grey shale and thin turbidite siltstones into the Gowanda Shale, roughly 70 m of bioturbated and non-bioturbated grey and lesser black shale and bundles of very thin- to medium-bedded siltstone. Black shale beds within the Dunkirk–Gowanda transition zone are laminated and range from several millimetres to more than 55 cm thick. TOC values of these black shale beds (1.07% < TOC < 2.34%) compare favourably with TOC reported from the top of the Dunkirk Shale. Grey shale interbedded with carbonaceous beds of the transition zone and poorly bedded grey shale in the upper two-thirds of the Gowanda Shale is organically lean (0.52% < TOC < 0.83%). The Gowanda Shale is overlain by more than 560 m of shale and very thin- to thick-bedded siltstone that records the gradual infilling of the Acadian foreland basin by the prograding Catskill Delta in this region of the Appalachian Basin (Baird & Lash 1990). Work reported herein focuses on the Hanover–Dunkirk–Gowanda sequence (Fig. 2). These data collected from the Lake Erie District are then compared with data sampled in the more proximal, deeper portion of the Catskill Delta sequence in the Finger Lakes District.

Joint development

The concept of joint development was well entrenched in the literature nearly 100 years ago when Sheldon (1912) reported from the Appalachian Plateau that a particular joint set was 'best developed in shale beds'. Sheldon's usage of the word 'developed' (i.e. development) reflected *joint density*, the number of joints per unit length of scanline and the inverse of joint spacing. In Figure 3 joint density is the number of joints per unit length of core (recalculated as joints m^{-1}) where the direction of coring defines the scanline orientation (i.e. subvertical in this case). Analysis of joint density data derived from EGSP cores reveals that while joint density is greatest in some black shale units, jointing is not uniformly developed among organic-rich shale units throughout the Appalachian Basin. If hydrocarbon production from black shales is dependent on joint density (i.e. development) and interconnectivity, then we conclude from Figure 3 that some stratigraphic levels are better targets for exploration than others.

Joint development was quantified by Wu & Pollard (1995), who suggested that a two-dimensional (2D) analysis of joint density is a more robust measure of joint development than that obtained by 1D scanlines. In their analysis of cumulative joint length per unit area of outcrop, poorly developed joint sets are those with joint lengths less than or roughly equal to orthogonal spacing. Well-developed joint sets are those whose component joint lengths are much greater than spacing. Regardless of lithology, most outcrops of Devonian shales on the Appalachian Plateau carry at least one well-developed regional joint set according to the definition of Wu & Pollard (1995). Still, development of a particular joint set as measured by spacing data may not be uniform in a temporal or spatial sense as indicated by data from the EGSP cores (Fig. 3).

Joint development in the Hanover–Dunkirk–Gowanda sequence, Lake Erie District

The control sample in our study of the relationship of TOC and joint development in Devonian shales is the Hanover–Dunkirk–Gowanda sequence of the Lake Erie District, which lies on the North American craton beyond the influence of Alleghanian folding above a detachment on Silurian salt (Fig. 1). Nevertheless, finite-strain analysis of Devonian rocks of far-western New York indicates that the imprint of the Alleghanian orogeny does reach into the craton through the Lake Erie District (Engelder 1979) and much farther to the west (Craddock & van der Pluijm 1989).

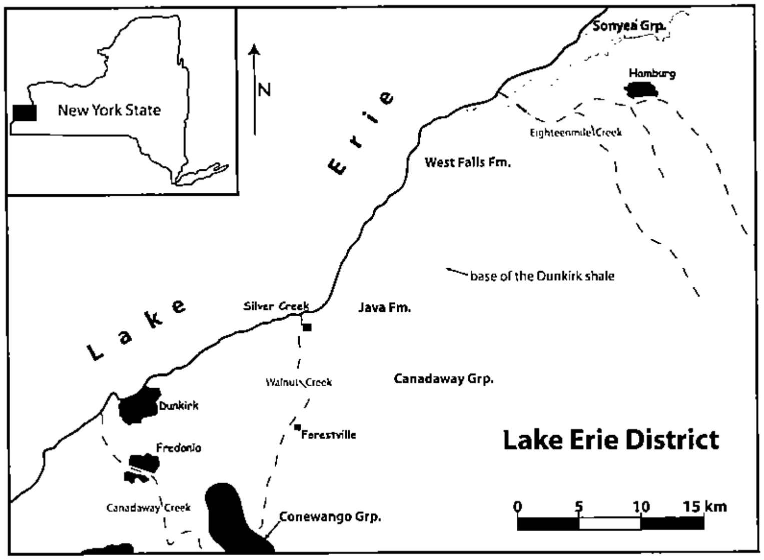

Fig. 6. Map of the Lake Erie shoreline region of the Lake Erie District (refer to Fig. 1) showing the location of Canadaway Creek, and the outcrop distribution of the Hanover Shale (Java Formation) and the Dunkirk and Gowanda shales (Canadaway Group) and other units.

Orientation data. Rocks of the Hanover–Dunkirk–Gowanda sequence typically carry two or three of five regional joint sets recognized in the Lake Erie District. NW (*c.* 310°), NNW (*c.* 352°) and ENE (*c.* 072°) sets are dominant over a WNW (*c.* 275°) set and a NE (*c.* 050°) set that appears to be the most recent (Fig. 8). Almost all joints studied are near vertical and none show evidence of slip, an observation that contrasts with reactivated joints observed deeper within the Catskill Delta Complex (e.g. Engelder *et al.* 2001). Of particular interest is the ENE set, which shows a very strong affinity for the Dunkirk black shale as well as black shale beds within the Dunkirk–Gowanda transition zone. Preferential jointing of organic-rich rocks in the Lake Erie District accords well with Sheldon's (1912) early observation of joint development in black shale further to the east and deeper in the sedimentary pile. ENE joints typically are planar and very continuous (locally >50 m, extending beyond the limits of exposure). Their observed heights (occasionally in excess of 4 m, the height of the exposure) are sometimes an order of magnitude greater than their spacing (Fig. 9A). The large height–spacing ratio indicates that ENE joints propagated through the mechanically isotropic Dunkirk Shale unimpeded by bedding interfaces. The planarity and continuity of these joints, as well as their straight overlapping geometries, suggest that ENE joints formed under conditions of relatively high (for mode I cracks) differential stress (Olson & Pollard 1989) perhaps as natural hydraulic fractures (Fischer *et al.* 1995). ENE joints appear to have propagated upward from the Dunkirk Shale into the Gowanda grey shale, yet very few ENE joints extend more than a few centimetres from the bottom of the Dunkirk into the Hanover grey shale. Thus, the base of the black shale unit is a sharp mechanical boundary (e.g. Gross 1993).

NW joints, too, are very planar and continuous in outcrop, extending more than 40 m, beyond the limits of outcrop. They differ from ENE-trending joints by being more a bit more pervasive throughout the Lake Erie District Upper Devonian shale section, but, like ENE joints, NW joints are more closely spaced in black shale. Locally within the Dunkirk Shale, NW joints attain heights of 2–3 m, and few NW joints extend from the base of the Dunkirk Shale into the Hanover Shale (Fig. 9B).

Joint development (spacing and density). We used simple scanline techniques to assess the relative uniformity of development of one or more joint sets. Our data are corrected for the orientation of the scanline by employing Terzaghi's (1965) geometrical formula and are then plotted in the form of box-and-whisker diagrams (e.g. Fig. 10). Spacing values of a particular joint set at a specific outcrop are plotted horizontally. The box encloses the interquartile range of the data-set population; a vertical line drawn through the box defines the median value of the data population. The interquartile range is bounded on the left by the 25th percentile (lower quartile) and on the right by the 75th percentile

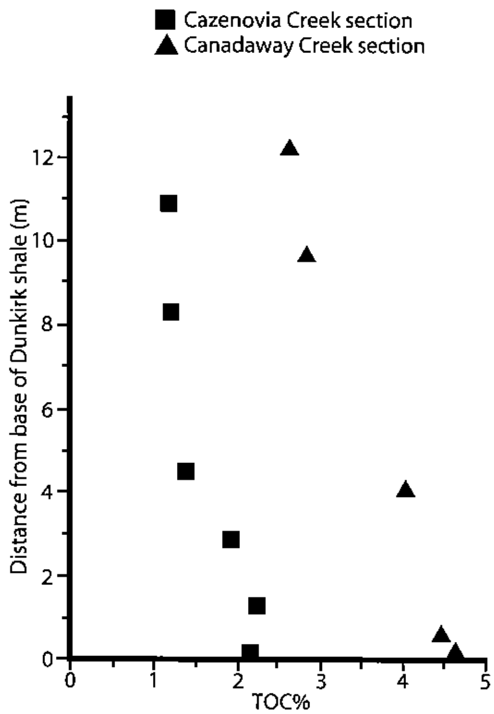

Fig. 7. Plot of total organic carbon (TOC) v. distance from the base of the Dunkirk Shale along the Canadaway Creek and Cazenovia Creek sections, Lake Erie District (refer to Fig. 6 for locations).

