Field Guide to Berea Sandstone Outcrops in the Black River Valley at Elyria, Ohio: Slumps, Slides, Mud Diapirs, and Associated Fracturing in Mississippian Delta Deposits[1]

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ABSTRACT. **Synsedimentary slumps of Berea Sandstone and diapirs of Cleveland and Bedford Shales are seen in complex delta-front facies at Elyria, Lorain County, OH. Analysis of orientations of fractures, bedding, and crossbeds helps interpret the history of deformation. In many instances, initial conjugate shears formed with least stress parallel to paleoflow, down the paleoslope. Some conjugate joints subsequently become normal and strike-slip faults. Some blocks of Berea show tilting and/or sliding to the extent of creating recumbent overturned drag folds in subjacent shales. Deformation of slide bases varies from brittle to plastic (fluidized). These features support the view that irregular thicknesses of Berea Sandstone are the result of deformation and are not fillings of deep valleys eroded in a "Red Bedford" delta. We suggest that the Berea represents rapid progradation of sands over formerly deep-water shales following rebound at the end of foreland-basin subsidence.**

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INTRODUCTION

This trip assesses syndepositional deformation in the Berea Sandstone at 12 stops along the Black River in Elyria, OH (Figs. 1, 2).

Using informal names, the Elyria section comprises Berea Sandstone, over red "Red Bedford" Shale, over grey Bedford Shale (with siltstones), over Cleveland Shale (Fig. 3). Their ages are slightly uncertain. The Devonian/Mississippian boundary has been placed at the base of the Bedford (Pepper et al. 1954), possibly low in the Bedford (DeWitt 1970), at the top of the Berea (Eames 1974), or at the Bedford-Berea contact (Burroughs 1914, Conkin et al. 1980).

The upper part of the Cleveland Shale is a classic black shale with a very limited marine fauna of well preserved fish, some other nektic organisms, variable bioturbation, and sparse body fossils of epibenthic organisms. The sea floor at this time must have been more or less dysaerobic. The shale and siltstones of the grey Bedford represent slightly more oxic and energetic conditions, possibly more proximal and/or with a greater supply of sand and silt. Silt, bioturbation, benthic fossils, and ripples are all more common, although the sediments are still pyritic. The "Red Bedford" is completely bioturbated, poor in organics, and finer than the grey Bedford. Pepper et al. (1954) considered it to be a red mud delta, Kohout and Malcuit (1969) proposed a back-barrier wind-tide mud flat, and Lewis (1976, 1988) suggested that diagenetically reddened muds were laid down below wave base in distal but shallow open waters.

The main part of the Berea is a medium-grained sandstone with large-scale bedforms. Its base locally forms deep "channels," but otherwise the Berea is a continuous blanket. The "channels" (the irregularities that are the subject of this trip) have had several explanations (Fig. 4). Pepper et al. (1954) considered them to be deep valleys cut in a "Red Bedford Delta" and filled, from the north, during deposition of the Berea delta (they call the features channels, but they clearly imply valley-fill deposits [Fig. 4A]). Lewis (1976, 1986) interpreted the "channels" as synsedimentary slumps in a marine distributary system that was built from the east or southeast, and he suggested eolian dunes in some parts of the upper Berea. On the basis of geophysical logs and isopach maps, Burrows (1988) inferred a wave-dominated, delta-plain to prodelta system that built southeastward across Medina County, onto shelf muds (Fig. 4C). He disagreed with Pepper et al., however, by identifying the "channels" as localized slumps into the Bedford.

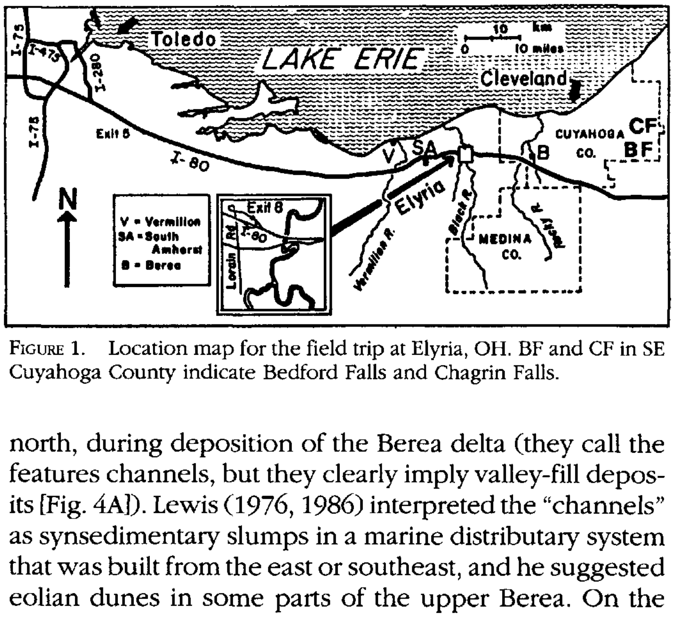

FIGURE 1. Location map for the field trip at Elyria, OH. BF and CF in SE Cuyahoga County indicate Bedford Falls and Chagrin Falls.

Thin sheets of thin-bedded and rippled sandstone lie over most exposures of the top of the main body of the Berea around the Rocky, Black, and Vermilion rivers, and under most parts of the main body west of the Black River. The top sheet seems to represent a transgressive and destructive phase, when Berea sands were spread by waves and currents after the abandonment of this part of the delta.

