From Husch, J. M. and Hozic, M. J. (eds.), Geology of the Newark Basin, Field Guide and Proceedings of the Fifth Annual Meeting of the Geological Association of New Jersey, Geological Association of New Jersey, Rider College, Lawrenceville, p. 43-65.

STRUCTURAL EVOLUTION OF THE NEWARK BASIN

Roy W. Schlische and Paul E. Olsen
Lamont-Doherty Geological Observatory
Department of Geological Sciences
Columbia University, Palisades, New York 10964

INTRODUCTION

The Newark basin of New York, New Jersey, and Pennsylvania is an eroded half-graben bounded on its northwestern and northern margins by the SE- to S-dipping border fault system. Synrift strata within the Newark basin generally dip toward the border fault, although they are warped into gently plunging folds in the hanging walls adjacent to the border fault and the two major intrabasinal faults, the Flemington and Hopewell faults (Figure 1). Based on outcrop studies and propreitary seismic reflection profiles of the Newark basin, corroborated by published profiles of coeval synrift basins on the continental shelf (Hutchinson *et al.*, 1986), younger strata generally dip at a shallower angle than older strata, although again complicated by the effects of folding adjacent to the border fault. These observations indicate that sedimentation and hanging wall rotation as a result of slip on the border fault system occurred simultaneously.

The border fault system strikes ENE in the northern Newark basin, NE in the central and southwestern portions of the basin, and ESE in the area west of Boyertown, Pennsylvania, and into the narrow neck between the Newark and Gettysburg basins. The faults appear to progressively step back to the northwest, going from northeast to southwest, such that the border fault system has a relay geometry (Figure 1). The dip of the border fault system decreases from 60° SE in Suffern, New York, to 30° SE and less in Pennsylvania (Ratcliffe and Burton, 1985). However, the border fault again appears to steepen markedly in the area west of Boyertown. The variations in the attitude of the Mesozoic border faults closely mimic that of the Paleozoic thrust faults formed during the Taconian, Acadian, and Alleghenian orogenies. In fact, all along the border fault system, Mesozoic brittle structures, including fault breccia and gouge, overprint but parallel the phyllonitic and mylonitic rocks of the Paleozoic faults. Hence, the border faults of the Newark basin, most of which were active during sedimentation (Arguden and Rodolfo, 1986), represent reactivated Paleozoic structures (Ratcliffe, 1980; Ratcliffe *et al.*, 1986).

According to the Ratcliffe and Burton (1985) model, the direction of fault slip depends on the orientation of (reactivated) faults with respect to the early Mesozoic extension direction. Faults oriented normal to the extension direction should experience pure dip-slip. Faults whose strike is oriented clockwise from the extension direction should experience a component of left-lateral slip, whereas those oriented counter-clockwise from the extension direction should experience a component of right-lateral slip.

We estimate the extension direction to be ESE, normal to the average strike of Early Jurassic diabase dikes (see Figure 1B), which typically form perpendicular to the σ_3 direction. This extension direction produced largely dip-slip on the majority of the border faults and the two intrabasinal faults, all of which strike NE, and left-lateral strike-slip on the E-W trending border fault west of Boyertown. A large component of strike-slip is supported by the observed steepening of the dip of the fault west of Boyertown and by studies of the border fault and related structures in the Jacksonwald syncline (Lucas *et al.*, 1988).

GEOMETRY AND ORIGIN OF FOLDING

In the hanging walls of the border fault system and the Flemington and Hopewell faults, folds whose axes are normal to the associated faults are a common and obvious feature of the Newark basin. Most of the axes are oriented within 15° of perpendicular to the faults (Figure 1B). It appears unlikely that these folds formed as a

---

*Figure 1: **(A)** Geologic map of the Newark basin. Regular stipple represents diabase intrusions, irregular stipple represents lava flows. Dotted lines are form lines of bedding, and thin black lines are gray and black units in the Passaic Formation. Abbreviations are: **S**, Stockton Fm.; **L**, Lockatong Fm; **P**, Passaic Fm., **O**, Orange Mountain Basalt; **F**, Feltville Fm.; **Pr**, Preakness Basalt; **T**, Towaco Fm., **H**, Hook Mountain Basalt; **B**, Boonton Fm.; **J**, Jacksonwald Basalt; and **Pd**, Palisades diabase. **(B)** Structural map of the Newark basin and surrounding area, illustrating the close correspondence in attitude between the border faults and Paleozoic thrust faults. Thin double lines represent dikes. Abbreviations are: **r**, Ramapo fault; **h**, Hopewell fault; **f**, Flemington fault; **c**, Chalfont fault; **z**, zone of intense normal faulting (shown schematically); **cl**, Cameron's line; **w**, Watchung syncline; **j**, Jacksonwald syncline; **bd**, Birdsboro dike; **da**, anomalous NW-striking dike; and **db**, dike apparently offset by Chalfont fault. Paleozoic structures after Lyttle and Epstein (1987) and Ratcliffe (1980).*


A
B
0 5 10 15 20 km
N

result of strike-slip along these faults for the following reasons: (a) folds formed by strike-slip have their axes oriented at 45° or less with the fault (Christie-Blick and Biddle, 1985); (b) the Newark basin folds are not *en echelon;* as are folds formed by strike-slip; and (c) the Newark basin faults experienced predominantly dip-slip. The only exception to this appears to be the Jacksonwald syncline, the axis of which trends at a much lower angle to the border fault, and probably was influenced by a strike-slip faulting, consistent with the attitude of the border fault.

In addition to their transverse nature, the folds die out away from their associated faults in the hanging wall, readily observable in the three lava flows of the northern Newark basin (Figure 1A). The associated faults themselves are not folded, and the folds are not found in the footwall. It therefore appears likely that these folds are intimately associated with the faults and faulting responsible for basin subsidence (Schlische and Olsen, 1987). In the following section, we document the evidence that these folds were growing during basin subsidence and sedimentation.

Our arguments hinge on the contemporaneity of the igneous rocks within the Newark basin. Existing radiometric dates for diabase intrusions continually point to an age of 201 Ma (Sutter, 1988). Dates on the extrusive rocks show a great deal of scatter, but also cluster around 201 Ma (Olsen *et al.*, 1987). Physical relationships suggest that many of the plutons have fed the extrusives: the Palisades diabase has been shown to have fed the Ladentown flows in New York (Ratcliffe, 1988). Furthermore, the pattern and hierarchy of Milankovitch-period lacustrine cycles in the sediments between the lava flows constrain the total duration of the extrusive igneous activity to less than 600,000 years (Olsen and Fedosh, 1988). Hence, it appears likely that all of the igneous rocks in the Newark basin date to 201 Ma, and for the purposes of this discussion, are considered coeval.