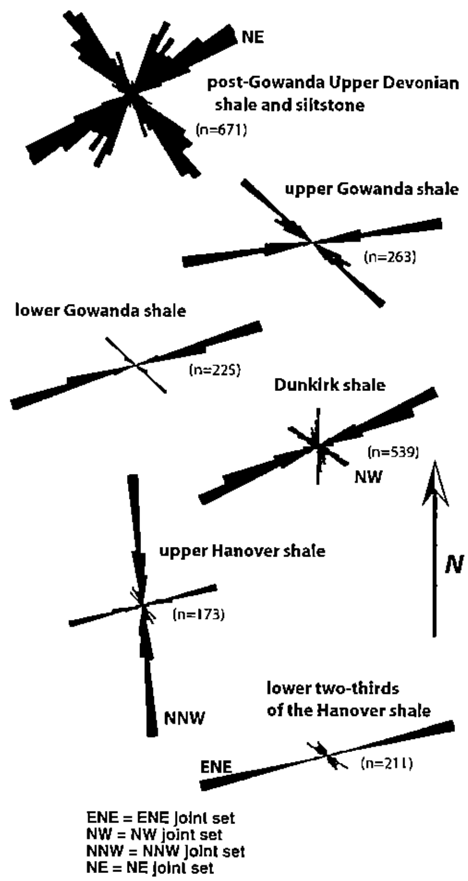

Fig. 8. Rose diagrams of joint orientations through the Hanover–Dunkirk–Gowanda sequence and overlying Devonian deposits of the Lake Erie District.

(upper quartile); the 'whiskers' mark the extremes of the sample range. We conclude that spacing data from two samples (i.e. spacing values collected from the same joint set at two sampling stations) is statistically related if the 25th percentile line of one plot (sample station) does not exceed the median value of the other (Walpole *et al.* 2002). If several samples of a specific joint set are statistically related, we infer that a joint set is similarly developed (i.e. similar spacing characteristics) among the sampling stations. One joint set is said to be better developed than another set at the same sampling station if the median value of the former lay to the left of (i.e. is less than) the 25th percentile value of the other joint set.

Scanline analysis of the Hanover–Dunkirk–Gowanda sequence along the Canadaway Creek section and the Lake Erie shoreline in the western part of the Lake Erie District (Fig. 6) reveals that the degree of development of ENE joints, as measured by orthogonal spacing, decreases up-section from the base of the unit (Fig. 10). Specifically, ENE joints are more evenly and closely spaced (better developed) in the Dunkirk black shale than they are in the overlying Gowanda grey shale. Moreover, the density of ENE joints is highest in the lower part of the Dunkirk Shale, the most organically rich rocks (compare Figs 7 and 10). ENE joint set scanline data collected from three exposures in the lower half of the Dunkirk Shale show little variation and have median values of less than 75 cm (Fig. 10). However, 25th percentile spacing values of the upper half of the Dunkirk Shale exceed median spacing values of ENE joints in the lower part of the unit (Fig. 10) suggesting that ENE joints in the lower half of the Dunkirk Shale are the better developed. ENE joints are present in the Gowanda Shale, although spacing increases markedly upwards through the grey shale (Fig. 10). The great variation in joint spacing/density within the Dunkirk–Gowanda transition zone (Fig. 10) reflects the preferential ENE fracturing of black shale interbedded with grey shale. Although some widely spaced joints escape the carbon-rich layers into encapsulating grey shale, most ENE joints are confined to black shale beds. Finally, ENE jointing

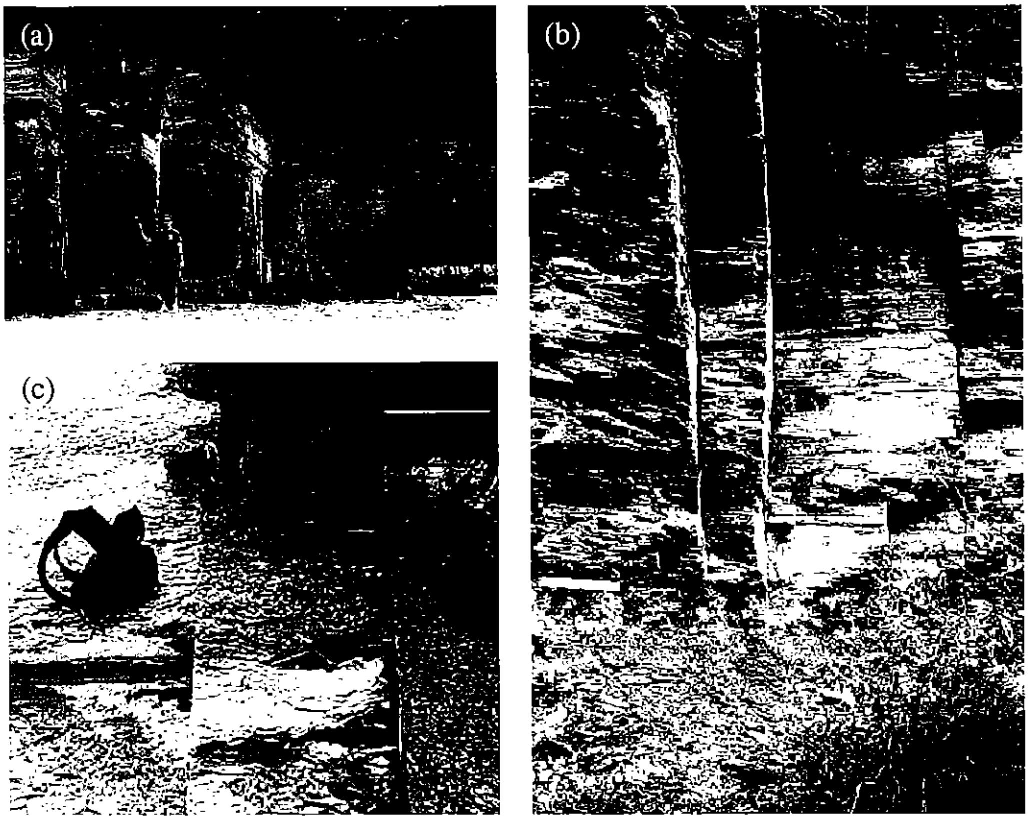

Fig. 9. (A) ENE (at high angle to the plane of the photograph) and NW (roughly parallel to the plane of the photograph) joints in the Dunkirk Shale, Lake Erie shoreline. (B) Large NW joints at the contact (white bar) of the Dunkirk Shale and underlying Hanover grey shale along Eighteenmile Creek (see Fig. 6 for location). Note the close spacing of these tall joints. White bar = 0.5 m. (C) NNW joints in the Hanover Shale (below white bar) terminating at the base of the Dunkirk Shale, Lake Erie shoreline.

in poorly bedded grey shale higher in the Gowanda Shale demonstrates a diminished degree of development, as revealed by a low joint density (Fig. 10).

Qualitative field observations of NW joints suggest a more subdued link to TOC in the Dunkirk Shale. Two trends that are recognized in the NW joint spacing data lend support to this hypothesis. First, the 25th percentile values from three scanlines across NW joints in the Gowanda grey shale far exceed the median spacing of NW joints in the three stratigraphically lowest scanlines of the Dunkirk Shale (Fig. 11). Second, the 25th percentiles of NW joints in the grey shale exceed median spacing of ENE joints carried by rocks at the same exposures (e.g. compare locations 2B34CC and 3B8CC in Figs 10 and 11). Similarly, the 25th percentile values of NW joints in the Dunkirk Shale exceed the median spacing of ENE joints at the same sampling stations (e.g. compare locations BD1CC, MdkCC and WC28CC in Figs 10 and 11). We conclude that, although both ENE and NW joint sets are best developed in black shale, ENE joints are the better developed.