Analytical procedures are summarized in the notes after Table 1. Owing to the difficulty of properly depicting and emphasizing angles and details on scale drawings of outcrops that are 200-300 m long and 10 m high, the diagrams herein are non-proportional and interpretive sketches, essentially geological caricatures. To avoid directional ambiguities, this paper will list dips in the form "dip magnitude toward dip direction" (e.g., 15° to 270°).

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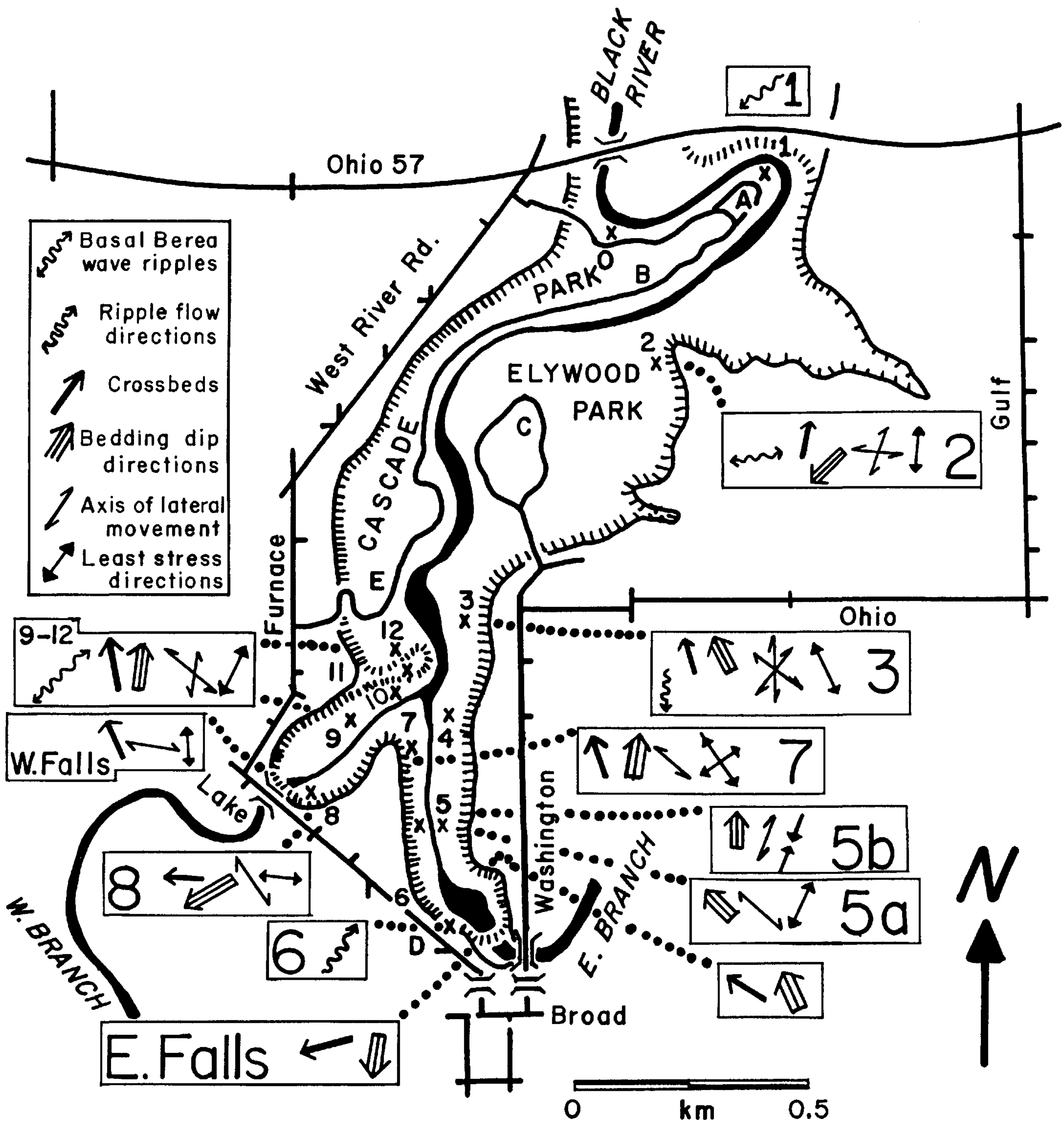

FIGURE 2. Detailed locations of the 12 stops on this trip and summary of paleocurrent directions, tilting directions, lateral movements, and directions of least stress (in boxes). Attitudes and paleocurrents have been rotated for tilting; results for low-angle surfaces depend greatly on choices of paleohorizontals. Determinations of least stress axes depend on considerable subjective interpretation (see Tables 1-4). For everywhere except Stop 5B, least and intermediate stresses are essentially horizontal, so only least stress axes are given.

Road Log

Km 0 (mi 0): Meeting point at tollbooth plaza at Exit #8 (Milepost 145.5), on I-80. Leave plaza. Keep to left (follow signs to Elyria, round 270° turn to join southbound Ohio 57).

Km 1.9 (mi 1.2): Turn left (east) onto Ohio Routes 57-113 ("Northeast Bypass") at second light south of bridge (leftmost two lanes turn left). Proceed 0.8 km (0.5 mi or two traffic lights) on Routes 57-113.

