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Jointing within the outer arc of a forebulge at the onset of the Alleghanian Orogeny

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Abstract

The oldest joint set in Devonian rocks of western New York state has an atypical NS strike and predates regionally more abundant NW-striking and ENE-striking joints driven by hydrocarbon-related fluid decompression. The NS joints originated in higher modulus diagenetic carbonate and were driven initially by a different mechanism, either joint-normal stretching and/or thermoelastic contraction. The origin of these joints in higher modulus carbonate concretions indicates the presence of a tensile stress produced by uniform regional extensional strain. Upper Devonian shale hosting the NS joints crops out in that area of the Appalachian Basin where a Morrowan erosional unconformity marks the region of maximum upward lithospheric flexure of an early Alleghanian forebulge. The NS strike of these early joints points to a forebulge stretching axis oriented approximately east-west and associated in time and space with crustal loading that drove both the Northfieldian Orogeny and the underplating of the Bronson Hill Anticlinorium in New England. Ultimately, subsidence of the Morrowan forebulge buried the Upper Devonian shale succession to the oil window during the latter part of the Alleghanian tectonic cycle resulting in the propagation of fluid driven NW- and ENE-trending joints in black shale.

Keywords: Joints; Alleghanian orogeny; Forebulge; Appalachian Basin; Joint-driving mechanisms

1. Introduction

Flexural bulges are generated as a consequence of lithospheric loading by glaciers and river deltas, and by the bending of lithosphere at subduction zones and the sites of continent–continent collisions (Watts, 2001). Flexure generates a component of tensile stress where stretching takes place in the outer arc of the bulge. Under some circumstances, this tensile fiber stress may become large enough to favor joint propagation. At least one example of joint propagation in response to the formation of a forebulge has been described (Billi and Salvini, 2003). In Italy, flexurally related joints propagated on the Apulian forebulge that formed in advance of the Apennine fold and thrust belt. Here, a flexure-induced tensile fiber stress in the outer-arc of a forebulge resulted in the propagation of systematic joints in higher modulus rocks, including limestone (Billi and Salvini, 2003).

This paper presents evidence for systematic joint development within the outer arc of a forebulge early in the Alleghanian deformation history of the central Appalachian orogen. These joints are characterized by an orientation and lithological affinity consistent with propagation driven by joint-normal stretching and/or thermoelastic contraction (Engelder and Fischer, 1996). Our thesis is that these mechanisms were initiated in stiff beds when they were subjected to tensile stress developed during upward flexure of the forebulge. Unlike the Apulian forebulge comprised of a thick section of carbonates, rocks of the Appalachian forebulge consisted principally of shale with relatively fewer stiff carbonate beds. Subsequent systematic joints sets hosted by rocks of this region of the

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Appalachian Basin were driven by fluid decompression when the organic-rich Devonian shale was buried to the oil window following subsidence of the forebulge.

2. Early Alleghanian tectonics

The inception of the Alleghanian orogeny in the central Appalachian Basin is nominally dated by the initial accumulation of the upper Chesterian Mauch Chunk delta deposits shed from an eastern source area (Hatcher et al., 1989; Faill, 1997). These deposits cover the Meramecian-Chesterian Greenbrier and Loyalhanna limestones. The end of the Mississippian witnessed a change in sedimentary facies from the low-energy Mauch Chunk facies to westward spreading high-energy fluvial conglomeratic deposits of the Pottsville Formation (Meckel, 1967; Colton, 1970). This transition has been attributed to renewed exhumation caused by crustal thickening during oblique convergence of the African portion of Gondwana against Laurentia from the ENE (modern coordinates) in New England and the Canadian Martimes Appalachians, perhaps with microcontinents such as the Goochland terrane sheared between them (Faill, 1997; Hatcher, 2002). The far-field stress regime induced by oblique convergence early in the Alleghanian orogeny (Atokan and younger) is manifested by (1) sequential dextral-slip deformation along much of the central and southern Appalachian internides and (2) development of ENE-trending (modern coordinates) face cleat in coal in the central and southern Appalachians and ENE-trending joints in Frasnian black shales of the Appalachian Plateau of New York state (Gates and Glover, 1989; Hatcher, 2002; Engelder and Whitaker, 2006).

The onset of Alleghanian tectonics in the northern central Appalachian chain is also manifested by a Morrowan erosional unconformity (Ettensohn and Chesnut, 1989; Faill, 1997). Loading of the Laurentian plate edge induced by oblique approach of Gondwana resulted in flexural exhumation of the Appalachian foreland basin causing the loss of much or all of the Mississippian (perhaps some of the Devonian) section in the western New York state and Pennsylvania region of the basin (Edmunds et al., 1979; Berg et al., 1983; Lindberg, 1985; Beaumont et al., 1987; Faill, 1997). The identification of unconformities caused by forebulge erosion can be equivocal (DeCelles and Giles, 1996). Still, the local nature of the unconformity at the top of the Devonian sequence in the basin (Edmunds et al., 1979; Berg et al., 1983; Lindberg, 1985) likely records the existence of the early Alleghanian forebulge much in the same way that the earlier Taghanic unconformity reflects formation of the Middle Devonian Acadian forebulge in the Appalachian Basin (Hamilton-Smith, 1993). Moreover, the progressive onlap of foreland basin deposits of the Pennsylvanian Pottsville Formation onto the eroded surface (Edmunds et al., 1979; Faill, 1997) offers further evidence for the early Alleghanian forebulge (e.g., Crampton and Allen, 1995).

Following the initial Alleghanian docking event outlined above, Gondwana pivoted clockwise around the New York Promontory resulting in the gradual knitting of Gondwana and Laurentia (Hatcher, 2002). Transpression related to progressive suturing ultimately drove the Blue Ridge-Piedmont megathrust from the SE (modern coordinates) into the foreland of the southern Appalachians (McBride et al., 2005).

This paper links a change in joint-driving mechanism observed in Upper Devonian shales of western New York state to the transition between early Alleghanian forebulge and later classic Alleghanian deformation. In so doing, this scenario offers an internally consistent explanation of an early north-south-trending systematic joint set present in the Upper Devonian shale succession that seems kinematically incompatible with the structural grain that would evolve during much of Alleghanian deformation (e.g., Hatcher, 2002; Engelder and Whitaker, 2006).

3. General stratigraphy and burial history

The Upper Devonian succession exposed along, and adjacent to, the Lake Erie shoreline in western New York state (Lake Erie District; Fig. 1) grades upward from marine shale and scattered siltstone beds into shallow marine or brackish water deposits (Baird and Lash, 1990) thus recording progradation of the Catskill Delta across the Acadian foreland basin (Faill, 1985; Ettensohn, 1992). The shale-dominated marine interval includes four intensely jointed, laminated black shale units; the Middlesex, Rhinestreet, Pipe Creek, and Dunkirk shales, in ascending order (Fig. 1). Each organic-rich unit passes upward through a transition zone of alternating black and gray shale into poorly bedded gray shale with occasional siltstone and thin black shale beds. Measured vitrinite reflectance (%R_o) values of the carbonaceous shale deposits (0.55–0.76%) indicate that they entered the oil window during their burial history (Fig. 2; Lash et al., 2004; Lash and Engelder, 2005).