The occurrence of joints in the Hanover Shale differs in several respects from jointing patterns in the Gowanda and Dunkirk shales. ENE joints are present at intervals throughout the Hanover, especially in the lower two-thirds of the unit, yet they are infrequent (very widely spaced) or absent near the top of the unit (Fig. 8). Scanlines completed in the Hanover Shale failed to yield enough data to evaluate; still, observations of ENE joints in these organically lean shales reveal that spacing typically exceeds 2 m. NW joints are not well represented in the Hanover Shale; indeed, they are less common in the upper half of the unit than are ENE joints (Fig. 8). The most intriguing joints carried by the Hanover Shale are those of the NNW set, which are found only in the upper half of this grey shale sequence (Fig. 8). NNW joints observed from bluffs along the Lake Erie shoreline are continuous for well over 100 m and display spacings of the order of 1–5 m,

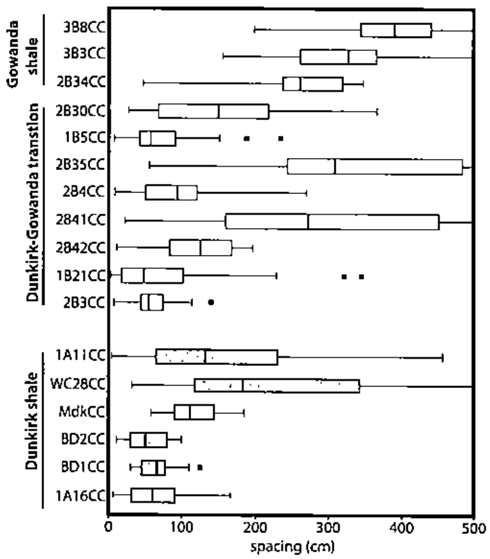

Fig. 10. Box-and-whisker diagrams representing joint-spacing distribution for ENE joints from the base of the Dunkirk Shale into the Gowanda Shale. Scanline data collected from Canadaway Creek and Lake Erie shoreline (as indicated by 'CC' in station locations), Lake Erie District. Stations are arranged in stratigraphic order.

depending on proximity to the contact with the Dunkirk Shale. Moreover, few of these joints extend more than several tens of centimetres into the Dunkirk (Fig. 9C).

Field evidence in the form of abutting relations suggests that NNW joints are older than both the NW and ENE joints. Moreover, ENE joints commonly abut (i.e. a T-shaped pattern or curving perpendicular geometry) NW and NNW joints, suggesting that they were open discontinuities during propagation of ENE joints (Dyer 1988). The classic interpretation for such abutting is that the ENE joints are the younger, a view held by Engelder (1982) and Hancock & Engelder (1989). Nevertheless, 20% mutually cross-cutting joint interactions between NW and ENE joints and the rare NW joint that abuts an ENE joint reveal the difficulties that attend relative age determination of jointing in black shale.

Joint development in the deeper portion of the Catskill Delta Complex, Finger Lakes District

Having established that the ENE joint set is best developed in the Dunkirk black shale but later than the NW joint set, we now move east and deeper into the stratigraphic pile of the Catskill Delta Complex (Fig. 12). In so doing we also move from rocks that were unaffected by Alleghanian folding to a section that was folded and experienced as much as 10% layer-parallel shortening. Furthermore, we progress much deeper into the Catskill Delta Complex where black shales may have entered the oil window by the close of the Acadian orogeny in the Early Carboniferous. We focus on joint development in the Middlesex Shale of the Sonyea Group and the Geneseo Shale of the Genesee Group (Figs 2 and 4).

Orientation data. Similar to previous work in the Catskill Delta Complex by Parker (1942), Nickelsen & Hough (1967) and Engelder & Geiser (1980), we identified multiple joint sets in both black and grey shales based on the clustering of orientation data. Three major joint sets are found in grey shales, the most prominent being a cross-fold joint set that varies in strike with the trend of Alleghanian folds from NNW–SSE to N–S (CF in Fig. 1). Some outcrops carry multiple cross-fold joint sets, one set in siltstone beds and another in interlayered grey shale (Younes & Engelder 1999). Two cross-fold joint sets are frequently observed in thick, weakly bedded shales, in some cases mutually cross-cutting; elsewhere a later set abuts an earlier set. There remains disagreement as to how to distinguish between these cross-fold joint sets and their mode of origin (e.g. Nickelsen & Hough, 1967; Engelder & Geiser 1980; Bahat & Engelder 1984; Helgeson and Aydin 1991; Evans 1994). We correlate the cross-fold joints carried by black shale in the Finger Lakes District with the NW joint set in the Dunkirk Shale of the Lake Erie District. Both sets reflect the transport direction during Alleghanian deformation of the Appalachian Plateau and, thus, are manifestations of the orientation of the maximum horizontal stress, S_H, in an Alleghanian stress field. Although NW joints in the Lake Erie District are best developed in the black shale, cross-fold joints in the Finger Lakes District are better developed in grey shale and siltstones.

A second joint set, particularly well developed in the thicker, weakly bedded shales of the Hamilton, Genesee and Sonyea groups, strikes consistently near 070°. This is set III of Parker (1942) and the strike set of Sheldon (1912). Some cross-joints and curvy cross-joints have the same orientation as the 070° joints, but joints of the 070° or ENE set are large and planar, cross-cut cross-fold joints, and are best developed in the deeper portion of the Catskill Delta Complex where shale is more common (ENE in Fig. 1). These joints do not vary in orientation with changes in the trend of the Alleghanian folds like cross-fold joints; rather, ENE joints transect folds obliquely (Fig. 1).

ENE and cross-fold joints mutually cross-cut in black shale precluding use of an abutting criterion to infer the relative ages of the two joint sets. In fact,

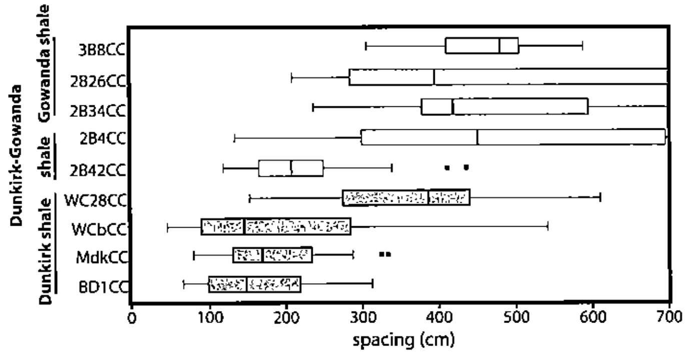

Fig. 11. Box-and-whisker diagrams representing joint-spacing distribution for NW joints from the base of the Dunkirk Shale into the Gowanda Shale. Scanline data collected from Canadaway Creek and Lake Erie shoreline (as indicated by 'CC' in station locations), Lake Erie District. Stations are arranged in stratigraphic order.

occasional ENE joints are displaced by slip on Alleghanian cross-fold joints, indicating that the ENE joints in the Finger Lakes District are pre-Alleghanian (Engelder *et al.* 2001). For these reasons, the ENE joints of the Finger Lakes District do not correlate in time with the ENE joints reported from the Lake Erie District despite having nearly the same orientation.

The thick, weakly-bedded black shales of the Catskill Delta Complex in the Finger Lakes District carry the same cross-fold joints, cross-joints (i.e. neotectonic) and ENE joints as the grey shales, but the thinner-bedded black shales of the Rhinestreet Shale and the Sherburne Member of the Ithaca Formation carry an additional joint set that is most common in these thin (<1 m) organic-rich beds (EW in Fig. 1). This set, which strikes approximately 085°, is rare in the grey shales and siltstones as well as in the thick, weakly bedded Geneseo and Middlesex black shale units. Like the ENE joint set, the EW (E–W) set does not vary in orientation with the trend of the local Alleghanian folds (Fig. 1).

Finally, outcrops of the Catskill Delta Complex carry non-systematic cross-joints (CJ in Fig. 1) that extend between systematic joints to form an outcrop pattern resembling the rungs on a ladder (e.g. Gross 1993). Some cross-joints have a sigmoidal shape in plan view. Engelder & Gross (1993) refer to the sigmoidal joints as 'curvy cross-joints' that propagated as neotectonic joints in the contemporary stress field. Cross-joints, both straight and curvy, appear best developed in siltstone beds within formations of the West Falls Group and younger strata. Many of these joints strike parallel to Appalachian Basin fold axes and orthogonal to bounding cross-fold joints. The strike of cross-fold joints in siltstone beds ranges from 045° in the west of the Finger Lakes District to 070° in eastern outcrops. Farther to the east, the fold-parallel set strikes E–W (Parker 1942). Our observations indicate that the fold-parallel joint set propagated as late-stage cross-joints whose orientations were controlled by either the contemporary tectonic stress field or bounding cross-fold joints.