Km 2.75 (mi 1.7): Turn right (SW) onto West River Road. Almost immediately, turn left onto Floradale. Turn left again, behind florist shop, and enter Cascade Park. Follow winding road down the hill.

At km 3.3 (mi 2.05 [Point 0 on Fig. 2]): As you get to the foot of the hill, look downstream (left) on the left bank of the Black River. The thin ledge just above river level at the bend in the river is a black shaly brachiopodal limestone,

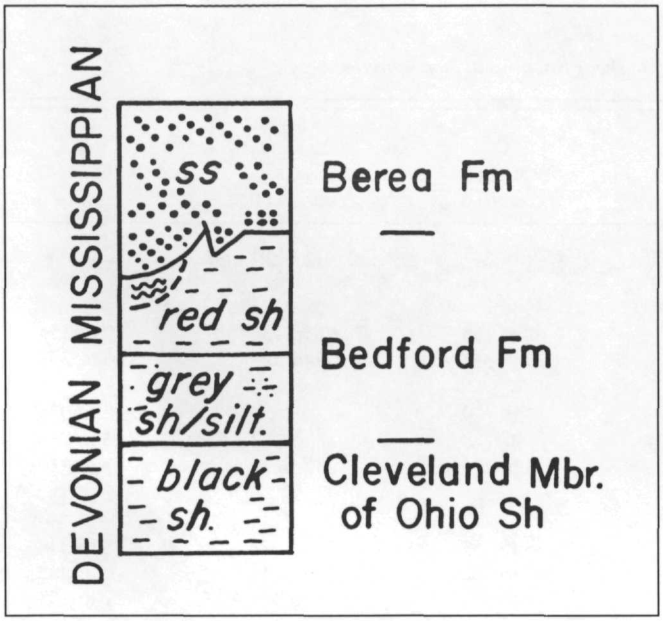

FIGURE 3. Generalized stratigraphic column for Cascade and Elywood parks (unlike the text, this diagram uses formal names, after Lewis [1988]).

near the Cleveland Shale-Bedford Shale boundary. It forms a very low broad anticline, which is typical deformation for this area, as can be seen in some places in cliffs along Lake Erie and along the Vermilion and Rocky rivers.

Follow the road (first right, then first left) to the northernmost part of the park, in the center of the meander, at km 3.6 (mi 2.25).

STOP 1. Introduction to Local Irregularities

At left (downstream). the Berea Sandstone caps the gorge. Its base and its beds dip at about 15° from the cliff top to near river level. The cliff directly across the river (under the Ohio Route 57 guardrail) shows Cleveland Shale from river level to cliff top (Fig. 5). The slopes to the right are composed mostly of "Red Bedford," with grey Bedford poorly exposed below and Cleveland Shale at low-water level farther upstream. The Cleveland Shale sits much higher at the bend than on either side and has been moved or squeezed up. Similar features at other stops, with better-exposed contacts, are interpreted as mudlumps or mud diapirs.

Return to vehicles and drive to parking lot A in Cascade Park. We will use a boat to cross the river to Stop 2, in Elywood Park.

For subsequent users of this field guide, return to Ohio Route 57, proceed right (east) to Gulf Road (first right, at first light, after 1 km [0.65 mi]). Turn right (south) on Gulf Road. Proceed 0.9 km (0.55 mi) to second light, and turn right (west) on Ohio Street, for three long blocks (1 km [0.65 mi]) to Washington Street, with a slight dog-leg to the left on Saint Clair Street. Now turn right (north) on Washington Street, and proceed 0.2 km (0.1 mi) to the entrance to Elywood Park. Park at foot of hill (point B, Fig. 2), descend to river level, and follow the trail 300 m downstream to the first sandstone cliffs.