The EASY%R_o kinetic model of vitrinite reflectance (Sweeney and Burnham, 1990) was used to model the burial/thermal history of the Rhinestreet black shale. This algorithm requires knowledge of (1) the age of the unit of interest (the base of the Rhinestreet shale), (2) at least a partial thickness of the local stratigraphic section (Fig. 2), and (3) the measured vitrinite reflectance of the unit of interest (average %R_o at the base of the Rhinestreet shale = 0.74%). We estimate that the contact of the Rhinestreet shale and underlying Cashaqua shale in the western New York state area of the Appalachian Basin was overlain by as much as 1155 m of Devonian strata (Lindberg, 1985) and that the age of the base of the Rhinestreet shale can be dated by the Belpre ash bed at ∼381 Ma (Fig. 2; Kaufmann, 2006). Our model also assumes a geothermal gradient of 30 °C/km and a 20 °C seabed temperature (e.g., Gerlach and Cercone, 1993). The Devonian sequence is locally overlain by the Kinderhookian-age Knapp conglomerate (Berg et al., 1983; Lindberg, 1985). The Pottsville-equivalent Olean Conglomerate accumulated unconformably on top of Upper Devonian and Kinderhookian strata eroded as a consequence of forebulge development (Edmunds et al., 1979; Berg et al., 1983; Lindberg, 1985; Dodge, 1992; Faill, 1997). The burial model for

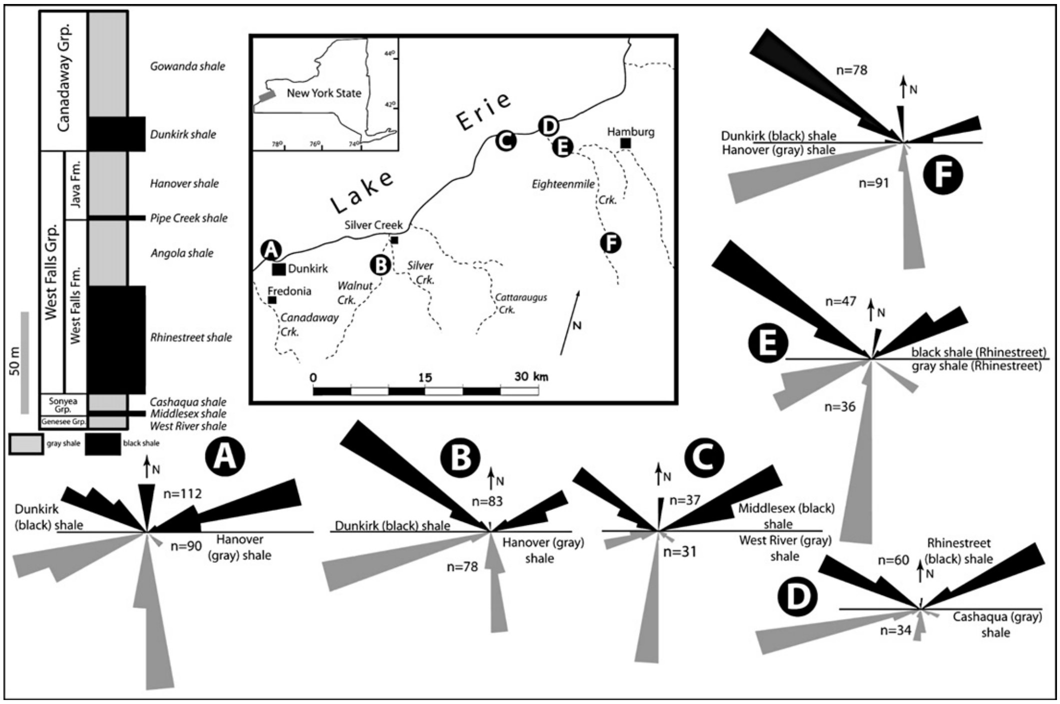

Fig. 1. Generalized stratigraphic column showing the Upper Devonian shale succession of the Lake Erie District and selected rose plots of systematic NS, NW, and ENE joints at gray shale–black shale contacts. The lettered rose plots are keyed to the location map. All rose diagrams use half of the 360° circle to illustrate strike orientations. The data are arranged stratigraphically; i.e., the upper half of each rose plot shows data from black shale and the lower half illustrates data from immediately underlying gray shale.

the Rhinestreet shale, which includes formation of the early Alleghanian forebulge (Fig. 2), requires ~1.5 km of Permian strata in this area of the basin, an amount close to that modeled by Beaumont et al. (1987). The calculated $\%R_o$ of the Rhinestreet shale immediately prior to forebulge-related exhumation is 0.42%, well shy of the oil window (Fig. 2). Moreover, the Rhinestreet and other Upper Devonian black shale units of the Lake Erie District appear not to have entered