Joint development (spacing and density). We have scanline data collected from more than two dozen high-quality outcrops in black shale (Loewy 1995). Results of these scanlines are best captured in the data from Boyd Point (STE01AY) in the Middlesex Shale of the Sonyea Group, and Squaw Point (YAT03AY) and Fillmore Glen (CAY-01-SL) in the Geneseo Shale of the Genesee Group (Fig. 12). The transition from the organic-rich Middlesex Shale to the Cashaqua grey shale at Boyd Point carries the ENE joint set and two cross-fold joint sets (326° and 008°) with the anticlockwise set of this pair the better developed set (Fig. 13). Two trends in the joint spacing data are evident. First, the 25th percentile for the ENE joint set in grey shale at the top of the Cashaqua Shale (scanline #5, Fig. 13) equals or exceeds the median spacing of the ENE joint set for two scanlines lower in the section where black shale is found (scanlines #1, #2 and #3, Fig. 13). Second, 25th percentiles of cross-fold joint sets in three scanlines exceed the median spacing of the ENE joint sets in all scanlines in both the black Middlesex and grey Cashaqua shales (Fig. 13). Both the cross-fold and ENE joints at Boyd Point illustrate relatively consistent spacing characteristics within their respective set, although each set is defined by distinctly different spacing populations. Hence, we conclude that the ENE set is better developed than the cross-fold joints. Moreover, the density of ENE joints gradually decreases up-section into the grey shale, similar to our observations of the transition from black to grey shale in the Lake Erie District.

The transition from the Geneseo black shale to the

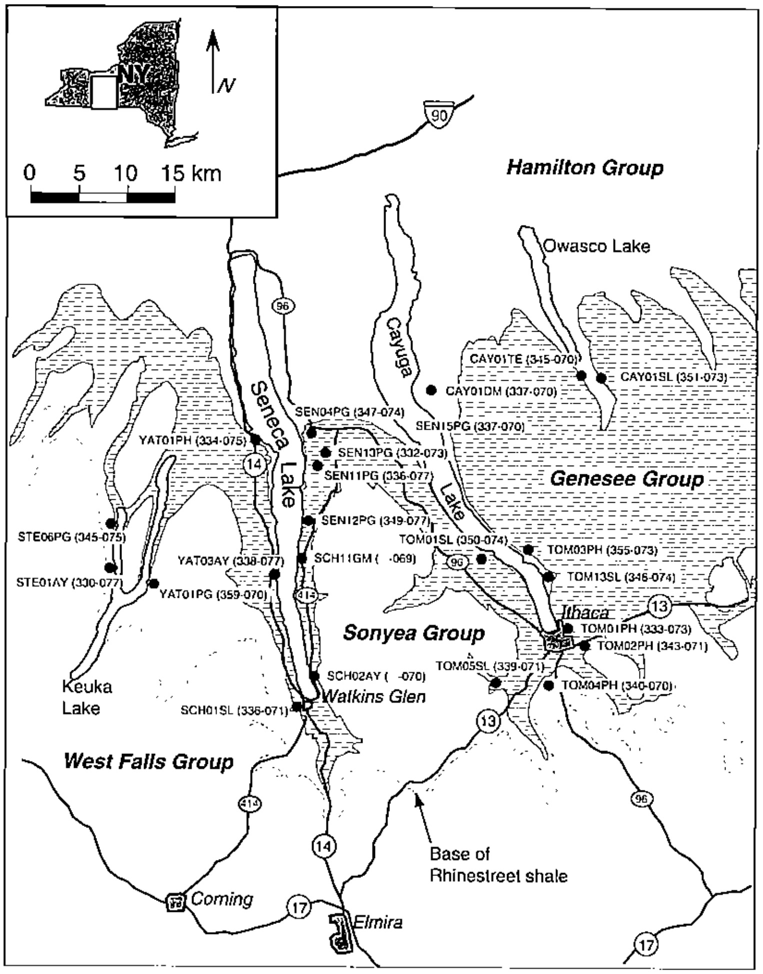

Fig. 12. Map of the Senaca–Cayuga lakes region of the Finger Lakes District showing the outcrop distribution of the Hamilton, Genesee, Sonyea and West Falls groups. The base of the Rhinestreet Shale marks the boundary between the West Falls and Sonyea groups. The Geneseo black shale crops out just above the base of the Genesee Group and the Middlesex black shale crops out just above the top of the Genesee Group (see stratigraphic section in Fig. 2). Median joint orientations for ENE and cross-fold joint sets are indicated for each outcrop.

grey shale of the Sherburne Member (Ithaca Formation) is exposed at Squaw Point (Fig. 12). One cross-fold joint set (i.e. 338°) and the ENE joint set occur throughout the section. A second cross-fold set is too poorly developed to be of use in our analysis. Again, two trends in the joint spacing data can be seen (Fig. 14). First, 25th percentile values for the three scanlines through the ENE joint set in the grey shale of the Sherburne Member equals or exceeds the median spacing of ENE joints in two scanlines through the Geneseo black shale and a scanline through the transition (Fig. 14). Second, the spacing of cross-fold joints in the black Geneseo and grey shale of the Sherburne Member is more variable, as indicated by the width of the interquartile range and range of median values. At Squaw Point cross-fold and ENE joints show dissimilar spacing characteristics. Here again, we conclude that ENE joints, most densely distributed in the black shale, constitute the better developed set.

The highest quality exposure through the Geneseo black shale and into the grey shale of the Sherburne Member is found at Fillmore Glen, an outcrop to the east of Squaw Point (Fig. 12) that was buried deeper than all sample stations to the west. As in previous examples, the ENE joint set is best developed at the base of the Geneseo and gradually decreases in density upwards into the overlying grey shale (Fig. 15). However, in the grey shale the cross-fold joint set is consistently better developed than is the ENE

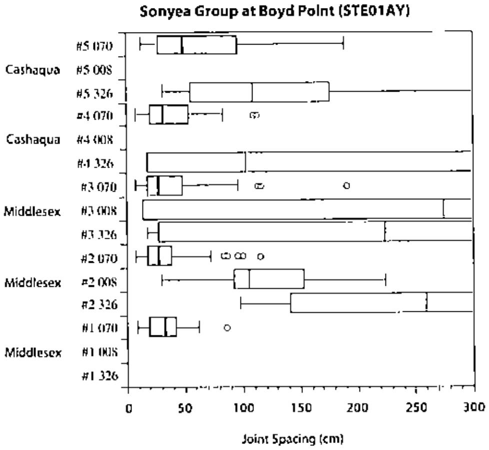

Fig. 13. Box-and-whisker diagrams representing the joint-spacing distribution for two joint sets (i.e. one cross-fold set and the 070° set) across the transition from the Middlesex Shale to the Cashaqua Shale at Boyd Point outcrop on Keuka Lake. Refer to Figure 12 for outcrop location STE01AY.

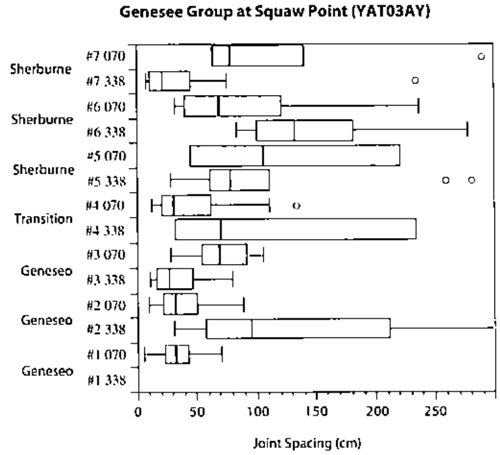

Fig. 14. Box-and-whisker diagrams representing the joint-spacing distribution for two joint sets (i.e. one cross-fold set and the 070° set) across the transition from the Geneseo Shale to the Sherburne Member of the Ithaca Formation at the Squaw Point outcrop on the west side of Seneca Lake. Refer to Figure 12 for outcrop location YAT03AY.

set (Fig. 15). The distinguishing feature of the Fillmore Glen section is that cross-fold joints are unusually well developed at the top of the black shale with spacing values less than those observed in any joint set at any other location in the Catskill Delta Complex. It is the focusing of cross-fold joint development at the top of this most deeply buried black shale section that provides a major clue to our understanding of the role of hydrocarbon generation as a joint-driving mechanism.

Data from the Boyd Point, Squaw Point and Fillmore Glen exposures, as well as other outcrops shown in Figure 12, enable us to distinguish joint development in black and grey shale. First, the ENE joint set is better developed in black shales than in grey shales. Second, in most black shale exposures that carry the ENE and cross-fold joint sets, the former is the better developed. Third, throughout the region shown in Figures 1 and 12, the orientation of the ENE joint set remains relatively consistent, unaffected by changes in the trend of local folds. Finally, the orientations of the cross-fold joint sets vary to maintain an orientation roughly normal to Alleghanian folds axes. Coupling these observations with our observations from the Lake Erie District, we conclude that conditions in the black shales most favoured development of the ENE joint set regardless of structural position and depth of burial within the northern portion of the Appalachian Basin. However, the ENE joints do not constitute a single set because they predate joints of the Alleghanian orogeny in the deeper, proximal portion of the Catskill Delta Complex and post-date joints of the Alleghanian orogeny in the shallower more distal region of the basin.