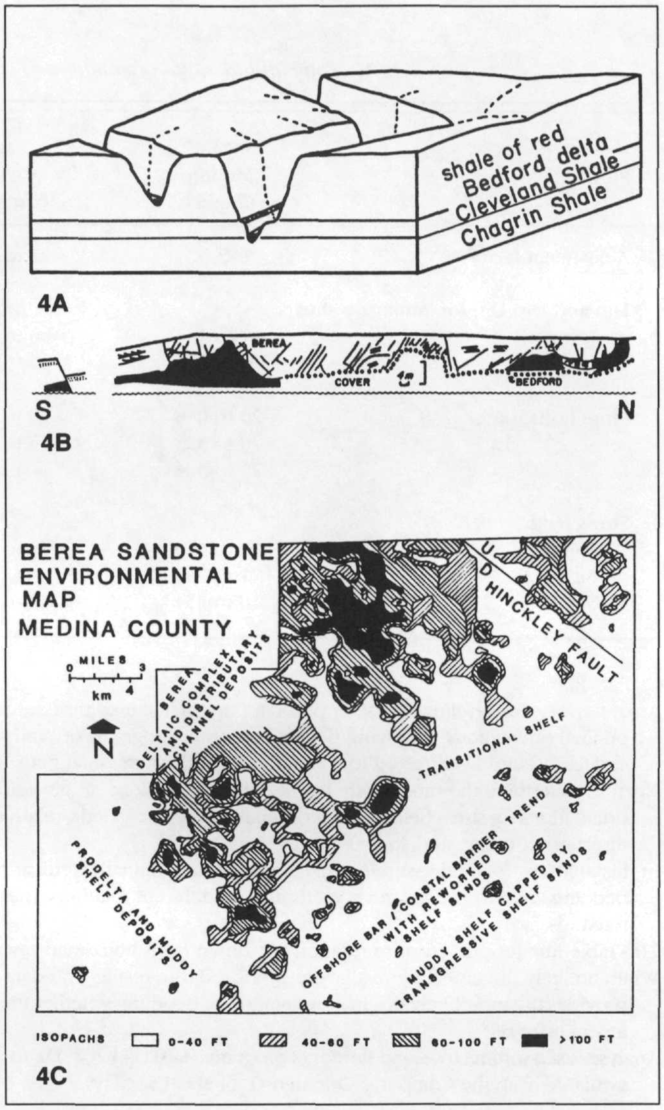

FIGURE 4. Illustrations of principal models for Berea deposition. A: Local thicknesses of Berea are viewed as post-Bedford valley-fill sandstones as epitomized at the South Amherst quarries, 14.5 km (9 mi) west of Elyria (Pepper et al. 1954). B: Sketch of the mudlump and synsedimentary faulting at the falls in Berea (the Berea type section, 26.5 km [16.5 mi] east of Elyria), based on work by Wells, but illustrating the view of Lewis (1988) that irregularities in the Berea are due to soft-sediment deformation. Shaded areas = outcrops of Bedford Shale; dots signify limits of cover. C: Berea Sandstone isopachs and paleoenvironments in the county south of Elyria (Burrows 1988). Burrows agrees with Pepper et al. (1954) about a northern source (Lewis [1976] infers an eastern source), but he interprets local thickness irregularities as slump accumulations rather than channels.

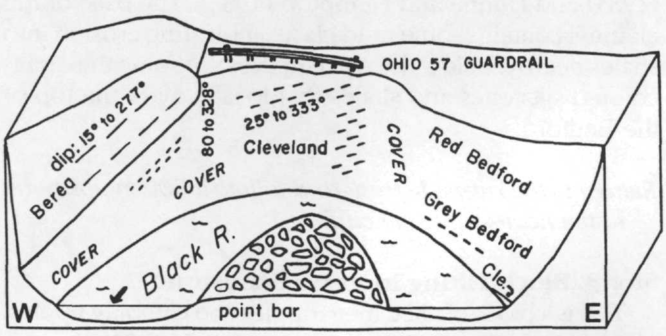

FIGURE 5. Caricature sketch of outcrop at Stop 1, view to north, showing uplifted Cleveland Shale and downdropped Berea Sandstone. Dips are given as, e.g., 80° toward 328°.

TABLE 1

Assessing attitudes and orientations of conjugate shear fractures at Stop 3, in degrees.

FEATURE	A Modern Orient'n	B Av. bed corr. to 0	C Best horiz. corr. to 0	D Poss. horiz. corr. to 0	E Sigma-1 corr. to 0
Adjustment factor	0	25 to 324	20 to 325	20 to 16	18 to 330
Dip and Dip Dir. for conjugate shears:					
A (tight)	41 to 155	66 to 152	61 to 153	57 to 165	59 to 154
B (looser)	74 to 333	49 to 335	54 to 334	60 to 327	56 to 333
Orig. horiz. beds?	20 to 016	20 to 91	17 to 79	0	15 to 075
	20 to 325	5 to 140	0	17 to 262	3 to 288
	25 to 324	0	5 to 320	20 to 275	7 to 310
Stress field					
Sigma-1	72 to 150	80 to 303	88 to 153	77 to 72	88 to 348
Sigma-2	1 to 242	4 to 61	0 to 62	14 to 244	0 to 242
Sigma-3	18 to 334	9 to 154	2 to 334	1 to 335	2 to 153

Explanation:

Analysis proceeds as follows: First, opposed groups of fractures are assumed to be conjugate shears. Second, stress axes are calculated for various possible original orientations, following pocket computer programs of Wells (1988): Col. A = present orientations; B = corrected for average of bounding surfaces; C and D corrected for possibly originally horizontal beds; and E assumes that the sigma-1 calculated in Col. A was originally vertical.

Next, to determine the most likely tilt, see if the directions all give similar results, and/or whether any corrections give reasonable or impossible orientations for stress fields and/or original beds or crossbeds, relative to other suggestions of paleoslope (axes of lateral movement, paleocurrents, direction of tilting, and so on).

In this analysis, rotation assuming that sigma-1 was originally vertical produces the best results, in terms of reducing dips of beds. Note that while bedding and crossbeds are very sensitive to different rotations, the stress field changes little because it is based on much more steeply inclined fractures.

This table implies post-fracture rotation 18° down from horizontal toward 330°, which is 3° from the axis of least stress during fracturing.

When unlikely or conflicting results are produced, the results and data are re-examined to see which correction is most reasonable, which rotation provides the most likely original orientation of bedding, whether the data could be differently grouped, and whether the shears were perhaps not a conjugate set.

Analyses used sorting, rose, and stereonet programs (LOTUS 1 2 3®, Darton Software SPLOT®, CLUSTRAN®, ROSE®, and especially P. Guth's MICRONET®, available from the Computer Oriented Geological Society).

STOP 2: The Base of the Berea

The megaripples in the main body of the Berea cut gently stepwise through a local basal facies of wave-rippled fine sandstone. They indicate paleoflow to 0°N, whereas the ripples indicate waves perpendicular to that. Small mudcracks oriented along the crests of one set of ripples suggest exposure and deposition in very shallow water. The wave-ripple facies contains a zone of considerable disruption, grading to fluidization. This may be analogous with earthquake effects described by Hempton and Dewey (1983) and Dunne and Hempton (1984). The base of the channel contains some mud clasts, indicating erosion into shales nearby. Below the wave ripples are some thin light-colored siltstones and shales that locally mark the top of the Bedford.