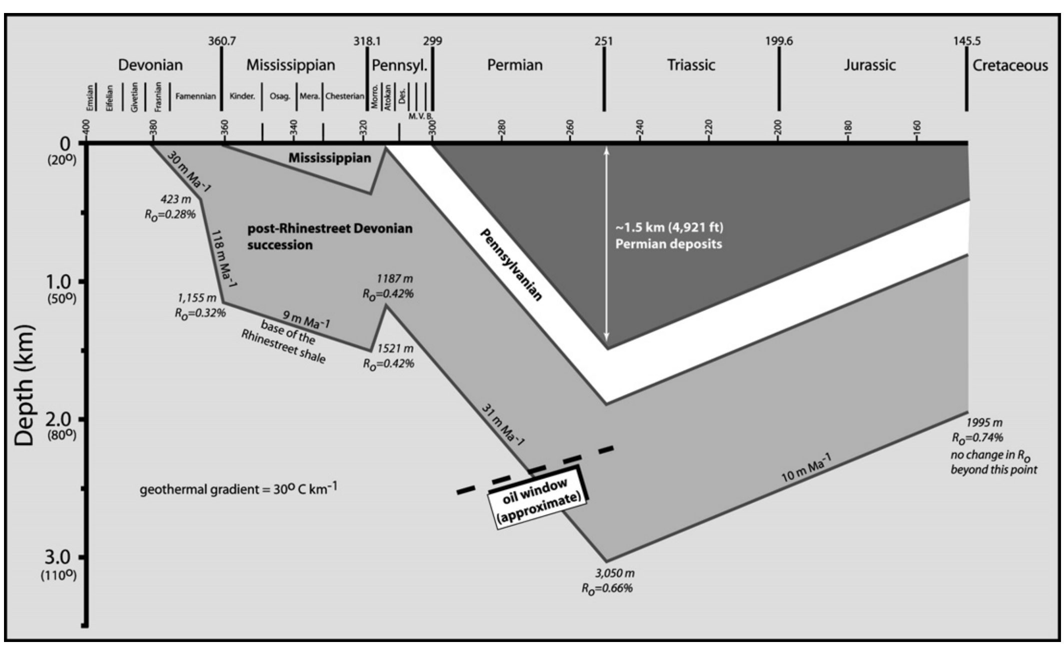

Fig. 2. Burial model of the base of the Rhinestreet shale based on a measured $\%R_o$ of 0.74%. The $\%R_o$ values shown at intervals are calculated for specific periods of time and based on incremental burial depths. Devonian and Mississippian subsidence rates are derived from stratigraphic reconstruction for western New York state and northwest Pennsylvania (Lash and Blood, 2006). The time of maximum burial is from Reed et al. (2005). The Pennsylvanian-Permian subsidence rate is predicated by the timing of peak burial. $\%R_o$ at the top of the oil window is 0.6%. Mississippian stages: Kinder., Kinderhookian. Pennsylvanian stages: Des., Desmoinesian; M., Missourian; V., Virgilian; B., Bursumian. Time scale is from Kaufmann (2006) and Gradstein et al. (2004).

the oil window until ∼270 Ma, near the end of the Alleghanian tectonic cycle, assuming that these rocks reached maximum burial depth at the end of the Permian (Fig. 2; e.g., Reed et al., 2005). Therefore, joints formed prior to this time would involve driving mechanisms not based on fluid decompression related to hydrocarbon generation.

4. Jointing in Devonian shale, Lake Erie District

Exposures of Upper Devonian shale in the Lake Erie District host as many as five systematic regional vertical joint sets (Lash et al., 2004). Joint orientation data (Fig. 1) were collected in two ways: (1) scanline surveys of a number of stratigraphic intervals in the Upper Devonian succession and (2) measurement of representative joints but beyond the limits of a scanline. The most pervasive joint sets, regionally and stratigraphically, are NW (315–345°)- and ENE (060–075°)-oriented sets. Systematic NS (352–007°)-trending joints are also common locally (Fig. 1).

4.1. Timing of jointing and stratigraphic affinity

Timing of joint propagation is indicated by joint–joint abutting relationships. In this regard, 50% of the observed contacts between NS joints and other joints are cross cutting; the balance of contacts always have NW and ENE joints abutting NS joints (Fig. 3A). Approximately 20% of observed NW and ENE joint–joint contacts are mutually cross-cutting; 75% of the ENE joints abut NW joints (Fig. 3B) and 5% of the NW joints abut ENE joints. Abutting relations among joints of the three sets indicate that the NS joints are the oldest structures and the systematic ENE-trending joints are the youngest (Lash et al., 2004; Lash, 2006). Joints of both sets, especially ENE-trending joints, show a strong affinity (i.e., greatest intensity) for black shale, particularly the basal, more organic-rich intervals of these units (Fig. 4A; Lash et al., 2004; Lash and Blood, 2006). ENE and NW joints seldom extend downward from the bases of black shale units into underlying gray shale (Fig. 5); instead, they appear to have propagated farther upward into the black shale and then into overlying gray shale (Lash et al., 2004).

Systematic NS-trending joints in the Lake Erie District, while grossly similar to younger NW and ENE joints, formed exclusively at the tops of the gray shale units and basal intervals of overlying black shale (Figs. 1 and 4B; Lash, 2006). NS joints have been observed at the bottom contacts of all Upper Devonian black shale units of the Lake Erie District and at almost all exposures of these contacts (Fig. 1). However, they are most intensely formed (i.e., smallest median spacing) at the Hanover shale-Dunkirk shale contact, the Cashaqua shale-Rhinestreet shale contact, and at contacts of gray shale intervals and overlying black shale within the Rhinestreet shale (Figs. 1 and 4B; Lash et al., 2004; Lash and Blood, 2006). Few NS joints observed in gray shale (∼20%) extend more than 20 cm into overlying black shale (Fig. 6A); roughly 50–60% of all NS joints examined in this study were arrested either below or at the base of the overlying black shale unit (Fig. 6B). Finally, NS joints are rarely found exclusively in black shale; indeed, >90% of NS joints observed in black shale units can be traced into underlying gray shale from which they appear to have propagated.

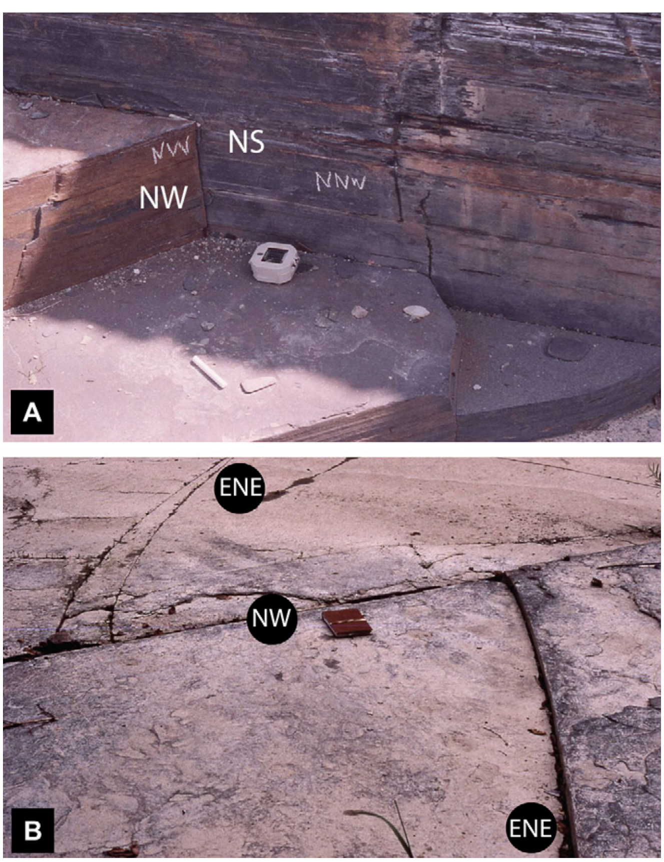

Fig. 3. Examples of abutting relations used in the field to define joint chronology: (A) NW joint (NW) abutting an older NS joint (NS); (B) ENE joint (ENE) abutting an older NW joint (NW).

4.2. Joint–concretion interactions

A more definitive judgment regarding the nature and origin of the various joint sets hosted by the shale-dominated Upper Devonian succession of the Lake Erie District can be gained by careful cataloguing of joint–concretion geometries (e.g., McConaughy and Engelder, 1999). Diagenetic carbonate concretions in Upper Devonian rocks of the Lake Erie District have two forms: (1) large ellipsoidal (aspect ratio ∼2) internally laminated concretions most common to black shale units (Lash and Blood, 2004) and (2) smaller lenticular (aspect ratio >4 to ≫10) internally massive concretionary bodies most frequently found in gray shale (Lash and Blood, 2006).