In the Sassamansville area of Pennsylvania, diabase plutons are concordant and sill-like in the synclines but discordant in the anticlines, as revealed by distinctive gray to black lacustrine cycles which strike directly into the contact of the diabase (Figure 2). If folding had completely postdated intrusion, it seems likely that the concordance and discordance of the diabase would have been random with respect to the folds. Therefore, some folding probably had occurred prior to or during intrusion of the diabase.

The Late Triassic/Early Jurassic-aged Passaic Formation, a 201 Ma diabase sill, the approximately 201 Ma Jacksonwald Basalt flow, and the Early Jurassic Feltville Formation are folded by the Jacksonwald syncline (Figure 2). Two other diabase bodies are present in the syncline but are restricted to the fold axis. Their geometry suggests that they are phacoliths, having been intruded as accommodation structures in the space created by the buckling of strata. Again, these diabase bodies were intruded during or after the folding of the enclosing Passaic Formation. While the phacoliths were intruded, the coeval Jacksonwald Basalt was extruded onto a nearly flat surface, as there is no evidence of ponding in the synclinal hinge. Folding continued after extrusion, because the Jacksonwald basalt and the overlying Feltville Formation are folded. Paleomagnetic work suggests that much of the folding of the 201 Ma sill occurred after intrusion (Stuck *et al.*, 1988).

Ratcliffe (1980) suggests that the Ladentown lava flows may have been ponded in a synclinal trough developed along the Ramapo fault, but the other lava flows of the northern Newark basin show no such evidence; hence, the majority of the folding occurred after extrusion. The folds developed along the Flemington fault developed late in the history of the basin (see discussion below).

Stratigraphic evidence also indicates that sedimentation and folding within the Passaic Formation were coeval. In Douglasville, Pennsylvania, large bedding-plane outcrops appear to be warped. Certain deep-water lacustrine units appear to have been **only** deposited within the **troughs** of this warped surface. If the warping is tectonic, then it may be evidence of folding during sedimentation. Further work will concentrate on the thickness variation of fixed period Milankovitch lacustrine cycles across the folds. If the folds were forming during sedimentation, we

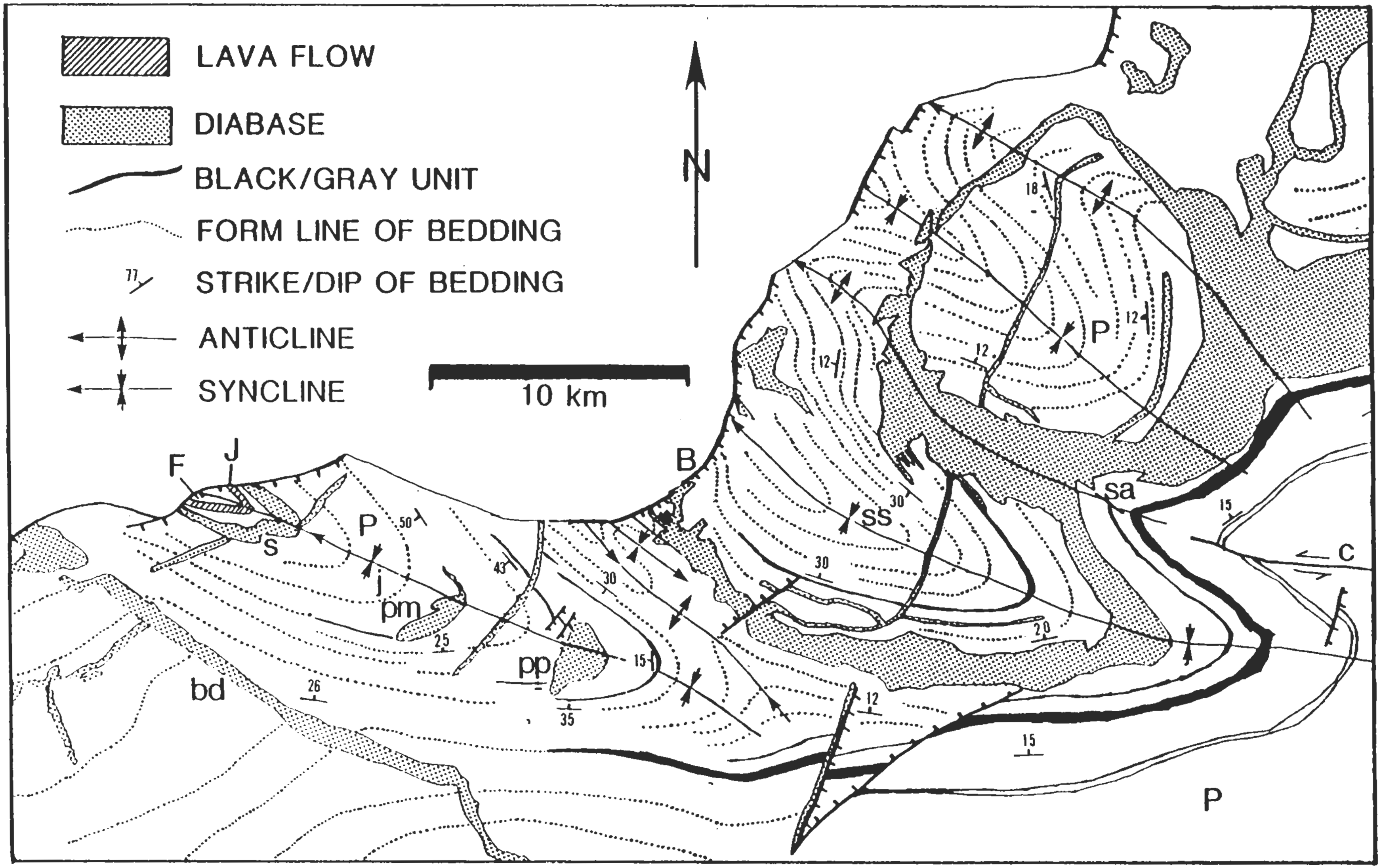

*Figure 2: Geologic map of the southwestern corner of the Newark basin in Pennsylvania. Abbreviations are : **B**, Boyertown, Pa.; **P**, Passaic Formation; **J**, Jacksonwald Basalt; **F**, Feltville Formation; **bd**, Birdsboro dike; **j**, Jacksonwald syncline; **s**, Jacksonwald sill; **pm**, Monocacy Station phacolith; **pp**, Pottstown phacolith; **ss**, Sassamansville syncline; **sa**, Sassamansville anticline; and **c**, Chalfont fault. Some data from Longwill and Wood (1965, Plate I).*

would expect a a greater cycle thickness in the hinges of the synclines and a lesser thickness on the hinges of the anticlines. Unfortunately, folding itself may induce structural thickening of beds in the hinge and thinning on the limbs (Ramsay and Huber, 1987). We hope to get around this problem by examining previously bedding-plane-perpendicular primary structures for evidence of systematic deformation during the buckling process.