Return to the riverside trail, and follow it 500 m upstream to the next sandstone cliff.

STOP 3. Block Tilting in Berea Sandstone

This is a block of tilted megaripples and climbing ripples. The interpretations below use features A-H in Fig. 6.

1) Fig. 7 gives the attitudes of fractures (illustrated at point D, Fig. 6), and Table 1 shows how they can be considered to be a conjugate shear set, originally formed symetrically around a vertical σ_1 axis, but which has since been tilted about 18° to 330°.
2) Three hypotheses might account for the formation of the structurally high shale at point C in Fig. 6: first, the shale at C is a mudlump, which pushed up block B; second, the block from B to G slid, broke at C, and overrode its toe, making i an overthrust; or third, A-G was broken by conjugate shears while horizontal and was then tilted northward, but D-G slid back southward along the now-tilted conjugate shear, making it a normal fault.

The last hypothesis might seem least likely because it implies collapse against the direction of tilting, or up-slope. However, fault i has almost the average orientation of one of the conjugate shears. Moreover, the close-spaced offsets of the Bedford-Berea contact shows that back-slip along i was repeatedly offset because of blockage by shales at the foot of the slide plane (Fig. 6). Note also how multiple movement, blockage, and rebreakage has created "false-bedding" within the fault plane. This probably results from binding of the fault plane by fragmented grains, spalled overgrowths, and the like, as described by Underhill and Woodcock (1987).

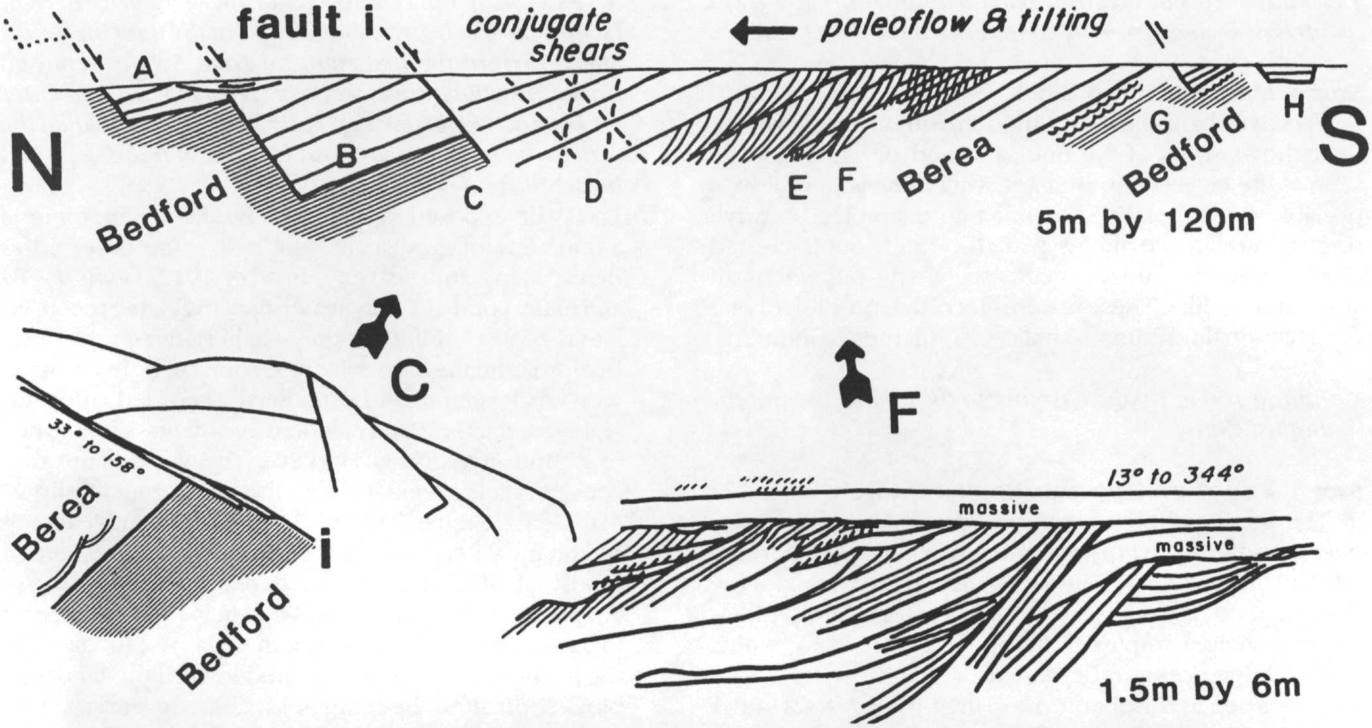

FIGURE 6. Caricature sketch of outcrop at Stop 3, a tilted block with complications at its toe. Shaded areas = outcrops of Bedford Shale; dots signify limits of cover; letters refer to points and features discussed in the text. The associated diagrams elaborate normal faulting along a pre-existing conjugate shear and bedding in a distributary mouthbar.