Many systematic NW and ENE joints show no deflection in propagation path as they approach concretions; instead, the joints propagated in-plane around the concretions (Fig. 7A). The occasional joint confined to a mechanical layer narrower than the width of the concretion with which it interacts defines a propagation path that deflects into an orientation

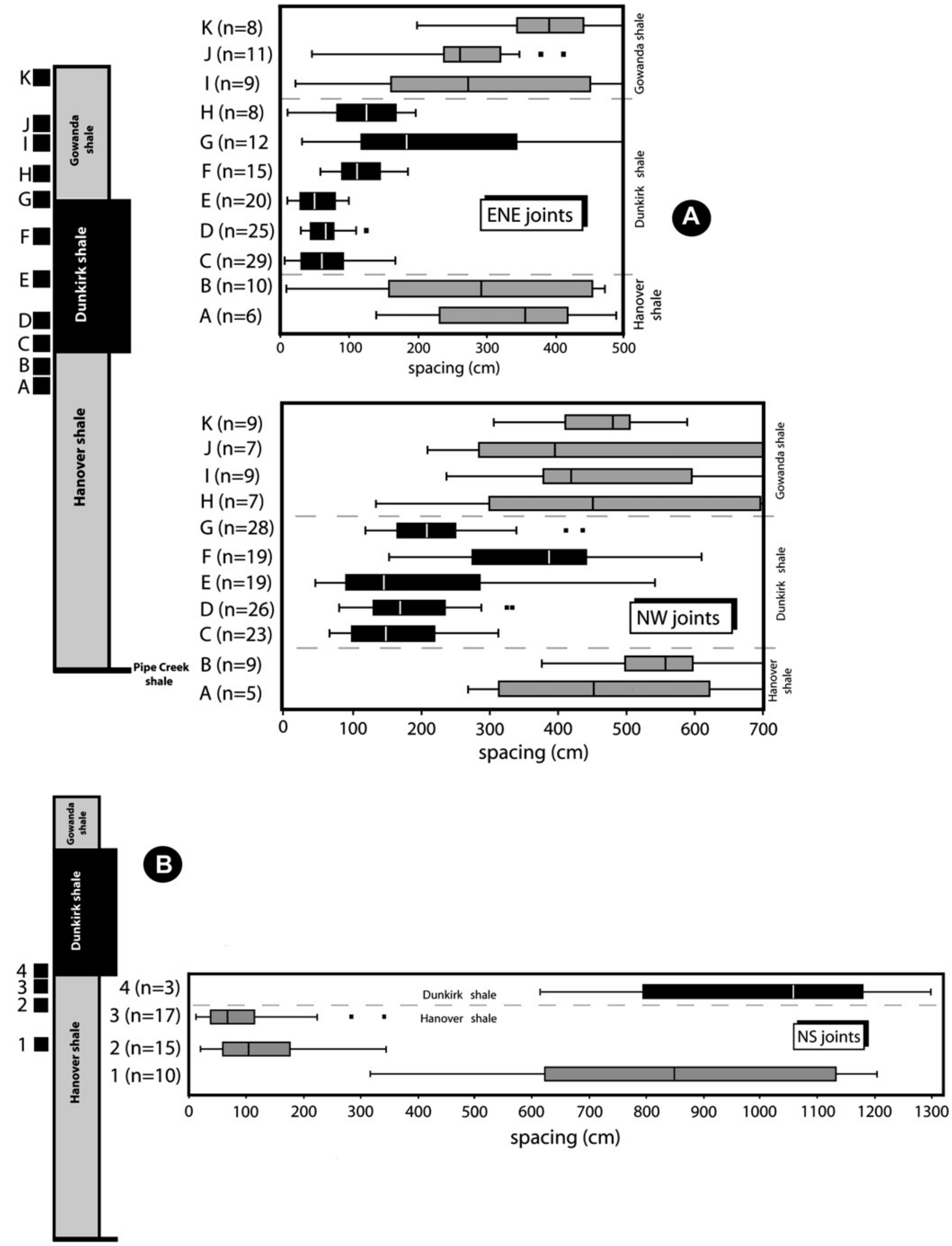

Fig. 4. Representative box-and-whisker plots showing joint density (orthogonal spacing) and the number of joints measured per station (n values) through the Hanover shale–Dunkirk black shale–Gowanda shale interval on Walnut Creek (see Fig. 1) for (A) NW and ENE joints and (B) NS joints. The box encloses the interquartile range of the data set population; bounded on the left by the 25th percentile (lower quartile) and on the right by the 75th percentile (upper quartile). The vertical line through the box is the median value and the ''whiskers'' represent the extremes of the sample range. Statistical outliers are represented by data points (filled squares) that fall outside of the extremes of the sample range.

approximately normal to the interface (e.g., McConaughy and Engelder, 1999). The majority of systematic NW and ENE joints (>90%) failed to penetrate concretions (Fig. 7B); one in ten ENE joints were observed to have propagated no more than a centimeter into concretions before arresting.

Systematic NS joints differ markedly from their younger counterparts in the nature of their interactions with embedded concretions. Anywhere from 30% to 70% of NS-trending joints, depending upon the field site, completely cleave lenticular concretions (Fig. 8A). The infrequent NS joints that propagated upward from gray shale into concretion-bearing black shale penetrate deeply (>4 cm) into the ellipsoidal concretions (Fig. 8B). Occasionally, NS joints in gray shale cut lenticular concretions of one stratigraphic interval but terminate against concretions in immediately over- and/or under-lying horizons (Fig. 8C). The few NS joints confined to mechanical layers narrower than the concretions with which they interact display propagation paths curving toward interfaces (Fig. 8D).

Fig. 5. Tall, close-spaced NW-trending joints at the contact (white dashed line) of the Dunkirk shale and underlying Hanover shale on Eighteenmile Creek (see Fig. 1 for location). White bar (at right), 1 m.

Initiation of NS joints in diagenetic carbonate is supported by the presence of NS joints confined to lenticular concretionary carbonate within gray shale units (Fig. 9). The fact that not all concretions originated NS joints may reflect variable elastic properties due to varying abundances of $CaCO_3$ (74–93%; Lash and Blood, 2004, and unpublished data). Further, NS joints appear to have failed to initiate in the more spherical concretions common to black shale. Bed-parallel stretching is far more likely to have generated a component of tension capable of initiating a joint in lenticular carbonate principally because much of the surface area of this form of concretionary carbonate would have been perpendicular to the direction of greatest normal stress (i.e., vertical stress) thereby inhibiting interfacial slip and associated release of tensile stress. On the other hand, minimal interfacial slip along semi-spherical or ellipsoidal concretions would likely have relieved a magnitude of tensile stress during bed-parallel stretching that would have inhibited the initiation of joints.

5. Joint-driving mechanisms

Joint-driving mechanisms are inferred from a combination of joint surface morphology and joint–concretion interactions (Engelder, 1987; McConaughy and Engelder, 1999). The general lack of any morphology or ornamentation on joint surfaces in the fine-grained rocks of the Lake Erie District precludes use of this criterion. Thus, interpretation of the loading configuration(s) and driving mechanism(s) of the systematic joints hosted by these rocks relies primarily on joint–concretion interactions.