Further evidence of the timing of the folding comes from minor structures from the Jacksonwald syncline. Mudcracks and reptile footprints within thinly bedded mudstones have been stretched parallel to the axis of the Jacksonwald syncline, or shortened perpendicular to the axis, or both. A slight crenulation is present, possibly indicative of microfolding. However, there is no indication of cleavage, nor does the rock break along any preferred orientation. Although thin-section analysis had not been completed at the time of this writing, we suspect that most of the detrital grains will show little, if any, evidence of penetrative deformation and, therefore, tentatively ascribe the observed strain to deformation in incompletely lithified or partially dewatered sediments, again suggesting folding during or immediately after sedimentation. An axial planar cleavage is locally found in the mudstones of the Jacksonwald syncline. This pressure solution cleavage does not fan about the fold axis, indicating that it formed late in the history of the folding (Lucas *et al.*, 1988).

The relationships between compressional and extensional structures is crucial for any kinematic interpretation. The fold axes generally are parallel with the early Mesozoic extension direction and, therefore, are perpendicular to the majority of the NE-striking Early Jurassic-aged diabase dikes. A regionally persistent set of joints parallel these dikes and presumably formed normal to the regional extension direction (Figure 3). Although ubiquitously present in a traverse across the basin, this NE-striking joint set was pervasively developed in hornfels surrounding the diabase intrusions, especially the phacoliths of the Jacksonwald syncline. We attribute the formation of these joints to hydrofracting associated with elevated fluid pressures at the time of intrusion. The density of the jointing diminishes

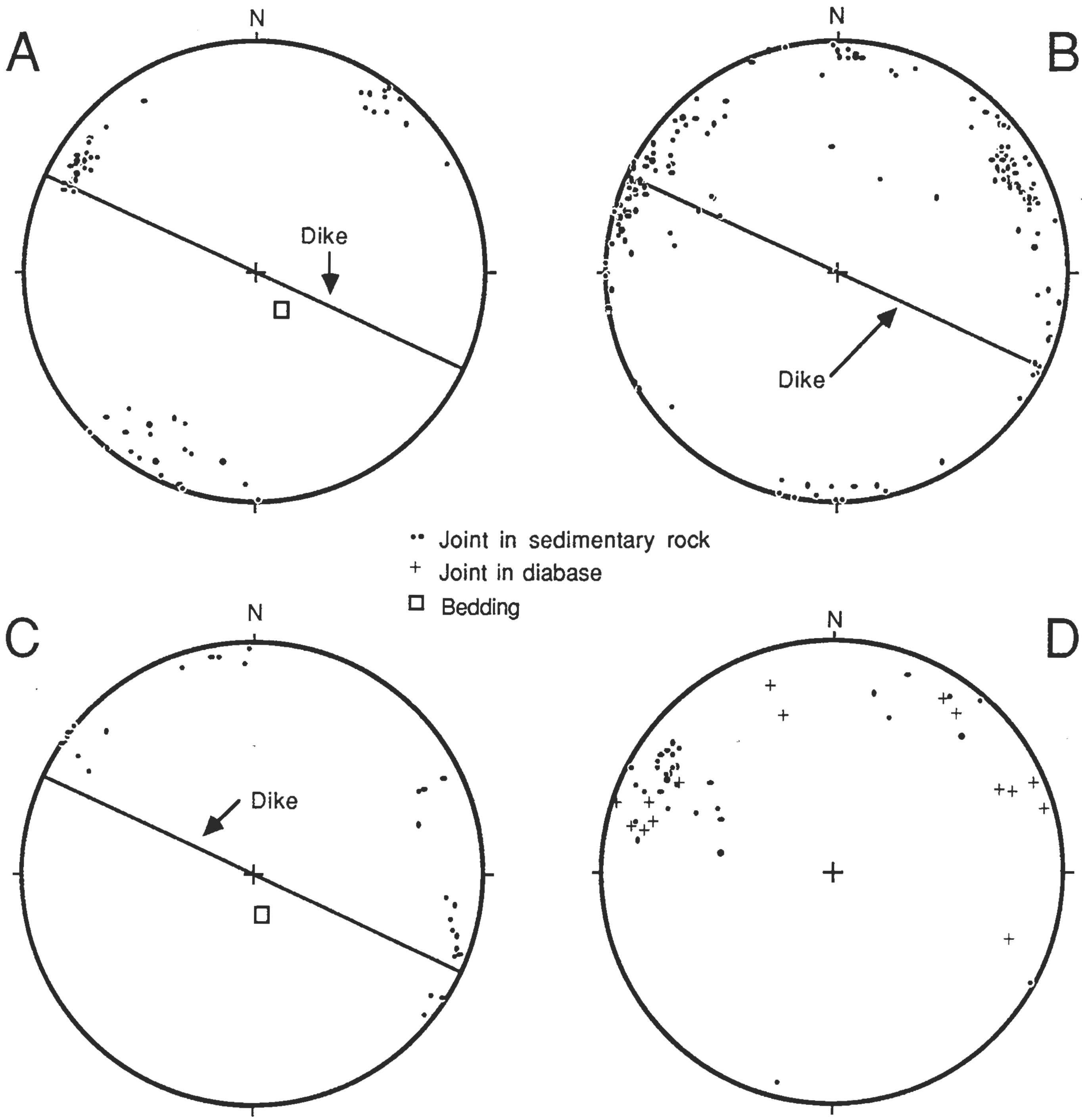

Figure 3: Equal area stereographic projections of poles to joints and bedding from (A) abandoned quarry in Stockton Formation, Rte. 29, near Stockton, N.J.; (B) Lockatong Formation along Rte. 29 near Byram,N.J.; (C) Lockatong Formation exposed in creek NE of Rte. 29 near Tumble Falls, N.J.; (D) contact between Passaic Formation and diabase in Pottstown Traprock Quarry, Jacksonwald syncline, Pottstown,Pa. Note that the NW-striking set of joints, which is subparallel to the anomalous dike, is best developed in A and B structurally below the inferred neutral surface and appears to die out upsection (see C). A majority of the joints in the Jacksonwald syncline strike NE, perpendicular to the regional extension direction.

markedly within the diabase itself, suggesting that the joints could not form in the still molten inner core of diabase. Since there is no fault between the diabase and hornfels, strain compatibility requires that the jointing occurred during intrusion, both as a consequence of regional extension and folding-induced hinge-parallel extension. The regional NE-striking joint set exclusive of those in the hornfels may have formed at the same time as those in the hornfels or any time thereafter as the result of the brittle release of the accumulated strains which resulted from regional extension.