3) The broken slice of Berea at A may have slid off the top of B-G when the latter came to a stop.
4) F is a composite macroform. Its northern end (at E) has 52° foresets (originally 34°), and the overlying bounding surface originally dipped 6° to 120°. The sets of crossbeds all show accumulation toward the north, but their reactivation-like bounding surfaces indicate many episodes of erosive attack from the north. F has been interpreted as a longitudinal exposure through the crest of a distributary mouth bar where northward river processes were episodically interrupted by southward-directed storm waves. Upflow, equivalent beds comprise thick cosets of climbing ripples, which presumably represent accumulation of sands ascending the stoss side of the bar. It is interesting that both the front and back of the bar show accumulation.

Locally above the bar, the megaripples can be seen to overtake one another, thereby combining their avalanche faces and doubling their height. Relative to the very uniform sections upflow and downflow from the macroform, and crest must have been the site of complex movement of sediment and water.
5) The cliff at G shows north-directed bedforms, but its base exposes the wave-rippled facies seen at Stop 2. In some other exposures in the park, this facies is partly to totally eroded (stops 2 and 10), and locally it seems never to have been deposited (e.g., at stop 6 where fine and flat-bedded basal Berea sandstone lies nonerosionally on shales). The thin megaripple zone between the ripples and the overlying northward-directed bedforms is unique in its southward-directed flow. The next overhang south shows well-developed in-phase climbing ripples.

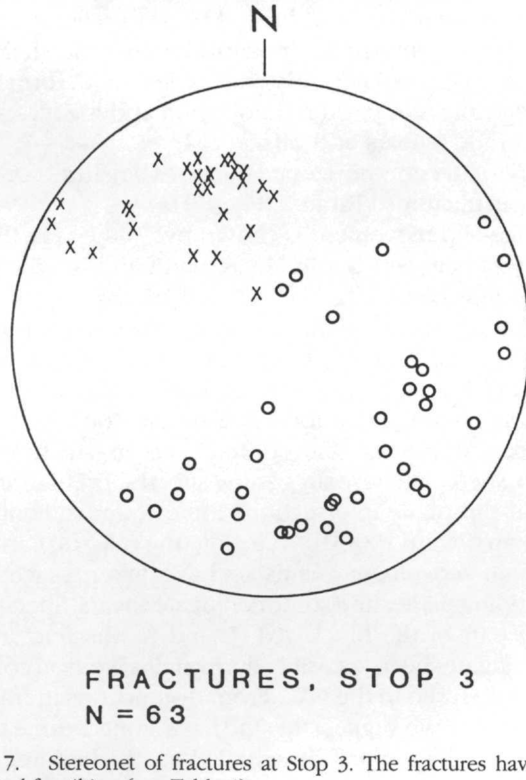

FIGURE 7. Stereonet of fractures at Stop 3. The fractures have been corrected for tilting (see Table 1).

G represents the up-tilt end of the B-G block. A small and intensely broken block of Berea (H) is exposed south of the broken staircase, but no Berea outcrops connect the two. It is presumably a fragment trailing behind the main tilted block.

Descend to riverside trail and follow it upstream to Stop 4, just up East Branch from its confluence with West Branch.

Stop 4. Modern Slump Block

The river bank here is a modern slump block whose float shows some of the fine sand and silt facies locally seen at the base of the Berea. If water levels permit, it is possible to find slabs showing fine examples of wave ripples, interference ripples, planed-off and double-crested ripples, wrinkle (runzel) marks, balls and pillows of all sizes, and the like. These features record deposition of fine sand flats on fluid muds in shallow to emergent conditions.

Continue 100 m up the east fork to the tip pile behind the Baptist Church.

Stop 5. Exposure Opposite Baptist Church

The Baptist Church has been tipping building wastes over the edge of the gorge in order to expand their parking lot. The pile is slumping into the river, so watch out for the deep arcuate fissures. Across the river from the tip pile is an extremely complex outcrop (Fig. 8), from which several inferences can be drawn:

1) The presence of ripped-up and drag-folded strata under the base of the Berea at B to F shows that this block suffered considerable WNW lateral movement as well as some vertical collapse (e.g., as along conjugate fractures at points I-K).
2) The way one fracture lifts C and climbs into the Berea, and another cuts F and E and passes up into G, shows that some detachment occurred within the shale.
3) The base of the sandstone varied in deformational behavior from plastic (fluidization and loadcasts at D) to brittle (shears and offsets at I).
4) Most of the non-horizontal fractures began as conjugate shear fractures (Table 2, Fig. 8B).
5) Strike-slip movement is shown by: a) the way that the shears between G and H can bend and "travel" along bedding planes; b) the oblique fractures connecting bedding plane shears at H2; c) the curved fractures without vertical offset, right of H2; and, d) the broken "rubbly" plane at J (between units 1 and 2, above I). Many fractures that look like simple conjugate shears separate blocks with differences in fractures and crossbeds, likewise suggesting lateral slip. Striae, curves, and slip-plane intersections indicate movement 5-10° down toward 290-310° (i.e., into the outcrop). In short, lateral movement seems to have taken place along bedding planes and some conjugate shears. Specifically, the part of the block at I, J, and K was fractured by conjugate shears, possibly during initial vertical collapse, and then slid to the NW. From disjunctions in fractures and beds, we suggest that the basal zone 1 came to rest, but that the top half detached along the bedding plane J, and so on, as enumerated in Fig. 8A and illustrated in Fig. 8C. For unknown reasons, sliding took place along the intermediate-stress axis of the conjugate fractures, not the least stress axis. Fractures antithetic to slumping are remarkably abundant.