5.1. Fluid decompression

The nature of joint–concretion interactions provides insight into joint driving mechanisms (McConaughy and Engelder, 1999). Joint penetration into the concretion is stopped because the stress intensity at the tip of a fluid-driven joint in a low modulus shale is blunted near the shale–concretion interface. Joints propagating under tensile stress will penetrate concretions whereas natural hydraulic fractures will not (McConaughy and Engelder, 1999). NW and ENE joints of the Lake Erie District propagated in-plane

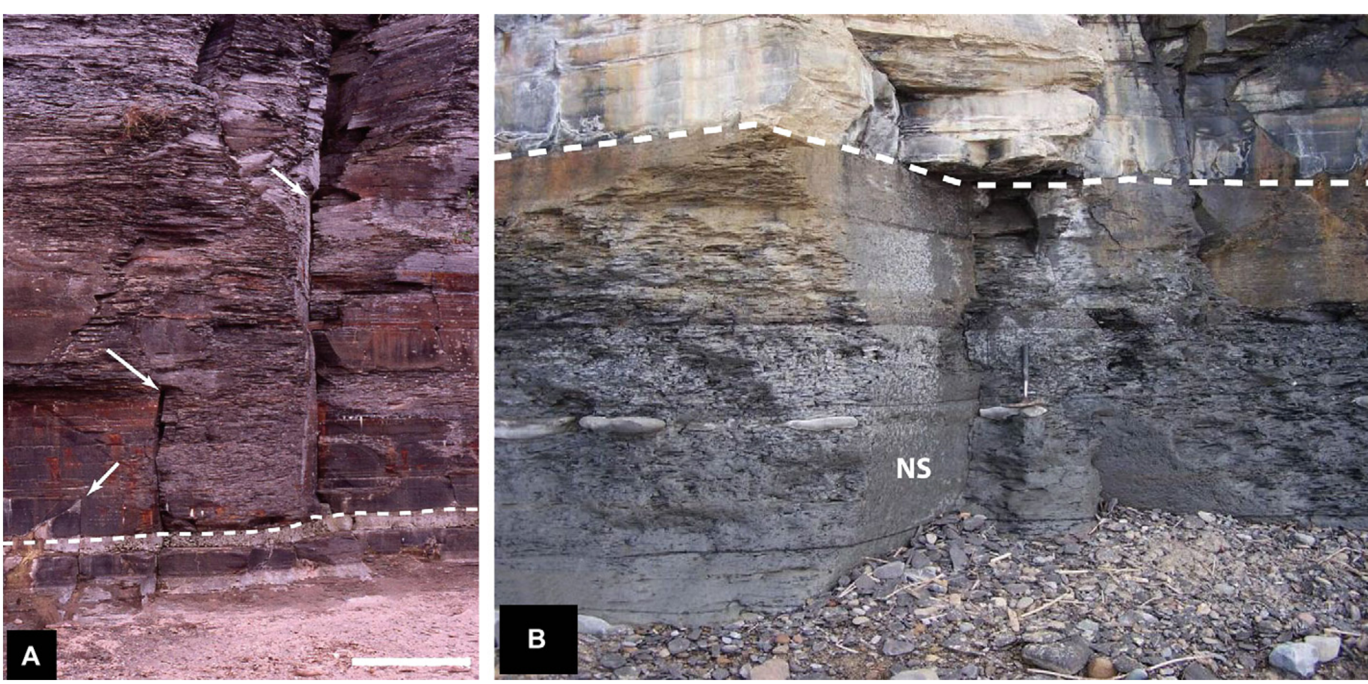

Fig. 6. NS joints terminating at gray shale–black shale contacts: (A) close-spaced NS joints at the Hanover shale–Dunkirk shale contact (dashed line). Arrows point to tips of NS joints that have propagated from the Hanover shale into the Dunkirk shale (white scale bar = 30 cm); (B) NS joint (NS) arrested at the contact of a gray shale (below white dashed line) interval and overlying black shale within the Rhinestreet shale. Note concretionary carbonate horizon in gray shale near the hammer.

Fig. 7. (A) Tall ENE joint that propagated in-plane around two large concretions in the Rhinestreet shale. Figure = 1.9 m; (B) close-up of the interface of a concretion (c) and a NW joint that propagated in-plane around a concretion. Note the lack of penetration in the circled area where the black shale has been eroded. Scale = 14 cm.

around concretions, a manifestation of natural hydraulic fracturing. This interpretation is buttressed by rare plumose structures decorating ENE and NW joint surfaces indicating growth by incremental propagation as is typical of fluid loading during natural hydraulic fracturing (Lacazette and Engelder, 1992). Incremental propagation occurs during the release of a work through fluid decompression, the joint driving mechanism under fluid loading (Engelder and Fischer, 1996). Finally, the close orthogonal spacing of NW- and ENE-trending joints relative to their height offers further evidence for their growth under conditions of fluid loading (Ladeira and Price, 1981; Fischer et al., 1995; Engelder and Fischer, 1996).

5.2. Joint-normal stretching and/or thermoelastic contraction

Systematic NS joints lack ornamentation and generally are more widely spaced than the younger NW and especially ENE joints (compare Fig. 4A and B). However, the critical difference between NW and ENE joints and the older NS joints of the Lake Erie District is that the latter penetrate deeply and/or completely cut many concretions. We contend that the NS joints originated within the concretionary carbonate, the most elastically stiff rocks at the time of jointing (i.e., Engelder and Fischer, 1996). This scenario requires a uniform level of extensional elastic strain distributed over the entire Upper Devonian shale succession of the Lake Erie District. Presuming elastic extension, the stiffer diagenetic carbonate beds and concretions would have failed in tension before the more compliant shale, which would have remained under effective compression at a given depth of burial.

Observed joint–concretion interactions indicate that bed-parallel stretching generated a component of tensile stress that initiated NS joints in lenticular carbonate layers such as found in the gray shale. Two joint-driving mechanisms are possible under conditions of bed-parallel stretching, the determining factor being the rate of loading (i.e., stretching) relative to the rate of joint propagation. When the loading rate keeps pace with the rate of propagation, the energy for joint growth derives from the release of work, in this case the joint-normal stretching driving mechanism (Engelder and Fischer, 1996). If, on the other hand, the rate of loading fails to keep up with the rate of joint propagation, the energy for joint development comes from the release of strain energy, which is the thermoelastic contraction driving mechanism, the same mechanism that accounts for columnar jointing (Engelder and Fischer, 1996). Given present field evidence, we are unable to distinguish between the joint-normal-stretching or thermoelastic-contraction driving mechanisms.