Discussion

In the following discussion we search for a self-consistent interpretation of joint development in black shale across the northern portion of the Appalachian Basin. We begin with the premise that cross-fold joints in the Finger Lakes District are Alleghanian in age (Engelder & Geiser 1980), an assertion that has not been challenged to date (Younes & Engelder 1999). The same premise applies to the Lake Erie District where the NW joint set is approximately coaxial with a very modest Alleghanian strain (e.g. Engelder 1979; Craddock & van der Pliujm 1989). Despite the strength of evidence pointing to an Alleghanian age for the cross-fold and NW joints, we are left with the dilemma that the best-developed joint set in Devonian black shale throughout the Catskill Delta Complex, the ENE set, appears to have no tectonic affinity for Alleghanian structures and is not even contemporaneous throughout the delta complex. Indeed, the ENE set seems to be uniformly oriented across the transition from the folded Appalachian Plateau of the Finger Lakes District to the unfolded rocks of the Lake Erie District. In addition, a joint set of the same orientation is the best developed set in Devonian black shales of the Michigan Basin (Apotria *et al.* 1994). While it might seem appropriate to correlate the ENE joint sets in the

Genesee Group at Fillmore Glen (CAY01SL)

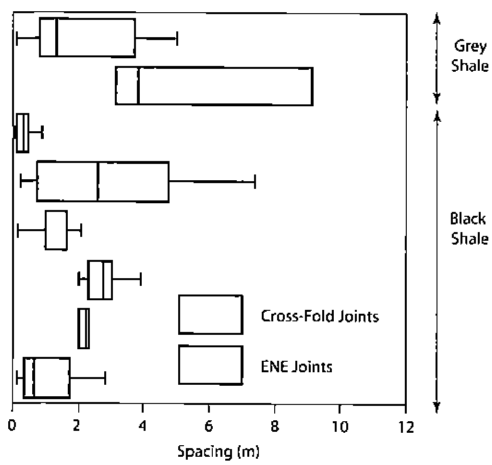

Fig. 15. Box-and-whisker diagrams representing the joint-spacing distribution for one cross-fold set and the 070° set across the transition from the Geneseo black shale into the grey shale of the Sherburne Member of the Ithaca Formation at the Fillmore Glen outcrop. Refer to Figure 12 for outcrop location CAY01SL.

Lake Erie and Finger Lake Districts based on orientation, evidence from abutting relationships makes it clear that these joints do not correlate in age.

Joint-driving mechanism

In order to more fully understand the role of TOC in jointing of the Devonian shale of the Appalachian Plateau, we need to understand the nature of joint-driving mechanisms in the carbon-rich shale. Analysis of joint-surface ornamentation facilitates the identification of joint-driving mechanisms. For example, cross-fold joints of the Finger Lakes District have a cyclic propagation pattern indicative of hydraulic fracturing (Lacazette & Engelder 1992). But, with the exception of the rare arrest line and plumose structure, all observed joint surfaces within Upper Devonian black shales are devoid of any surface morphology that might provide information regarding the origin of the joints. This is largely a consequence of the rock being so fine grained that the rupture path is not disrupted by small-scale heterogeneities. It is these small-scale heterogeneities that give rise to surface morphology in coarser-grained clastic rocks (Scott *et al.* 1992).

Still, there is evidence that both ENE and NW joints in black shales in both the Lake Erie and Finger Lakes Districts are natural hydraulic fractures. For example, the locally large height–spacing ratio of the ENE joints is at odds with spacing as a consequence of stress-reduction shadows in joints developed under extension of beds (Gross *et al.* 1995). Rather, the close spacing of the studied joints is more consistent with their formation as hydraulic fractures than tensile joints produced by joint-normal loading or stretching (Laderia & Price 1981; Fischer *et al.* 1995; Engelder & Fischer 1996). The NW joint set of the Lake Erie District also displays the same large height–spacing ratio as do cross-fold joints at the top of the Geneseo black shale in the Fillmore Glen section of the Finger Lakes District. Equally compelling evidence comes from abutting relations of NW and ENE joints and carbonate concretions within black shale throughout the delta sequence. Joints of both sets consistently retain their planar nature as they approach and eventually make contact with concretions. Most joints terminate at concretion surfaces, although some penetrate or even cleave small concretions (Fig. 16). These relations suggest that NW and ENE joints propagated under a fluid-driven mechanism characterized by high crack-tip stress (McConaughy & Engelder 1999).

The degree of development of the ENE joints in post-Gowanda units in the Lake Erie District (as revealed by low joint density) is markedly lower than that in the underlying shale-dominated section. This may mean that the fluid-driven mechanism was not as effective in these coarser-grained rocks, which could have effectively drained the section thereby preventing a build-up of higher fluid pressure. Individual joints are curvilinear, almost always less than 0.5 m high and seldom extend more than 10 m horizontally. Moreover, siltstone beds thicker than 3 cm virtually never carry systematic ENE joints. Two joint sets, a NW and younger NE (*c.* 050°) set, are recognized in these rocks; both display a greater level of circular variance than that seen in any systematic joint set recognized in the Gowanda Shale and older units (see Fig. 8). The NE set is interpreted to have formed at relatively shallow depths under the influence of the contemporary stress field in this region of the Appalachian Plateau (S_H = N58°E ± 8°; Plumb & Cox 1987). Where NE-trending joints can be observed in the Hanover–Dunkirk–Gowanda sequence, abutting relationships clearly indicate that these joints are younger than ENE joints.

The transition in jointing style from the shale-dominated to siltstone-rich section in the Lake Erie District resembles the same transition from the deeper shale section of the Sonyea and Genesee groups to the overlying sandstones in the Finger Lakes District (Engelder & Oertel 1985). Circular variance of Alleghanian cross-fold joints of the Finger Lakes District increases upward from the deeper, overpressured section (as indicated by undercompaction) to the overlying sandier section (Engelder & Oertel 1985). ENE joints, best developed in black shale sections throughout the

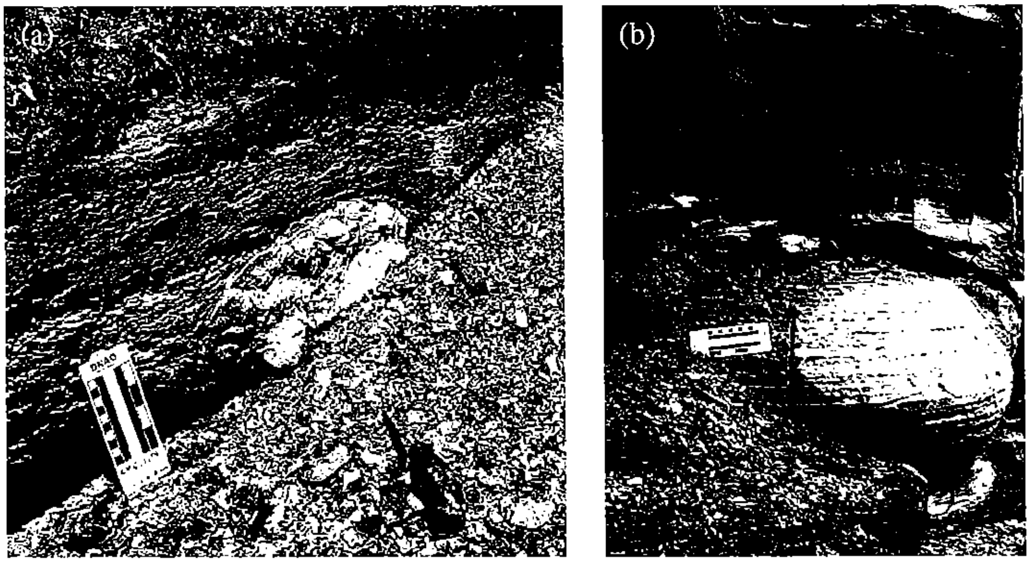

Fig. 16. (A) Small carbonate concretion in the Dunkirk Shale cleaved by an ENE joint (Walnut Creek). (B) Carbonate concretion penetrated (indicated by vertical scar on the concretion surface on the immediate right of the scale) by a NW joint (perpendicular to the plane of the photograph). Note that an ENE joint (subparallel to plane of the image) shows no obvious deviation around the concretion.

Appalachian Plateau, disappear upwards into siltier and sandier units in both the Finger Lakes and Lake Erie districts. There seems to be little doubt that the hydraulic-fracture-driving mechanism of the ENE joints was tied directly to the black shales. The mechanism responsible for driving the Alleghanian cross-fold joints into the coarser-grained section of the Devonian sequence is the same. However, the striking difference in orientation of the ENE and cross-fold joints is testimony to the asynchronicity of these fracturing events. Moreover, the fact that joints of both sets are hydraulic fractures suggests that asynchronous jointing was a function not only of the stratigraphic host but also of the specific timing and mechanism by which overpressure was generated in the first place.