At either end of the basin, the fold axes **parallel** the Birdsboro dike (**bd** in Figures 1B and 2), which separates the Newark basin from the narrow neck in Pennsylvania, and the dike-like extension of the Palisades intrusion in New York. The inferred directions of maximum shortening and maximum extension were parallel immediately adjacent to one another at the same time, an apparent contradiction.

A northwest-striking dike (**da** in Figure 1B) is located approximately 30 km southeast of the border fault in the fault block bounded by the border and Flemington faults. In this region, no folds are present, having disappeared about 10 to 15 km from the border fault. A set of NW-striking joints also is well developed in this area, in addition to the NE-striking set (Figure 3). Hence, heading southeast from the border fault, we pass from a region of fault-parallel shortening with fault-normal extension into a region of fault-parallel extension with fault-normal extension.

In order to explain the origin of the folds and the other coeval structures, we invoke a model inspired by fault-displacement geometries (Shelton, 1984; Barnett *et al.*, 1987). The net slip on a single fault has been shown to be maximized at its center and to die out in all directions. Because the Newark basin is widest and deepest at its center and dies out toward either end, we have applied this displacement geometry to the system of border faults. Neglecting the effects of the later intrabasinal faulting, such a displacement field results in a basin which can best be described as a giant synform plunging toward the border fault system (see Figure 4) . According to the folding model of

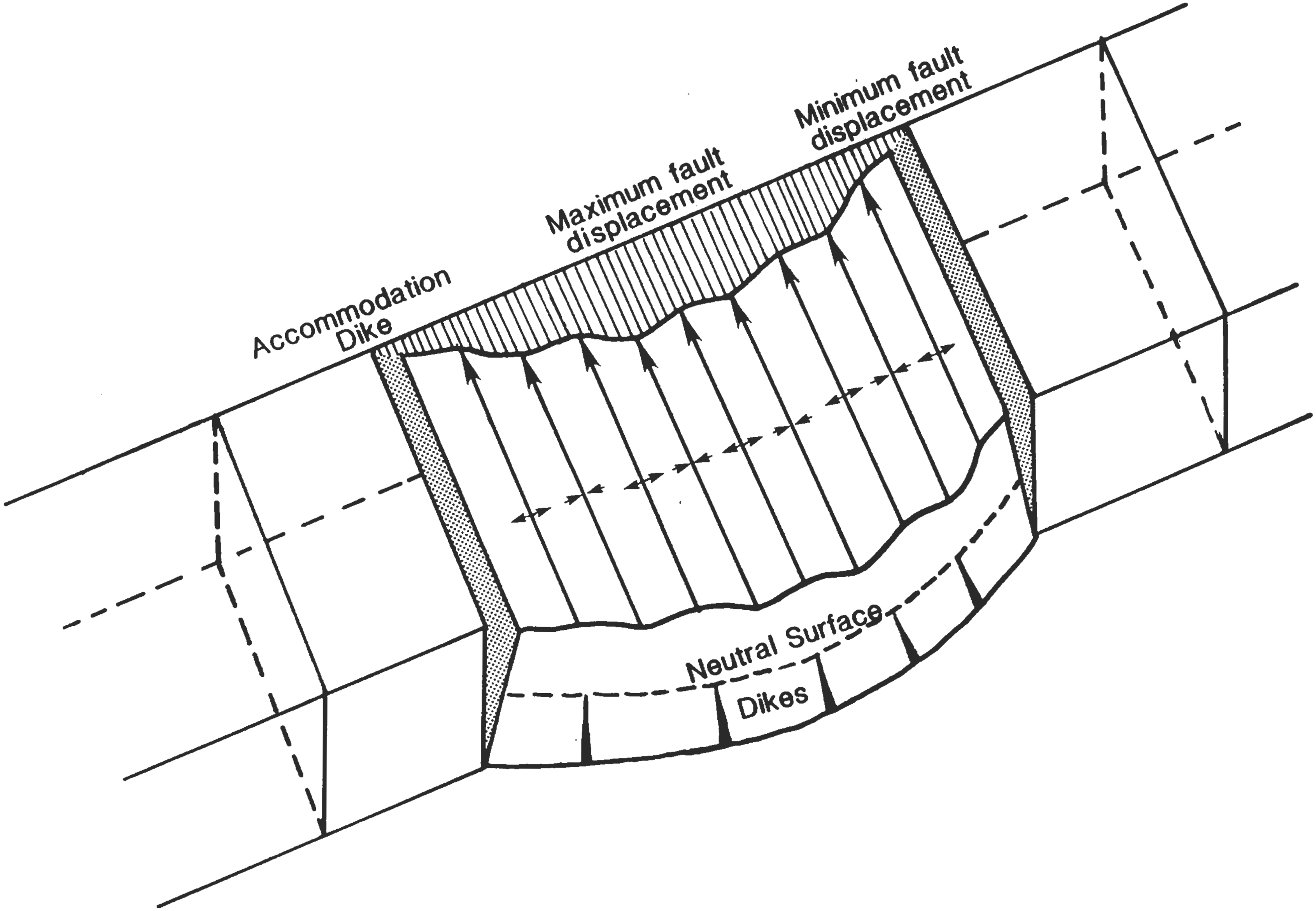

Figure 4: Highly simplified model for generating the compressional and extensional structures of the Newark basin, based on a variable displacement field for the border fault, which produces a synform-shaped basin plunging toward the border fault. In this down-plunge view, the basin fill has been omitted for clarity of presentation. The upper surface of the synform has been shortened and the lower surface extended. Accommodation structures are required on either end of the basin.

tangential longitudinal strain (Ramsay and Huber, 1987), the upper concave surface of the model's plunging synform may experience fault-parallel shortening, producing fault-perpendicular folds, whereas the lower convex surface may experience fault-parallel extension. A neutral surface of no finite strain separates these two regions. Because these structures plunge toward the border fault and the present-day erosional surface is approximately horizontal, both the local folds and extensional structures can be observed in a basin-normal transect. The folds appear to die out away from their associated faults (a) as the neutral surface is approached and (b) because subsidence and therefore shortening also die out away from the fault. The NW-striking dike and the associated joints are easily explained as structures which formed under localized extensional conditions structurally below the neutral surface. This mechanism of fold formation also introduces large gaps at either end of the basin to accommodate the subsidence and shortening within the basin. When filled with igneous material, these structures become the Birdsboro dike and the northern extension of the Palisades sill.