Bed-parallel stretching occurs at steady-state rates characteristic of the relative differential motion of lithospheric plates. Joint propagation that takes place at the same rate as stretching occurs in the subcritical regime at about 10^{-12} to 10^{-13} m/s, at least four orders of magnitude slower than that allowed by the longest practical-duration laboratory experiments (i.e., Swanson, 1984). Joint growth at 10^{-12} to 10^{-13} m/s is driven by joint-normal stretching (Engelder and Fischer, 1996). However, joint tips may remain stationary until a threshold in stress intensity, K_{Io}, is reached at which point a subcritical propagation rate may commence at conventional laboratory velocities of $>10^{-8}$ m/s (Atkinson and Meredith, 1987). It is true that joint-normal stretching would bring the starter flaw to failure if there is a threshold in stress intensity, yet the release of work induced by joint-normal stretching is not available for propagation velocities $>10^{-8}$ m/s because the rate of stretching fails to keep pace with joint propagation. Under this latter condition, the energy for joint propagation comes from the release of strain energy through thermoelastic contraction (Engelder and Fischer, 1996).

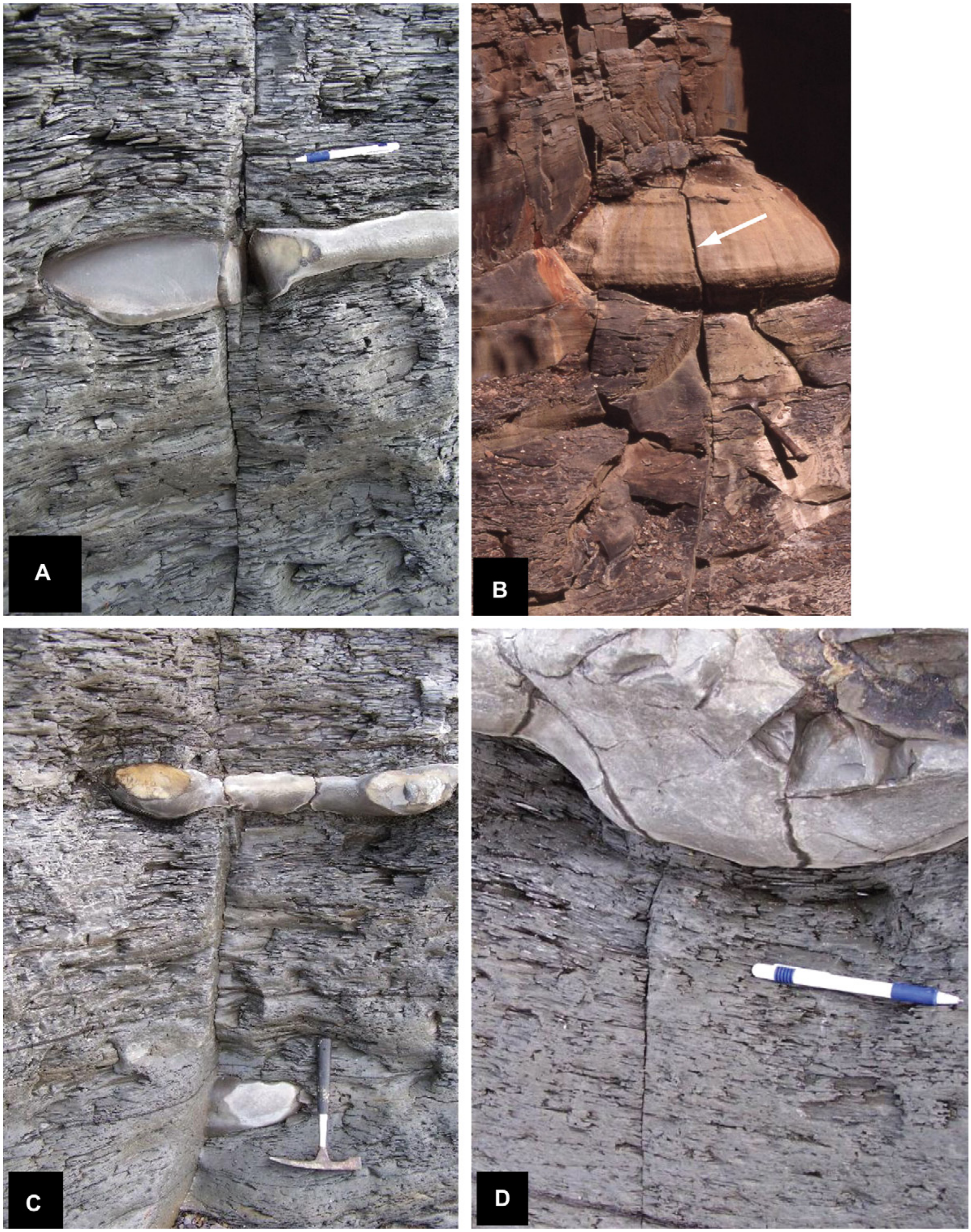

Fig. 8. (A) NS joint that cut a concretion in a gray shale interval of the Rhinestreet shale. Pen = 11 cm; (B) NS joint (indicated by arrow) that penetrated a large ellipsoidal carbonate concretion in the Rhinestreet shale. An ENE joint (ENE) propagated in-plane (parallel to the picture) around the concretion. Note hammer for scale; (C) NS joint that cut the upper concretionary carbonate body but propagated in-plane around the lower concretion; (D) the propagation path of a narrow (relative to the width of the concretion) NS joint deflecting into a path perpendicular to the concretion interface. Pen = 11 cm.

6. Jointing history and the early Alleghanian forebulge

Bed-parallel stretching accompanies development of tensile stress outside a neutral fiber during fold growth; however, visible folds are absent at the distal edge of the Appalachian Basin of western New York state. Further, the NS joint set is regional in nature, having been identified in Middle Devonian shale cores southward into West Virginia (Evans, 1994)

Fig. 9. NS joints (NS) that failed to propagate out of a thin diagenetic carbonate layer at the top of the Hanover shale. Knife = 8 cm long.

(Fig. 10). For this regional joint set to have formed in association with folding, the folds must have been both very subtle and on the scale of the entire Laurentian crust. Such is the nature of flexural bending and exhumation related to forebulge development (Watts, 2001). Our premise is that load-induced flexural bending of the Laurentian plate generated a curvature-related component of tensile stress responsible for the NS joint set, and that this set parallels a forebulge hinge in the western New York state and Pennsylvania region of the Appalachian Basin.

A forebulge was induced by crustal loading during oblique closure of the African portion of Gondwana against the Laurentian plate in Morrowan time (Beaumont et al., 1987; Root and Onasch, 1999). The location of the early Alleghanian forebulge reflects the complex interaction of a number of parameters that evolved over time, including the elastic modulus and effective elastic thickness of Laurentia and the thickness of the load near the edge of the Laurentian plate (Watts, 2001). The orientation of the NS joints suggests that the continental lithosphere flexed about a similarly oriented axis as a result of a line load directly to the east. However, the inferred NS axis of Morrowan loading does not mimic the NNE-SSW trend of the keel of clastic sedimentation in the Appalachian Basin that started with the Pottsville Formation and equivalent deposits, nor is it consistent with the hypothesized Early Pennsylvanian ''southern loads'' (Slingerland and Beaumont, 1989). The loading that caused the post-Pottsville keel is inferred to have been directed from the ESE (modern coordinates) (Beaumont at al., 1987). The position of the Morrowan load is constrained by the areal extent of the Morrowan unconformity in the central Appalachian orogen (Edmunds et al., 1979; Ettensohn and Chesnut, 1989; Faill, 1997) and the depth of the Morrowan erosion (Fig. 10).