Mechanisms for generating overpressure

The generation of abnormal pressures in a sedimentary sequence commonly reflects the interplay of two or more mechanisms (Magara 1981; Gaarenstroom *et al.* 1993; Sweeney *et al.* 1995; Swarbrick & Osborne 1998). It is possible that accumulation of the increasingly coarse-grained deposits that overlie the Gowanda Shale resulted in disequilibrium compaction of deeper shales, thereby inhibiting expulsion of pore water from these low-permeability rocks (e.g. Swarbrick & Osborne,1998). Chapman (1980) noted that disequilibrium compaction is most common to regressive sequences, and Burrus *et al.* (1993) pointed out that deeper shales within the Mahakan Delta Complex, Indonesia, are overpressured whereas shallow sand-rich deposits are hydrostatically pressured. In fact, undercompaction and, hence, palaeodisequilibrium compaction has been documented in shales of the Finger Lakes District (Engelder & Oertel 1985). Nevertheless, disequilibrium compaction alone is insufficient to generate fluid pressures capable of driving natural hydraulic fractures (Hart *et al.* 1995; Kooi 1997).

The strong correlation between the degree of development of ENE joints and TOC in thermally mature Upper Devonian black shale of the northern Appalachian Basin suggests a genetic link. Numerous authors have cited thermal maturation of organic material as a mechanism capable of generating abnormal fluid pressures in source rocks (Snarsky 1962; Meissner 1978; Momper 1978; Spencer 1987; Stainforth 1984; Buhrig 1989; Gaarenstroom *et al.* 1993; Leonard 1993; Holm 1998, among others). We suggest that the active generation of hydrocarbons boosted formation pressures high enough to induce propagation of hydraulic fractures within the impermeable, organic-rich Dunkirk Shale of the Lake Erie District and the Middlesex and Geneseo black shales deeper in the section and farther to the east in the Catskill Delta Complex. Organically lean strata of the Gowanda and Hanover shales of the Lake Erie District, as well as their counterparts in the Finger Lakes District, are not nearly as well jointed as vertically adjacent black shale and could not have developed high formation pressures by internal hydrocarbon generation. Instead, episodic expulsion of highly pressured fluids (water, oil, gas) from mature source rocks, or perhaps vertically propagating water and/or methane-filled hydraulic fractures (e.g. Nunn & Meulbrock 2002), may have been crucial to the hydraulic fracturing of the Gowanda grey shale. The same may be said for the presence of ENE joints in the immediate post-Middlesex and Geneseo grey shale in the more proximal portion of the Catskill Delta Complex

Alleghanian joints (i.e. the NW or cross-fold joints) are best developed in the black shale in the Lake Erie District but pervade the section in the Finger Lakes District. Although the generation of hydrocarbons was responsible for the production of overpressures in the distal, organic-rich, portion of the delta complex during the Allghanian orogeny, the level of pressure or volume of fluid was insufficient to fracture the entire *Upper Devonian* sedimentary pile. Therefore, another mechanism may have been active in the folded region of the complex to drive a more pervasive hydraulic fracturing event. The strongly oriented character of ENE joints, and NW and cross-fold joints, along our transect suggests that hydraulic fracturing occurred under an anisotropic horizontal stress field associated with tectonics in the upper crust. However, the presence of an anisotropic horizontal stress field does not mean that the differential stress was high enough to cause lateral compaction, which can lead to a marked increase in pore pressure in a sequence of rocks encompassing zones of under-compacted low permeability strata (Hubbert & Rubey 1959; Pickering & Indelicato 1985; Grauls 1998). Layer-parallel shortening strain of the folded region of the Appalachian Plateau evinces a large component of lateral compaction during the Alleghanian orogeny in the Finger Lakes District; however, layer-parallel strain in the Lake Erie District was minimal (Engelder 1979). We believe that while the orientation of NW hydraulic fractures in black shale of the Lake Erie District was probably controlled by an Alleghanian stress field, the hard overpressures required to hydraulically fracture the rocks were generated during a period of hydrocarbon maturation without the benefit of lateral compaction. For the same reason, the presence of ENE joints in both districts, unrelated to documented folding of the western New York Appalachian Plateau, reflects a well-organized stress field but one that did not generate elevated pore pressure as a consequence of significant lateral strain. However, further to the east and down-section in the Catskill Delta Complex, tectonic compaction associated with the Alleghanian orogeny may have played a very important role in boosting the pore pressure to induce hydraulic fractures throughout the non-source rock portion of the section.

Relative timing of joint propagation: cross-cutting v. abutting joint relationships

The one significant difference between ENE joints in the Lake Erie District and those of the Finger Lakes District is the nature of their relationships with cross-fold or NW joints (i.e. Alleghanian jointing). In brief, only 20% of the interactions between NW and ENE joints in the Lake Erie District are mutually cross-cutting. The situation is very different in the Finger Lakes District, where more than 90% of all joint interactions are mutually cross-cutting. The high frequency of mutually cross-cutting joints in the Finger Lakes District is a function of the greater overburden at the time of joint propagation. Isopach maps of the Appalachian Basin show that Devonian rocks of the Finger Lakes District were more deeply buried than Devonian shales of the Lake Erie District (Colton 1970), a relationship confirmed by the analyses of vitrinite reflectance of black shales of both districts described earlier. In addition, Engelder *et al.* (2001) described rare occurrences of slippage of ENE joints along cross-fold joints that they believed to be contemporaneous with the main phase of layer-parallel shortening during the Alleghanian orogeny necessitating that ENE joints were in place by this time. This scenario requires that the thermal generation of hydrocarbons in Devonian strata of the Finger Lakes District started before major Alleghanian layer-parallel shortening. Evidence from the Lake Erie District, notably the preferential development of NW joints in the black shale discussed earlier, suggests that thermal generation of hydrocarbons in this region of the Appalachian Plateau occurred during the Alleghanian orogeny. However, because of its deeper burial, we entertain the possibility that Upper Devonian black shale of the Finger Lakes District reached the hydrocarbon window prior to the onset of the Alleghanian orogeny. Below we discuss joint development in the Lake Erie District by distinguishing its burial history from that recognized in the Finger Lakes District. We conclude that despite the fact that all other evidence points to a common mechanism of origin for ENE joints throughout the Catskill Delta Complex, the actual history of joint development along our transect varied markedly because of differences in thermal and tectonic history.

Relative timing of maturation of source rocks in the Catskill Delta Complex

NNW and NW joints in the shale-dominated Lake Erie District sequence record an anticlockwise rotation of the remote Alleghanian stress field, an interpretation consistent with observations made elsewhere in the western New York Appalachian Plateau (Zhao & Jacobi 1997). NW joints are pervasive throughout much of the Hanover–Dunkirk–Gowanda sequence and underlying shales, yet there are two noteworthy observations regarding their occurrence: (1) NW joints are uncommon (locally absent) at the top of the Hanover Shale and generally infrequent throughout this unit; and (2) NW joints display a preference for the Dunkirk black shale, especially the organic-rich lower part of the unit. The latter point suggests that early hydrocarbon generation may have worked in tandem with disequilibrium compaction to elevate pore pressure to the fracture gradient inducing formation of NW-trending hydraulic fractures in the Dunkirk Shale during the Alleghanian orogeny. Plentiful solid bitumen in Dunkirk Shale samples provides evidence for the generation and expulsion of oil at some point in the thermal history of these rocks (Momper 1978; Comer & Hinch 1987).

The high height–spacing ratios of NW joints at the bottom of the Dunkirk Shale suggest that hydraulic fracturing occurred episodically (e.g. Roberts & Nunn 1995). Elevation of pore pressure to the fracture gradient resulted in hydraulic fracturing followed by rapid dissipation of fluid pressure and closure of the joint. When pore pressure again rose new joints formed well within stress-reduction shadows of early formed joints, and/or older joints were re-opened and lengthened (Roberts & Nunn 1995; Holm 1998). Buoyancy pressure created by overpressured water and newly formed hydrocarbons (e.g. Pickering & Indelicato 1985; Zieglar 1992; Roberts & Nunn 1995) kept NW joints from propagating downwards from the base of the Dunkirk Shale and may have fostered joint propagation into overlying organically lean rocks (e.g. Nunn & Meulbrock 2002). Similarly, highly pressured fluids generated in the underlying organic-rich Pipe Creek Shale may have opened NW joints deeper in the Hanover Shale.