For this mechanism to work, it requires a degree of coupling between layers during the overall synformal downwarping of the basin. If all of the layers were allowed to undergo pure flexural-slip folding with its attendant bedding-plane slip, then the upper surface of the basin's synform never would have experienced shortening. A detachment horizon at some depth also is required. In addition, one end of the hanging wall block containing the basin needs to have been free to move to allow for the shortening of the upper surface. If both ends were pinned, then both the upper and lower surfaces of the synform would have experienced extension.

Although the evidence for some of the requirements of the model are lacking, the model does kinematically explain the origin of all compressional and extensional structures, something which previous models have failed to do. Models calling for post-rift shortening (Sanders, 1963; Swanson, 1982) or syn-rift strike-slip (Manspeizer, 1980; Burton and Ratcliffe, 1985) can be ruled out because the folds were forming during basin subsidence along faults which experienced predominantly dip-slip. Wheeler (1939) proposed that the folds formed as the hanging wall slid down a corrugated fault surface, but the geometry of the faults has not borne this out (*e.g.*, the nearly straight Ramapo fault).

INTRABASINAL FAULTING

On the basis of the style and density of intrabasinal faulting and the nature of the preserved sedimentary record, the Newark basin can be divided into three subbasins, representative cross-sections of which are shown in Figure 5. The New Jersey subbasin comprises the northeastern portion of the basin, includes the Watchung syncline, and contains the thickest preserved accumulation of Jurassic sedimentary rocks. The Delaware River subbasin consists of that portion of the basin north of the Chalfont fault and includes the Flemington and Hopewell fault blocks. The Pennsylvania subbasin forms the remainder of the Newark basin, south of the Chalfont fault and east of the narrow neck. In both the Delaware River and Pennsylvania subbasins, Jurassic sedimentary rocks are only preserved in the structural cores of synclines.

In the New Jersey subbasin, extension was taken up almost exclusively on the moderately to steeply dipping border fault system, allowing for the greatest subsidence of all three subbasins, which resulted in the thickest accumulation and eventual preservation of synrift strata. In the Delaware River subbasin, extension was taken up partly on the shallow-dipping border fault system and partly on the Flemington and Hopewell faults. In part because of the shallow dip of the border fault and in part because of the distributed extension, the Delaware River subbasin subsided less than the New Jersey subbasin and, therefore, contains a much smaller preserved section of Jurassic strata. In the Pennsylvania subbasin, extension was partly taken up on the very shallow-dipping border fault system and partly along a dense network or minor normal faults (**z** in Figure 1B). A particularly stunning example of this type of faulting is exposed in a railroad cut south of Gwynedd, Pennsylvania (Figure 6). The faults strike NE, and the stratigraphic separation generally is less than a meter or two. Nevertheless, the faults produced an

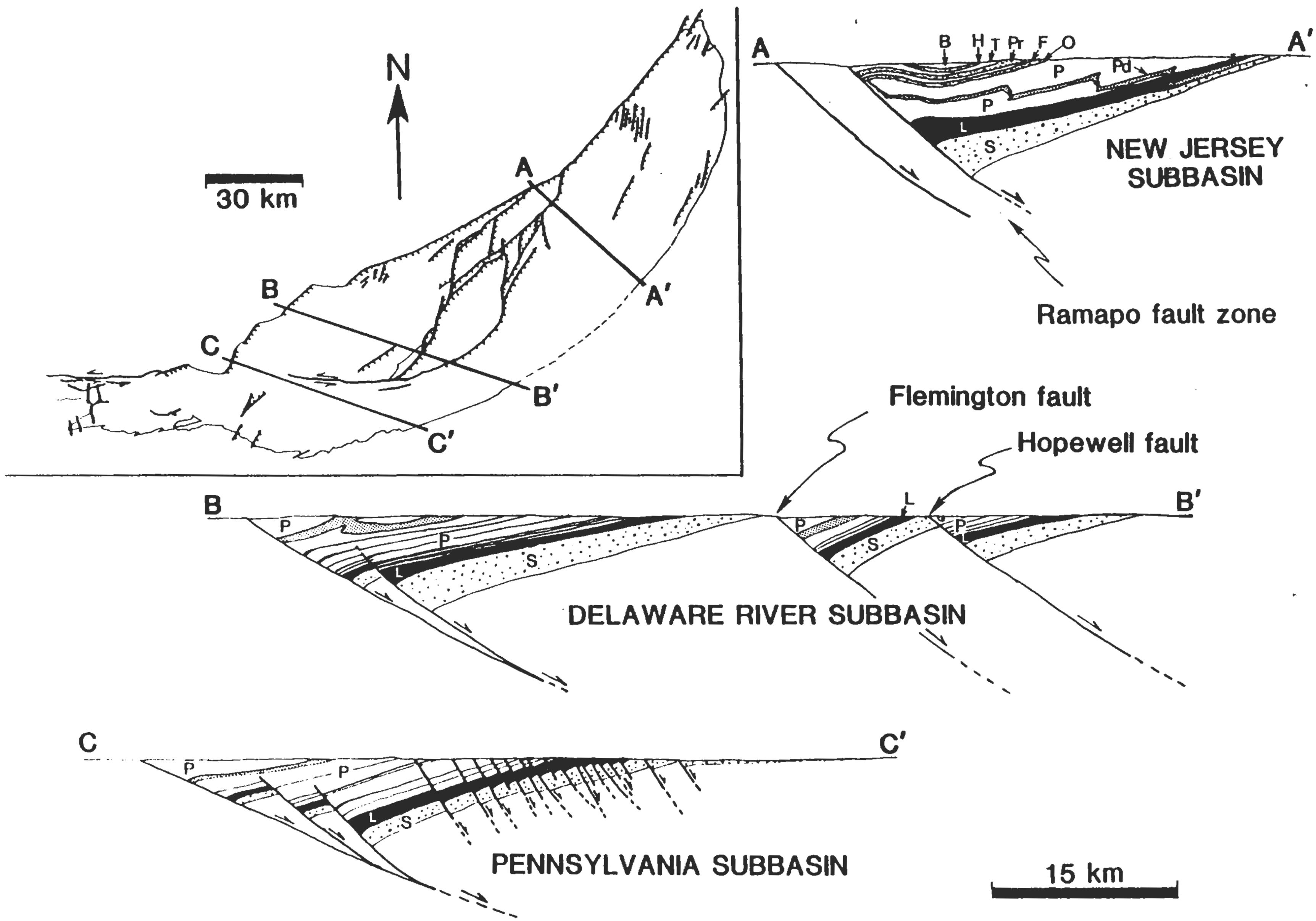

Figure 5: Representative cross-sections through the three subbasins of the Newark basin, illustrating the major structural differences. Abbreviations as in Figure 1.