If water levels permit, cross the river by boat here to look more closely at the base, overthrust J, blocks L and M, and so on. If not, climb out of the gorge, turn right (south) on Washington, turn right at the light on Broad Street, turn at the first right on Lake Avenue, and go under the railway bridge. Park (D on Fig. 2), and enter the park at the sign for Two Falls Trail. Proceed down the trail to the broken steps, and climb down the slope just before the end of the fence.

6) The shale exposed at K is "Red Bedford," but there is a thin zone of grey shale right below the base of the Berea. Many authors (e.g., Prosser 1912, Lewis 1988) and many Lorain County water-well logs have recorded a thin zone of "blue" or grey shale between the "Red Bedford" and the bases of low sections of Berea in areas west of Cleveland, and some have accorded it considerable stratigraphic and paleoenvironmental significance (e.g., Burroughs 1911). However, the way that the grey zone parallels irregularities in the Berea contact shows that it can be caused entirely by reduction and leaching of iron by waters percolating through pyrite-cemented sandstone at the base of the Berea.
7) Block L (reconstructed with slab M in Fig. 8D) is inferred to have been a piece of Berea that was not involved in the main slide, but which rotated toward the landslide block soon after. Bedding in block L suggests rotation of 30° to 360°, which would be back-rotation of the block as it moved at right angles to the big slide, southward into its axis. Striae down the northern face of L (and continued on slab M) show that movement. The original orientation of that face, tilt-corrected from 33° to 319° back to 64° to 202°, shows that it began as a conjugate shear related to those in the main slide block before either block moved (Table 2). Therefore, block L is inferred to have slumped down into the axis of the slide "channel" from its "bank," after the latter slumped downward and slid northwestward.

   The peculiar south face of block L shows complete multiple small offsets along three sets of close-spaced fractures (Table 2, Fig. 8D). After tilt-correction for bedding, σ_2 in block L is identical to σ_2 and the axis of sliding in the main block. In the main block, σ_3 has been exchanged with σ_2 in L, and fracture set 1 is perpendicular to σ_2. The significance of this is unclear.

   Slab M, formerly the pyrite-cemented base of block L, shows protuberant bulges on L's front face. These bulges confirm that the base of this bed in part flowed into the shale. However, the bulges also show diffuse offsets and irregularities. Note that there is a distinctive vertical pocketing at the base of the front face; these result from set 1 vertical fracturing (perhaps shale insertion and water ejection along the vertical fractures lessened their rate of movement into the shale relative to the parts between the fractures). The subhorizontal, set 3, offset fractures are not seen in the partly fluidized basal zones in M, but resulted where the upper parts of the sand body overslid its lower parts when the latter became lodged in the mud.
8) The boulder conglomerate preserved in front of block L is Holocene river-gravel, wedged into pockets eroded around block L.

Climb up north end of outcrop to Two Falls Trail, and head uphill.