The remote stress field had undergone a major change in orientation by the time ENE joints formed in the Lake Erie District. This is one of the clearest facts but one of the most difficult to explain. There is no independent evidence for an Alleghanian stress field defined by a maximum horizontal stress in the ENE direction. However, the chronological age of ENE joints in the Lake Erie District suggests that they may have formed during Late Permian–Early Jurassic erosion-related rebound of the Appalachian foreland basin and related relaxation of horizontal stress (Blackmer *et al.* 1994). The strongly oriented character of ENE joints may reflect the Early Cretaceous change in the remote stress system from one dominated by rift-related dynamics to one of compression caused by seafloor spreading of the North Atlantic Ocean (Miller & Duddy 1989).

We used the EASY%R_o kinetic model of vitrinite reflectance (Sweeney & Burnham 1990) to model the thermal history of the black shale in the Catskill Delta Complex (Figs 17 and 18). Thermal modelling based on the EASY%R_o algorithm requires knowledge of: (1) the age(s) of the unit(s) of interest (the base of the Dunkirk and Geneseo shales for our models); (2) at least a partial thickness of the local stratigraphic sequence; and (3) the measured vitrinite reflectance of the unit(s) of interest (vitrinite reflectance of the base of the Dunkirk Shale = 0.62% and the Geneseo Shale = 1.74%). Our model assumes a geothermal gradient of 30 °C km^{-1} and a 20 °C seabed temperature (e.g. Gerlach & Cercone 1993). For the Lake Erie District we estimate that the Hanover Shale along the Lake Erie shoreline was overlain by approximately 660 m of Devonian strata (including the Dunkirk Shale), and that the age of the Hanover–Dunkirk contact (essentially the Frasnian–Famennian boundary) is 376.5 Ma (Tucker *et al.* 1998). For the Finger Lakes District, we estimate that the Tully Limestone between Fillmore Glen and Squaw Point was overlain by approximately 2120 m of Devonian strata (including the Geneseo Shale; Lindberg 1985) and that the age of the Tully–Geneseo contact is 383.5 Ma. The Devonian–Carboniferous boundary is 362 Ma (Tucker *et al.* 1998). We further assume that all post-Devonian strata had accumulated by the end of the Carboniferous (i.e. essentially no net sediment accumulation during Permian time; Gerlach & Cercone 1993). Finally, we adopt the Appalachian Basin unroofing history detailed by Blackmer *et al.* (1994) in which post-Alleghanian uplift due to flexural rebound of the foreland basin occurred from Late Permian to Early/Middle Jurassic time followed by a period of little or no unroofing that persisted until the Late Oligocene. Rapid uplift occurred from the Miocene to the present.

For the Lake Erie District, EASY%R_o modelling indicates that by the end of the Devonian, following accumulation of 660 m of sediment over the Hanover Shale, the vitrinite reflectance of the Dunkirk shale was 0.38%, a value well shy of the top of the oil window (Fig. 17). Thermal maturation was more advanced by the end of the Devonian in the Finger Lakes Distict, where a minimum estimate for overburden (i.e. 1642 m) brings the vitrinite reflectance of the Geneseo to 0.39%; the addition of 150 m of Pocono Group deposits brings R_o to 0.43%. This leaves the Finger Lakes District thermally immature, as was the case for its counterpart to the west. A less conservative extrapolation of Devonian stratigraphic thickness from Pennsylvania using Lindberg's (1985) compilation yields a post-Geneseo Devonian thickness of 2120 m (Fig. 18). Assuming a Devonian section this thick, the estimated temperature of the Geneseo was 83.6 °C and R_o = 0.45% placing the Geneseo close to the top of the oil window. The addition of 170 m of late Acadian strata (Pocono Group) during Early Carboniferous time brings the Geneseo inside the oil

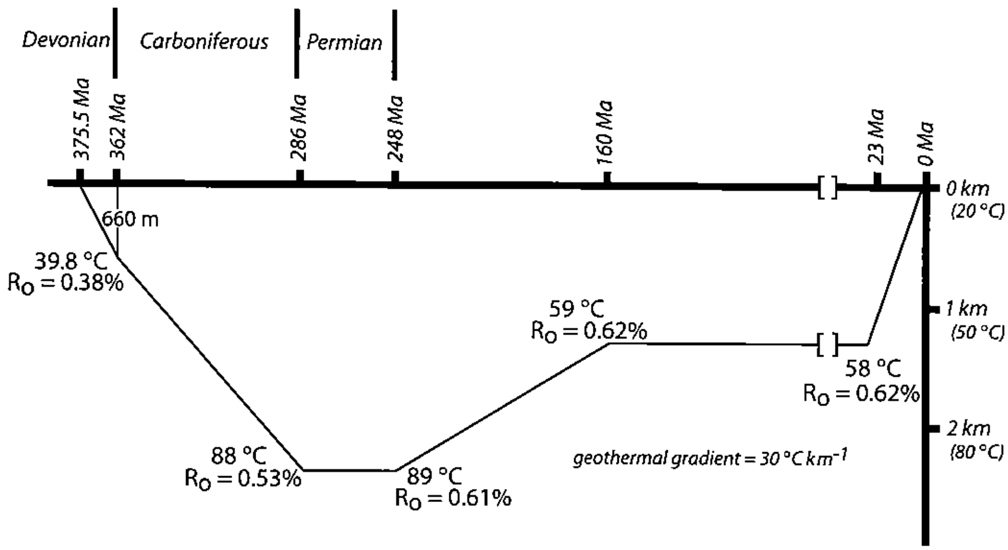

Fig. 17. EASY%R_o thermal model for the burial history of the Dunkirk Shale, Lake Erie District. Refer to text for discussion.

window with a temperature of 88.7 °C and R_o = 0.52% (Fig. 18).

By the end of the Carboniferous the depth of burial of the base of the Dunkirk Shale was a bit short of 2.3 km and the calculated vitrinite reflectance was 0.53% (burial temperature approximately 88 °C), meaning that the Dunkirk Shale had just entered the oil window (Fig. 17) (Peters 1986; Tissot *et al.* 1987; Hunt 1996). Assuming virtually no net sediment accumulation during Permian time, the vitrinite reflectance of the Dunkirk Shale at the end of the Palaeozoic would have been 0.61%, farther into the oil window (Fig. 17). Therefore, according to our model, the thermal maturity of the Dunkirk Shale at the end of the Carboniferous (362 Ma) equalled that of the Geneseo at the end of Pocono deposition (*c.* 355 Ma).

Earliest joint propagation by hydrocarbon-generated hydraulic fracturing in the deeper, more proximal portions of the Catskill Delta Complex could have taken place in an Acadian (Early Carboniferous) stress field and, indeed, the earliest joints strike ENE, an orientation consistent with Acadian tectonics to the east in the Acadian Highlands of New England (Engelder *et al.* 2001). Earliest joint propagation by hydraulic fracturing in the distal Lake Erie District was delayed until the effects of Alleghanian sedimentation had pushed the Dunkirk black shale into the oil window. We see the first stages of hydrocarbon-induced hydraulic fracturing (i.e. NW jointing) in the Lake Erie District when a second set of joints has started to propagate in the Finger Lakes District (i.e. the cross-fold joints). This second set cross-cuts the original ENE joint set because depth of burial maintained a compressive effective stress on the original ENE joint set.

Uplift of the Dunkirk Shale of, perhaps, 1 km from the end of the Permian–Early/Middle Jurassic (*c.* 160 Ma) time would have resulted in minor further maturation to a reflectance of 0.62%, the measured value. Erosion of only 750 m during this time interval would have raised the vitrinite reflectance only to 0.63%. Regardless of the amount of uplift, no further maturation of the Dunkirk Shale would have occurred after Jurassic time. While the generation of new joint sets was completed by the end of the Alleghanian orogeny in the Finger Lakes District, it continued in the Lake Erie District during the Permian–Early/Middle Jurassic.