apparent thickening of the section of 35%, and the amount of extension is 3.35% (Watson, 1958). Again, as a result of this distributed extension observed at Gwynedd and elsewhere in this subbasin, and in part because of the very shallow dip of the border fault in this region, the Pennsylvania subbasin subsided less than the New Jersey subbasin, and Jurassic sedimentary rocks are only preserved in the structural core of the Jacksonwald syncline.

The ESE-striking Chalfont fault has long been regarded as a down-to-the-south normal fault. The stratigraphic separation of the mapped contact between the Lockatong and Passaic formations is consistent with either down-to-the south normal faulting or left-lateral strike-slip. The offset of an Early Jurassic diabase intrusion (**db** in Figure 1B) holds promise in establishing the true nature of the type of fault slip. The intrusions on either side of the Chalfont fault belong to the same geochemical family (Smith *et al.*, 1975), suggesting that they may once have been a continuous feature. If the intrusion is a sill, then the exact nature of the slip cannot be determined. If, however, the intrusion is a dike intruded originally perpendicular to bedding, then the offset of the Lockatong-Passaic contact and of the dike require left-lateral strike-slip. Existing maps show the intrusion to be discordant with bedding over much of its length. Recent field work has established that the intrusion is steeply dipping south of the Chalfont fault and consists of a number of subparallel, perhaps *en echelon*, segments north of the fault, suggesting that the intrusion is a dike. Minor structures, consisting of steeply dipping, ESE-striking faults with subhorizontal slickenlines and a similarly oriented shear zone with a left-lateral sense of shear, observed in the town of Chalfont, Pennsylvania, immediately adjacent to the fault suggest that the Chalfont fault is a strike-slip fault.

Perhaps the most compelling reason for the strike-slip interpretation for the Chalfont fault stems from kinematic arguments. The Chalfont fault separates the Pennsylvania and Delaware River subbasins. South of the Chalfont fault, the basin fill was extended along a series of closely spaced normal faults (*e.g.*, Figure 6). Immediately north of the Chalfont fault, the

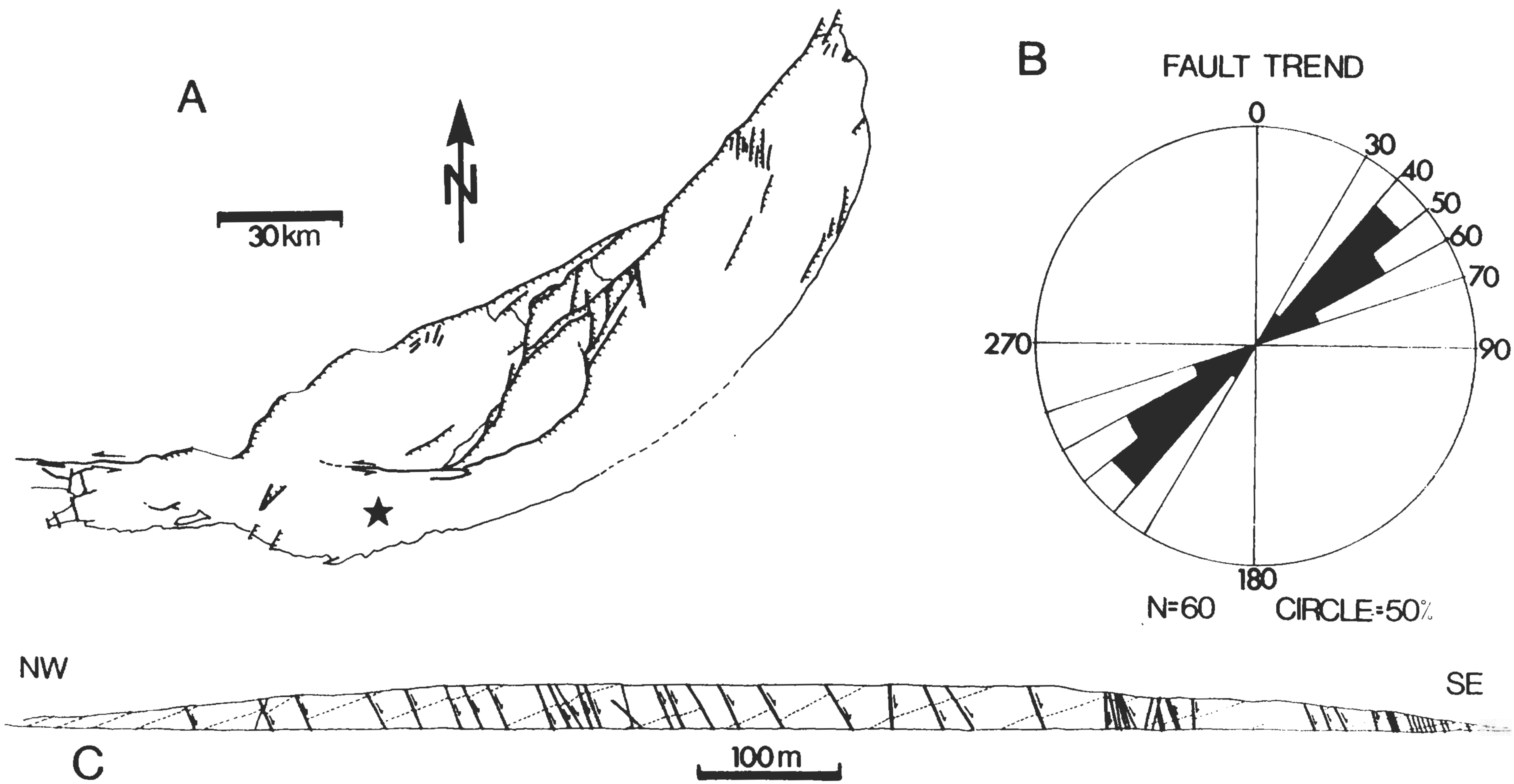

Figure 6: High-density normal faulting in Reading Railroad cut south of Gwynedd, Pennsylvania. ***(A)*** *Location of railroad cut marked by a star.* ***(B)*** *Rose diagram of fault trends.* ***(C)*** *Sketch of railroad cut. Dashed lines represent bedding. Data and sketch from Watson (1958).*