Models for lithospheric flexure (i.e., Watts, 2001) are useful for establishing the location of the load responsible for Morrowan flexural bending of Laurentia. Starting with the assumption that the magnitude of the flexural bulge is a proxy for the depth of the erosional unconformity produced by flexural loading of Laurentia, ~330 m (Fig. 2), the maximum downward bend, y_{max}, of Laurentia depends on whether Laurentia acted as a beam of semi-infinite length by detaching from its ocean lithosphere or whether it remained attached

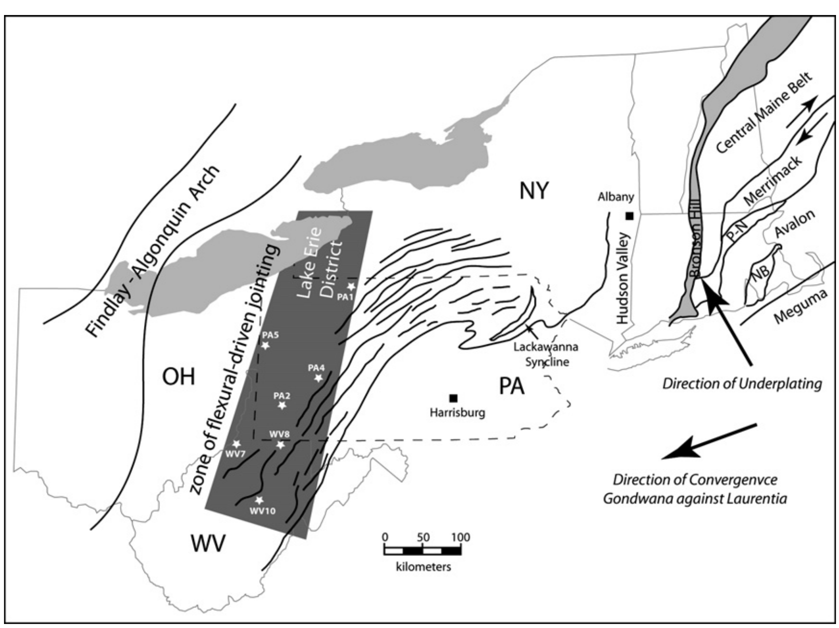

Fig. 10. Map showing the occurrence of NS joints (gray shaded area) and key Alleghanian tectonic features. White stars show locations of EGSP (Eastern Gas Shales Project) cores with NS joints in Middle Devonian rocks (Evans, 1994; Cliffs Minerals, 1982). The Bronson Hill Anticlinorium is the shaded area in New England east of the Lake Erie District. NB is the Narragansett Basin. P-N is the Putnam-Nashoba terrane. The major dextral fault shown in New England is the Norumbega Fault.

thereby behaving as a beam of infinite length (Watts, 2001). For a semi-infinite beam, $y_{\max} = 4.9$ km according to

$$y_{\max} = -\frac{y}{0.0671}; \tag{1}$$

for an infinite beam, $y_{\max} = 7.6$ km according to

$$y_{\max} = -\frac{y}{0.0432}. \tag{2}$$

We assume a detached Laurentia because the Morrowan load occurred at or near the site of a continent-continent collision. For $y_{\max} = 4.9$ km, the line load, P_b, responsible for flexural bending of the detached Laurentia lithosphere can be calculated from the following expression:

$$P_b = \frac{y_{\max}(\rho_m - \rho_{if})g}{2\lambda} \tag{3}$$

where ρ_m is the density of the substrate, ρ_{if} is the density of the basin infill, and g is gravitational acceleration (Watts, 2001). λ, the inverse of the flexural parameter, is calculated as

$$\lambda = \left[\frac{(\rho_m - \rho_{if})g}{4D}\right]^{1/4} \tag{4}$$

where D, the flexural rigidity of the lithosphere, a function of the elastic thickness of the Laurentian margin, is given by

$$D = \frac{ET_e^3}{12(1-\nu^2)} \tag{5}$$

where E is Young's modulus, T_e is the elastic thickness of Laurentia, and ν is Poisson's ratio. Estimates of the elastic thickness, T_e, of Laurentia range from 70 km (i.e., Stewart and Watts, 1997) to 105 km (i.e., Karner and Watts, 1983). Combining the results of Eqs. (3), (4), and (5) enables us to define the form of the load-induced deflection of the detached Laurentian lithosphere, y, according to

$$y = \frac{2P_b\lambda}{(\rho_m - \rho_{if})g} e^{-\lambda x}\cos\lambda x \tag{6}$$

where x is the distance west from the line load (Fig. 11A).

Assigning values to T_e and E of Laurentia of 70 km and 100 GPa, respectively, and placing the Morrowan forebulge within the Lake Erie District locates the line load just east of the Bronson Hill Anticlinorium (Fig. 11B). A T_e of 105 km moves the line load ~200 km farther east and closer to the Alleghanian suture. It is noteworthy that the position of the line load varies little in response to different values of E (Fig. 11A).

Published T_e values of Laurentian lithosphere (Karner and Watts, 1983; Stewart and Watts, 1997) place the line load of the Morrowan forebulge at least as far east as the Bronson Hill Anticlinorium, if not closer to the Laurentian–Gondwanan suture. This calculation is significant because crustal loading in the vicinity of the Bronson Hill Anticlinorium appears to have been synchronous with forebulge flexure in the Lake Erie District (Wintsch et al., 2003). Specifically,

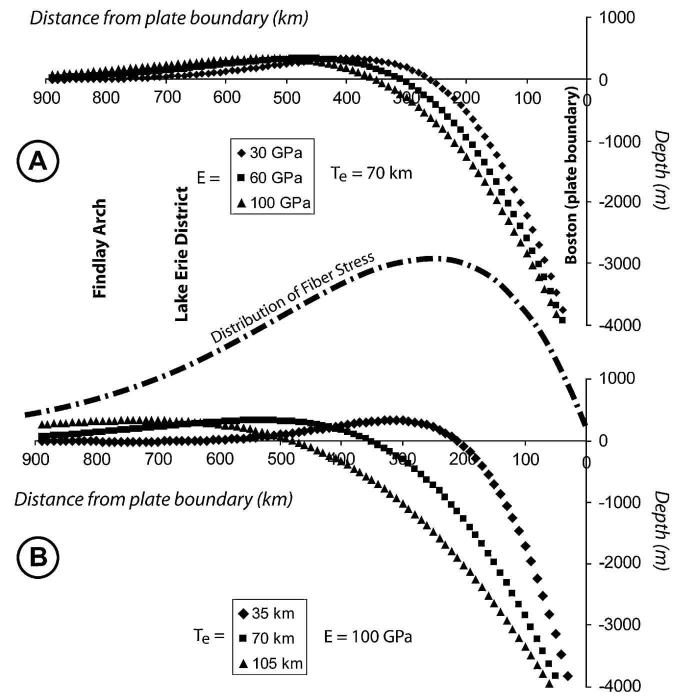

Fig. 11. Models of the Alleghanian forebulge showing (A) effect of variations in the Young's modulus (E) for an elastic thickness of 70 km and (B) effect of various elastic thicknesses (T_e) for a Young's modulus of 100 GPa. The dashed line shows the form of the distribution of a tensile fiber stress caused by plate flexure for $E = 100$ GPa and $T_e = 70$. Poisson's ratio, $\nu = 0.25$, $\rho_m = 3300$ kg/m^3, and $\rho_{if} = 2670$ kg/m^3 in these calculations. Fiber stress curve shows the relative magnitude and is not intended to show absolute stresses.