Mechanisms for overpressure generation during the Alleghanian orogeny

Our thermal models, given their constraints, suggest that the Dunkirk Shale reached the oil window during the Permian (perhaps near the end of Carboniferous time). At the same time, hydraulic fractures were propagating through much of the Devonian section of the Finger Lakes District, especially in that part of the section below the Rhinestreet Shale. Our observations in the Lake Erie District suggest that thermal maturation of organic shale alone is not sufficient to generate pervasive overpressures throughout a section containing significant thicknesses of grey shale and siltstone. Thus, an additional mechanism must be invoked to explain the more pervasive development of cross-fold joints in the Finger Lakes

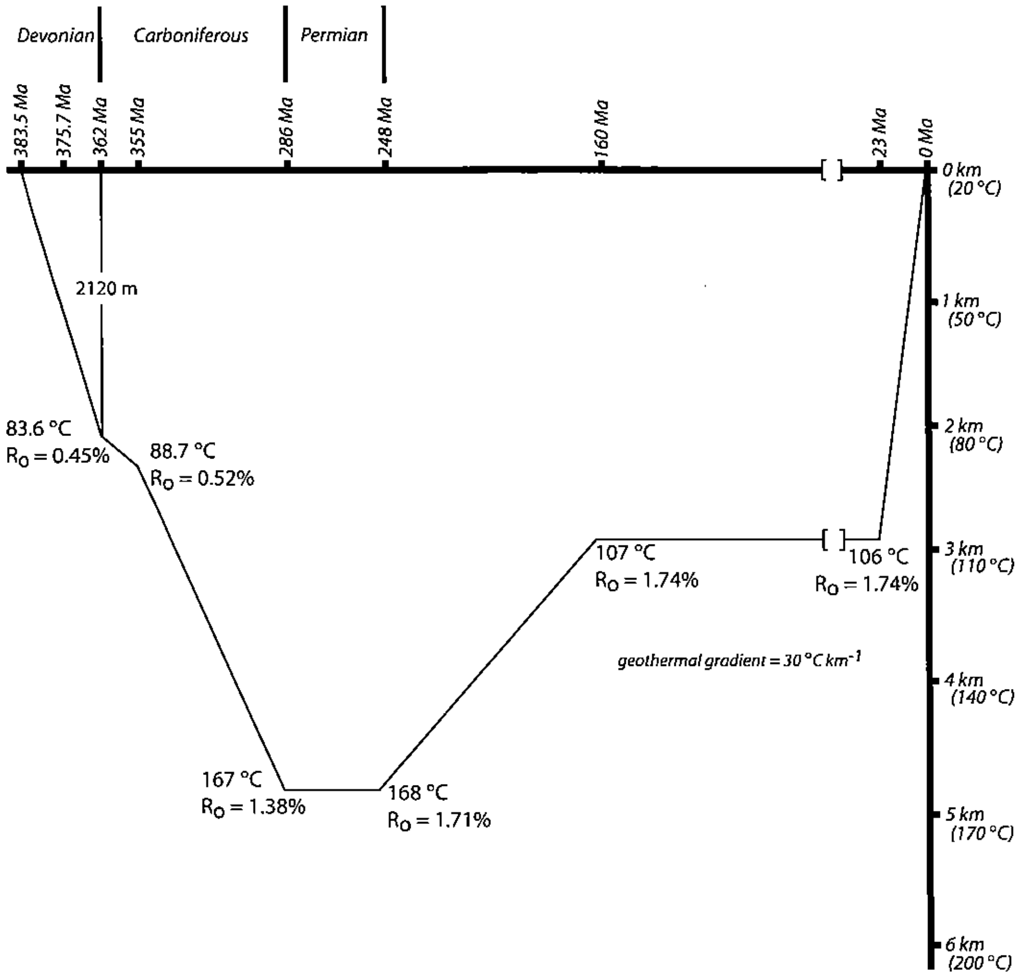

Fig. 18. EASY%R_o thermal model for the burial history of the Geneseo Shale, Finger Lakes District. Refer to text for discussion.

District. Lateral compaction of the Devonian section could have been the mechanism that pervasively overpressured the sub-Rhinestreet sequence. At the same time maturation continued in the black shales as witnessed by the density of cross-fold joints at the top of the Geneseo Shale at Fillmore Glen (note the modelled increase in the level of thermal maturation in these rocks during the Permian; Fig. 18). A hydrocarbon column produced by continued maturation of organic matter could have further elevated the level of overpressures of the upper part of a pressure compartment characterized by well-connected fractures. Indeed, modelled temperatures of the Geneseo black shale (>160°C; Fig. 18) suggest that these rocks may have been affected by the cracking of oil and bitumen to lighter hydrocarbons such as methane, a particularly efficient mode of boosting formation pressures to lithostatic levels (Barker 1990; Swarbrick & Osborne 1998).

Further maturation of the impermeable Dunkirk Shale and associated hydrocarbon generation during the Permian in the absence of increasing overburden (i.e. no change in the vertical component of stress) would have reduced local differential stress (σ_d) by increasing the least horizontal component of stress as a result of elevated pore pressure, a poroelastic response (e.g. Engelder & Leftwich 1997). Diminished σ_d coupled with a reduction in effective stress caused by the build-up of pore pressure resulted in the propagation of the NW-trending hydraulic fractures in the black shale. Our thermal model indicates that the Dunkirk Shale could have continued to mature, albeit minimally, during post-Alleghanian uplift, which may explain the high degree of development of ENE joints in the black shale. That is, at about the time the Dunkirk had reached its peak thermal maturity (and hydrocarbon generation), unroofing of the Appalachian Plateau brought the overpressured black shale closer to the surface, resulting in thermoelastic contraction. Moreover, relaxation of the regional horizontal compressive stress combined with the overpressured nature of the impermeable black shale provided the mechanism for the preferential development of effective tensile stress within the black shale relative to grey shale (Hanover and Gowanda shales). Propagation of ENE joints in the Lake Erie District, thus, may reflect development of effective tension primarily as a consequence of post-Alleghanian uplift rather than active hydrocarbon generation.

The strong correlation of ENE joint development and TOC links formation of these joints to organic content. The documented decrease in degree of development of ENE joints from the base of the Dunkirk Shale upwards follows dwindling TOC and may chronicle a reduction in pore pressure generated by conversion of organic matter to hydrocarbons. Hydrocarbon buoyancy prevented ENE joints at the base of the Dunkirk Shale from propagating downwards into the lean Hanover Shale. Thus, overpressured fluids were transmitted vertically towards the normally pressured part of the sediment pile, the post-Gowanda Shale strata, inducing modest ENE hydraulic fracturing of the lean Gowanda grey shale.

Locally, high height–spacing ratios of ENE joints within the Dunkirk Shale suggest that jointing was episodic, each episode being followed by closure of at least part of the fracture network as pore pressure leaked off. Formation pressure would again build as a consequence of continued hydrocarbon generation until another episode of hydraulic fracturing reopened and lengthened early formed joints and formed new ones. All of this forces one to question how it was that overpressures generated during formation of ENE joints did not bleed off through older NW joints. Although there are no easy answers to this question, it is conceivable that the spacing of NW joints and their lack of interconnectivity failed to provide the necessary permeability capable of keeping pace with the generation of hydrocarbons in the Dunkirk Shale during propagation of ENE joints. Moreover, mutually cross-cutting NW and ENE joints indicate that the apertures of some of the former joints had been diminished enough during formation of the latter to enable the transmission of ENE joint-tip stress across the NW joints.

Conclusion

ENE joints (and to a lesser extent NW joints of the Lake Erie District) of the Appalachian Plateau display an especially strong affinity for Devonian black shale units suggesting that their propagation was linked in some way to the generation of hydrocarbons. Crucial to understanding the complex nature of jointing in Devonian black shale deposits of the Appalachian Plateau is sorting out the timing of the ENE joints. Field evidence cited here suggests that ENE jointing of organic-rich rocks of the Lake Erie District occurred late in its deformation history, during post-Alleghanian uplift of the Appalachian Plateau. To the east, though, in the Finger Lakes District of New York State, ENE joints in older black shale deposits appear to have formed before all other joint sets, perhaps near the close of the Acadian orogeny. Our thermal modelling suggests that while the Dunkirk Shale remained thermally immature at the end of Devonian time, the deeper Geneseo Shale of the Finger Lakes District was closely approaching the oil window. Further burial of the Geneseo beneath late Acadian strata during Early Carboniferous time carried the Geneseo inside the oil window. It was at this time that ENE hydraulic fractures, consistent with the orientation of Acadian tectonics to the east, formed in black shales of the Finger Lakers District. The earliest phase of hydrocarbon-generated hydraulic fracturing in the Lake Erie District – the NW joint set – did not occur until the Dunkirk Shale was buried to the oil window during the Alleghanian orogeny. Continued thermal maturation of the Finger Lakes District section, perhaps enhanced by the thermal cracking of oil to methane, coupled with lateral compaction resulted in the pervasive development of cross-fold joints. Lateral compaction was minimal in the Lake Erie District, yet NW joints propagated upwards from the thermally mature organic-rich Dunkirk Shale. ENE joints in the Lake Erie District are interpreted to have formed when unroofing of the Appalachian Plateau brought the overpressured Dunkirk Shale closer to the surface, resulting in thermoelastic contraction and relaxation of the regional least horizontal compressive stress. The complex jointing history of the Devonian black shales of the Appalachian Plateau decribed here demonstrates the critical role that variations in the timing of thermal maturity may play in the basin-wide fracturing history of shale deposits, and reveals how the structural history of potential hydrocarbon source and reservoir rocks can very over relatively small distances. Further, it provides a coincidence of nature in which seemingly contemporaneous joints formed at different times and under very different conditions

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