rocks are relatively unextended, although the whole subbasin was extended along the Flemington and Hopewell faults. The Chalfont fault dies out to the west because the spacing and intensity of the normal faulting similarly die out. At the fault's termination, the rocks on either side are relatively unextended. The differential extension across the Chalfont fault suggests that it is a left-lateral transfer fault, kinematically required to take up the variations in strain in an extending region (Bally, 1981; Gibbs, 1984; Lister *et al.*, 1986). In the same vein, a broad zone consisting of anastomosing and bifurcating NNE-striking normal faults accommodated the variations in strain between the New Jersey and Delaware River subbasins.

The structures and strata preserved within the fault blocks of the Delaware River subbasin allow us to constrain the timing and origin of the intrabasinal faulting. Strata within the hanging walls of the Flemington and Hopewell faults dip more steeply than those of the border fault (Figure 5), indicating that the hanging walls of the two intrabasinal faults experienced an added component of rotation over that of the border fault, suggesting that these two faults were at some point in the basin's history more active than the border fault. In addition, the Flemington and Hopewell faults dip somewhat more steeply than the border fault (Ratcliffe and Burton, 1988).

None of the formations (Stockton, Lockatong, Passaic, and Feltville) preserved within the hanging walls of the Flemington and Hopewell faults shows any evidence of syndepositional faulting (Olsen, 1980), strongly suggesting that the faulting post-dates the Early Jurassic Feltville Formation. In fact, the timing of faulting may coincide with a period of extensive hydrothermal alteration hypothesized to have reset the radiometric clocks of Newark igneous rocks to 175 Ma (Sutter, 1988). Hence, the Flemington and Hopewell faults appear to have developed late in the history of the basin, possibly to more easily accommodate the extension than was possible on the shallow-dipping, possibly shallowing, border fault (Schlische and Olsen, 1988). As extension progressed and the crust was tectonically denuded, the already shallow-dipping border fault system may have been isostatically rotated to an even shallower dip, which Sibson (1985) has shown makes slip more difficult. Extension may then have been transferred to two new, more steeply dipping faults whose hanging walls suffered an added component of rotation over that which had been imparted to the previously unfaulted hanging wall of the border fault. A displacement field and folding model similar to that postulated to have occurred along the border fault may have been responsible for the folds developed in the hanging wall of the Flemington fault.

In the New Jersey subbasin, the steeper dip of the border fault system prevented it from locking during the course of extension. Hence, the New Jersey subbasin is relatively unextended. In contrast, numerous small faults took up the extension when the border fault locked in the Pennsylvania subbasin. The differences in the style of faulting among the subbasins may reflect the initial dips and, therefore, the thicknesses of the hanging wall blocks (Figure 5). In the Pennsylvania subbasin, in which the utilized border faults were located furthest toward the hinterland and therefore had the shallowest dips, the hanging wall block was thinner, consequently weaker, and therefore prone to the high-density normal faulting. Note that the thickest hanging wall block--that of the New Jersey subbasin--is relatively unfractured. The Chalfont fault and the accommodation zone between the New Jersey and Delaware River subbasins may delineate significant subsurface changes in the dip of the border faults.

The Chalfont fault is additionally significant for it allows us to further constrain the early Mesozoic extension direction. Transfer faults are kinematically analogous to transform faults in the oceanic crust and hence are parallel to the extension direction. The Chalfont fault, therefore, gives an ESE extension direction, the same provided by the average strike of Early Jurassic-aged diabase dikes. This extension direction is more east-directed than that given by Ratcliffe and Burton (1985) and therefore fails to account for their observed right-oblique slip along the Ramapo fault, according to their fault reactivation model. These differences may be resolved if the extension direction varied after the Early Jurassic or if the Ramapo fault were reactivated in a stress field unrelated to Newark basin extension. A third possibility is that the right-oblique slip resulted from a combination of dip-slip (predicted by our extension direction) and the fold-forming shortening of the hanging wall in that region.

SUMMARY

The Newark basin is characterized by transverse folds, many of which were growing during sedimentation. These folds apparently formed as accommodation structures within the upper surface of the synformal basin induced by a variable displacement field for the border fault system. A similar mechanism could account for the folds developed in the hanging walls of the intrabasinal faults, which formed late in the history of rifting to more easily accommodate the extension than was possible on the shallow-dipping border fault. Transverse folds are also well developed in the Hartford-Deerfield, Gettysburg, Culpeper, and Dan River basins of the Newark Supergroup. If our model of fold formation is correct, then such folds should be an important component of other rift basins, where such folds have not been reported. Is this a function of the poor exposure of these basins with respect to the Newark basin? Or are these folds simply not present? If the latter is true, we must ask: What makes the basins of the Newark Supergroup so special?

ACKNOWLEDGMENTS

We thank Nick Christie-Blick for valuable discussions, Bruce Cornet and Jonathan Husch for their helpful reviews, and Michael Angel for assistance in the field. The research for this paper was supported by Nuclear Regulatory Commission Grant (NRC 111-02) to L. Seeber and P. Olsen, National Science Foundation grant (BSR 87-17707) to P. Olsen, and by the Donors of the American Chemical Society, administered by the Petroleum Research Foundation.

REFERENCES

Arguden, A.T., and Rodolfo, K.S., 1986, Sedimentary facies and tectonic implications of lower Mesozoic alluvial-fan conglomerates of the Newark basin, northeastern United States: *Sedimentary Geology*, v. 51, p. 97- 118.

Bally, A.W., 1981, Atlantic-type margins, *in* A.W. Bally, ed., Geology of passive continental margins: history, structure, and sedimentologic record (with emphasis on the Atlantic margin): *American Association of Petroleum Geologists Education Coarse Note Series 19*, p. 1-1 to 1-48.

Barnett, J.A.M., Mortimer, J., Rippon, J.H., Walsh, J.J., and Watterson, J., 1987, Displacement geometry in the volume containing a single normal fault: *American Association of Petroleum Geologists Bulletin*, v. 71, p. 925-937.

Burton, W.C., and Ratcliffe, N.M., 1985, Compressional structures associated with right-oblique normal faulting of Triassic strata of the Newark basin near Flemington, New Jersey: *Geological Society of America Abstracts with Programs*, v. 17, p. 9.