initiation of the Northfieldian Orogeny (310–285 Ma) was attended by Morrowan crustal loading east of the Bronson Hill Anticlinorium (Robinson et al., 1998). Underplating buried Bronson Hill rocks as deep as 30 km as the basal portion of a crustal duplex. Furthermore, both underplating and Morrowan forebulge development are contemporaneous with the docking of the Reguibat Promontory against the New York Promontory (Faill, 1997). Dextral faulting along the Appalachian chain and the orientation of foreland joint sets suggest that Gondwana approached Laurentia from the ENE (modern coordinates) (Engelder and Whitaker, 2006). As Reguibat sliced past New England in the Morrowan, transpressional deformation thickened the upper crust by underplating in the region of the Bronson Hill Anticlinorium (Wintsch et al., 2003), which caused a 4.9 km downwarping of Laurentia in the vicinity of the Bronson Hill Anticlinorium and a concomitant forebulge in the Late Erie District (Fig. 10).

Modeling of the Alleghanian forebulge as having formed in response to the imposition of a line load east of the Bronson Hill Anticlinorium and an overthrust fill of 4.9 km predicts that the tensile fiber stress, σ_x, calculated by the following equation

$$\sigma_x = \frac{E}{(1-\nu^2)} \frac{2P_b\lambda^3 T_e}{(\rho_m - \rho_{if})g} e^{-\lambda x}\sin\lambda x \tag{7}$$

was highest just to the west of the approximate location of the Hudson Valley, ~150 km west of Bronson Hill (Fig. 11).

However, the greater depth of burial and consequent component of overburden-induced compressive stress in this proximal area of the basin superimposed on curvature-related tensile stress to keep the rocks under effective compression (Friedman and Sanders, 1982). Flexure-related exhumation resulted in erosion of most of the Mississippian and younger section in the Lake Erie District and to the south into western Pennsylvania (Edmunds et al., 1979; Berg et al., 1983; Lindberg, 1985; Faill, 1997). Although the calculated tensile stress in this region of the Appalachian Basin was approximately two-thirds the maximum tensile fiber stress magnitude generated by the bulge (Fig. 11), exhumation of the Upper Devonian shale succession and consequent reduced overburden-induced compressive stress would have enhanced the likelihood that these rocks were subject to effective tensile stress. Flexural-related exhumation of the Upper Devonian shale succession to within ∼1.2 km of the surface (Fig. 2), then, created the effective tension necessary for joint-normal stretching-driven or thermoelastic contraction-driven jointing within high modulus lenticular carbonate concretions of the Lake Erie District. However, the fact that these joints are not pervasive throughout the entire succession suggests that, with the exception of the diagenetic carbonate, the Upper Devonian rocks remained in effective compression.

Extension of NS joints through the compliant gray shale after exiting the stiff diagenetic carbonate requires explanation. In essence, the problem reduces to finding a means of maintaining an effective tensile stress in the lower modulus shale. A likely candidate is hydrostatic to slightly elevated pore fluid pressure immediately beneath black shale units, the stratigraphic interval where NS joints are most intensely developed (Fig. 1; Lash, 2006). The Upper Devonian shale succession had not been buried much more than ∼1500 m, short of the oil window, by the time of Morrowan exhumation (Fig. 2) indicating that the pore fluid was hydrous. Pore fluid, perhaps slightly above hydrostatic, migrated into the nascent open joints upon their emergence from the interiors of the concretions thereby reducing the effective stress on the joint plane. Evidence for pore fluid-aided-propagation by either thermoelastic contraction or joint-normal stretching includes NS joints that cut concretions at one stratigraphic level (point of initiation) but failed to cleave or even penetrate over- and/or under-lying concretions. Instead, the joints propagated in-plane around inclusions (Fig. 8C). Further, the curving of some NS joint trajectories toward normal to concretion interfaces (Fig. 8D) is typical of fluid-aided joint propagation (McConaughy and Engelder, 1999).

Slightly elevated pore pressure within the gray shale immediately below black shale units may have been caused by a marked increase in sedimentation rate at the end of the Devonian, perhaps glacio-eustatic in origin (Veevers and Powell, 1987), and consequent disequilibrium compaction (Lash and Blood, 2006). Overpressure in the gray shale may have been maintained by the formation of gas capillary seals induced by biogenic methanogenesis in the organic-rich deposits overlying the gray shale (Blood and Lash, 2006; Lash, 2006). Termination of the NS joints at the base of, or a short distance within, the black shale may reflect a relatively low Young's modulus in the organic-rich deposits that suppressed the tensile stress carried by these rocks.

7. Conclusions

A fundamental switch in joint driving mechanism is recorded by the Upper Devonian shale succession of the Lake Erie District from joint-normal stretching and/or thermoelastic contraction early in the Alleghanian orogeny to fluid decompression later in the tectonic cycle. Flexural forebulge uplift and consequent tensile fiber stresses caused by the loading of Laurentia during oblique convergence with Gondwana in the northern and Canadian Maritimes Appalachians initiated NS joints in higher modulus concretionary carbonate; lower modulus organic-lean host gray shale remained in a compressive state of stress. Propagation of NS joints into the compliant host shale immediately beneath the black shale units may have been aided by an effective tensile stress induced by slightly greater than hydrostatic pore pressure in these deposits.

There is little evidence that the forebulge migrated over time. Indeed, forebulge formation in lithosphere of variable strength can be episodic, even when the load is migrating basinward (Waschbusch and Royden, 1992). The locus of NS jointing in the Appalachian Basin (Fig. 10) may have been limited to the west by diminishing tensile stress; its eastern extent likely was controlled by increasing depth of burial and concomitant overburden-related compressive stress. Subsidence of the forebulge and burial of the Upper Devonian shale succession to the oil window resulted in propagation of the NW- and ENE-trending joints. The high compressive stress that attended deep burial kept the higher modulus diagenetic carbonate in a compressive state while the heavily overpressured black shale was subjected to effective tensile stress leading to initiation of natural hydraulic fractures by the fluid decompression driving mechanism.

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