Christie-Blick, N., and K.T. Biddle, 1985, Deformation and basin formation along strike-slip faults, *in* Biddle, K.T., and Christie-Blick, N., eds., Strike-slip deformation, basin formation, and sedimentation: *Society of Economic Paleontologists and Mineralogists Special Publication 37*, p. 1-34.

Gibbs, A.D., 1984, Structural evolution of extensional basin margins: *Journal of the Geological Society of London*, v. 141, p. 609-620.

Hutchinson, D.R., Klitgord, K.D.,and Detrick, R.S., 1986, Rift basins of the Long Island Platform: Geological Society of America Bulletin, v. 97, p. 688-702.

Lister, G.S., Etheridge, M.A., and Symonds, P.A., 1986, Detachment faulting and the evolution of passive continental margins: *Geology*, v. 14, p. 246-250.

Longwill, S.M., and Wood, C.R., 1965, Ground-water resources of the Brunswick Formation in Montgomery and Berks Counties, Pennsylvania: *Pennsylvania Geological Survey Bulletin W22*, 59 p.

Lucas, M., Hull, J., and Manspeizer, W., 1988, A foreland-type fold and related structures of the Newark rift basin, *in* Manspeizer, W., ed., *Triassic-Jurassic rifting and the opening of the Atlantic Ocean*: Amsterdam, Elsevier (in press).

Lyttle, P.T., and Epstein, J.B., 1987, Geologic map of the Newark 1x2^{o} Quadrangle, New Jersey, Pennsylvania, and New York: *U.S.*

Geological Survey Miscellaneous Investigations Series, Map I-1715.

Manspeizer, W., 1980, Rift tectonics inferred from volcanic and clastic structures, *in* Manspeizer, W., ed., *Field studies of New Jersey geology and guide to field trips: 52nd Annual Meeting of the New York State Geological Association*, Rutgers University, Newark, p. 314-350.

Olsen, P.E., 1980, The Latest Triassic and Early Jurassic Formations of the Newark Basin (Eastern North America, Newark Supergroup): Stratigraphy, Structure, and Correlation: *New Jersey Academy of Science Bulletin*, v. 25, p. 25-51.

Olsen, P. E., and Fedosh, M., 1988, Duration of Early Mesozoic extrusive igneous episode in eastern North America determined by use of Milankovitch-type lake cycles: *Geological Society of America Abstracts with Programs*, v. 20, p. 59.

Olsen, P.E., Shubin, N.H., and Anders, M.H.,1987, New Early Jurassic tetrapod assemblages constrain Triassic-Jurassic event: *Science*, v. 237, p. 1025-1029.

Ramsay, J.G., and Huber, M.I., 1987, *The Techniques of Modern Structural Geology; Volume 2: Folds and Fractures*: New York, Academic Press, 700 p.

Ratcliffe, N.M., 1980, Brittle faults (Ramapo fault) and phyllonitic ductile shear zones in the basement rocks of the Ramapo seismic zones, New York and New Jersey, and their relationship to current seismicity, *in* W. Manspeizer, ed., *Field studies of New Jersey Geology and guide to field trips: 52nd Annual Meeting of the New York State Geological Association*, Rutgers University, Newark, p. 278-311.

Ratcliffe, N.M., 1988, Reinterpretation of the relationships of the western extension of the Palisades sill to the lava flows at Ladentown, New York, based on new core data, *in* Froelich, A.J., and Robinson, G.R., Jr., eds., Studies of the Early Mesozoic Basins in the Eastern United States: *U.S. Geological Survey Bulletin 1776*, in press.

Ratcliffe, N.M., and Burton, W.C., 1985, Fault reactivation models for the origin of the Newark basin and studies related to U.S. eastern seismicity: *U.S. Geological Survey Circular 946*, p. 36-45.

Ratcliffe, N.M., and Burton, W.C.,1988, Structural analysis of the Furlong fault and the relationship of mineralization to faulting and diabase intrusion, Newark basin, Pennsylvania, *in* Froelich, A.J., and Robinson, G.R., Jr., eds., Studies of the Early Mesozoic Basins in the Eastern United States: *U.S. Geological Survey Bulletin 1776*, in press.

Ratcliffe, N.M., Burton, W.C., D'Angelo, R.M., and Costain, J.K., 1986, Low-angle extensional faulting, reactivated mylonites, and seismic reflection geometry of the Newark basin margin in eastern Pennsylvania: *Geology*, v. 14, p. 766-770.

Sanders, J.E., 1963, Late Triassic tectonic history of northeastern United States: *American Journal of Science*, v. 261, p. 501-524.

Schlische, R.W., and Olsen, P.E., 1987, Comparison of growth structures in dip-slip vs. strike-slip dominated rifts: eastern North America: *Geological Society of America Abstracts with Programs*, v. 19, p. 833.

Schlische, R.W., and Olsen, P.E., 1988, A model for the structural evolution of the Newark basin: *Geological Society of America Abstracts with Programs*, v. 20, p. 68.

Shelton, J.W., 1984, Listric normal faults: an illustrated summary: *American Association of Petroleum Geologists Bulletin*, v. 68, p. 801-815.

Sibson, R.H., 1985, A note on fault reactivation: *Journal of Structural Geology*, v. 7, p. 751-754.

Smith, R.C. II, Rose, A.W., and Lanning, R.M., 1975, Geology and geochemistry of Triassic diabase in Pennsylvania: *Geological Society of America Bulletin*, v. 86, p. 943-955.

Stuck, R.J., Vanderslice, J.E., and Hozik, M.J., 1988, Paleomagnetism of igneous rocks in the Jacksonwald syncline, Pennsylvania: *Geological Society of America Abstracts with Programs*, v. 20, p. 74.

Sutter, J.F., 1988, Innovative approaches to the dating of igneous events in the Early Mesozoic basins, *in* Froelich, A.J., and Robinson, G.R., Jr., eds., Studies of the Early Mesozoic Basins in the Eastern United States: *U.S. Geological Survey Bulletin 1776*, in press.

Swanson, M.T., 1982, Preliminary model for early transform history in central Atlantic rifting: *Geology*, v. 10, p. 317-320.

Watson, E.H., 1958, Triassic faulting near Gwynedd, Pennsylvania: *Proceedings of the Pennsylvania Academy of Sciences*, v. 32, p. 122-127.

Wheeler, G., 1939, Triassic fault-line deflections and associated warping: *Journal of Geology*, v. 47, p. 337-370.