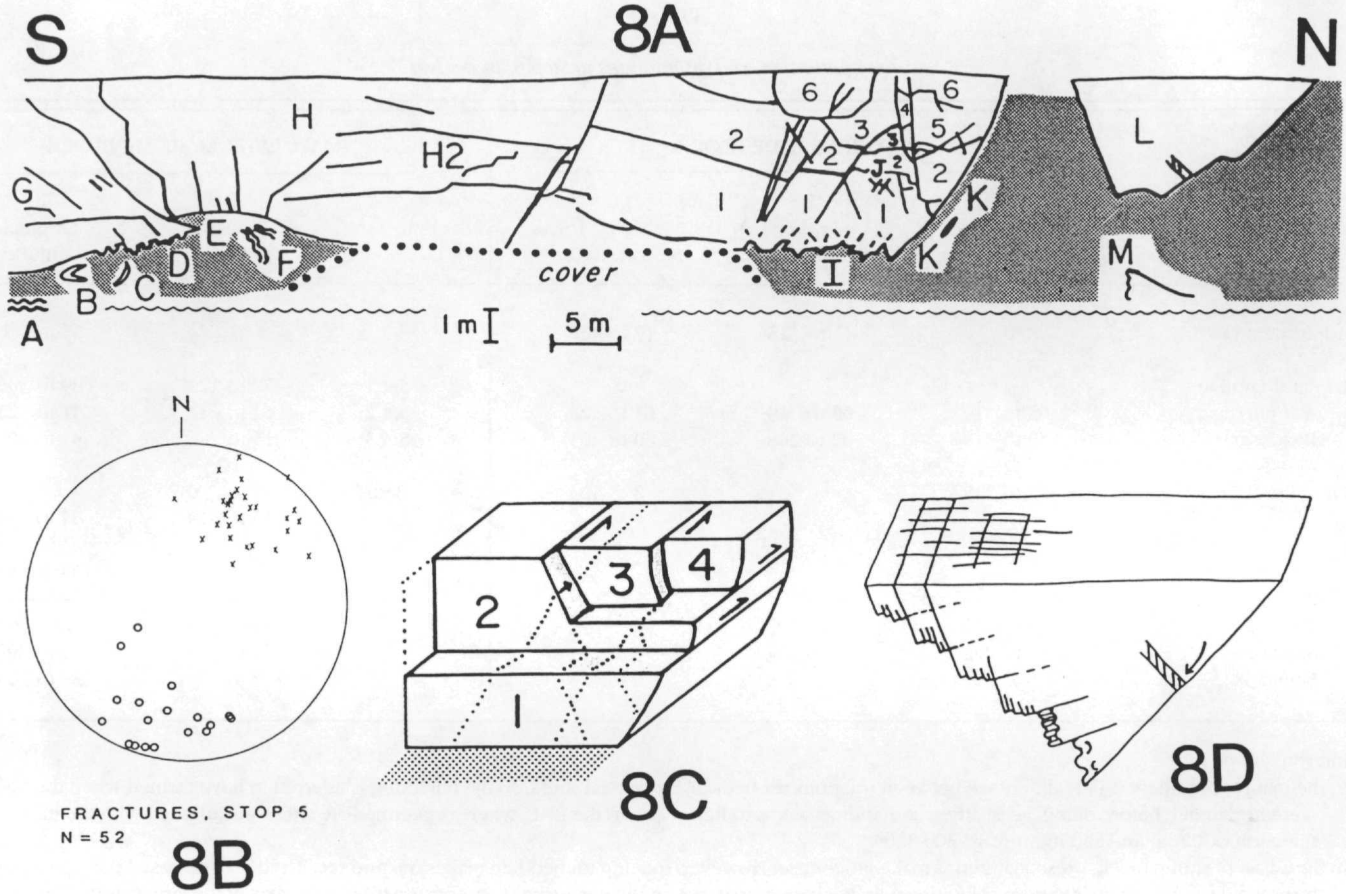

FIGURE 8. 8A: Caricature sketch of outcrop at Stop 5. Shaded areas = outcrops of Bedford Shale; dots signify limits of cover. Points: A = Thin rippled siltstones *in situ* under Berea. These are only visible if the river level is extremely low. B = Recumbent roll-over drag-fold in underlying shale (the slabs of whitish rock in front are travertine deposits fallen from a small seep at the base of the Berea). C = Small upthrust slice of siltstone and shale. D = Wedge of massive sandstone, with udder-like loadcasts underneath. E = Ductile intrusion of shales into sandstone, permitted where large faults cut down to base. F = Upturned and overthrust slice of Bedford siltstones, identical to that seen at A. G = Shears and faults, some of which began as conjugate shears. H and H2 = Bedding planes that have become horizontal faults (see explanation in text). I = Conjugate shears offsetting base of Berea Sandstone. J = Originally a fault plane, where unit 2-3-4-5-6 slid over unit 1. It is now considerably offset by normal faulting along conjugate shear planes. K = "Red Bedford," exposed below base. L = Isolated block of Berea, surrounded by Bedford. Ripples at nose show that originally horizontal bedding now dips 35° to N. M = The nose of this block, fallen upside down into the river.
8B: Stereonet of fractures at Stop 5. The fractures have been corrected for tilting (see Table 2). 8C: Simplified illustration of differential slippage within the sand body at the N end of Stop 5. 8D: Reconstruction and interpretation of blocks L and M from Figure 8A. Note bulges and outpocketings at base of block indicating fluidization.

Where the Berea crops out beside the trail (near the eroded wooden steps, more or less above block L), the upper Berea beds seem to flatten out upward, from 24° to 010°, through 14° to 016°, to 5° to 360°.

Head uphill for lunch at roadside park on Lake Street. After lunch, head back down trail to overlook over East Branch Falls.

STOP 6. East Branch Falls

The falls expose a thick body of Berea whose base is just below waterline. The trail down to the falls shows a very steep (70°) contact between the Berea and the "Red Bedford," which forms the cliff across the plunge pool. Near the other side of the outlet, the Berea again descends very steeply from high in the valley walls to river level. The plunge pool seems to be a large mud diapir, probably of the sort described by Morgan et al. (1968). The convex-up fractures in the cliff east of the falls, which arch up and away from the proposed mudlump, resemble the cone sheets (upward pressure fractures) described above a magmatic intrusion by Anderson and Jeffreys (1936).

Go a few meters down the side trail to the falls, and follow the base of the Berea under the overlook.

The base of the Berea is at mid-gorge level here. The contact is flat and sharp, and comprises a flat-bedded sandstone with abundant mica and small plant fragments lying nonerosively on flat shale.

Return to Two Falls Trail and go downstream to the confluence of the East and West Branches of the Black River. Just before the confluence, climb up to the Berea outcrop where it is closest to the path.

STOP 7. Two Forks Trail at Confluence of Rivers

This exposure exhibits: 1) characteristics of typical trough crossbedding; 2) another macroform; 3) asymmetrical breakage; and, 4) probable syndepositional tilt-

TABLE 2

Assessing attitudes and orientations at Stop 5, in degrees.

FEATURE	PRINCIPAL SLIDE BLOCK A Modern Orient'n	B Av. bed corr. to 0	C Sigma-1 corr. to 0	SMALL LATERAL SLUMP BLOCK	D Modern Orient'n	E Original Attitude
Adjustment factor	0	11 to 315	18 to 302		0	35 to 0
Dip and Dip Dir.						
A (tight)	65 to 14	60 to 19	61 to 23	Set 1:	72 to 122	89 to 306
B (looser)	59 to 214	62 to 208	60 to 203	Set 2:	64 to 13	31 to 22
				Set 3:	15 to 286	34 to 206
Orig. horiz. beds?	11 to 315	0	8 to 103	Beds	35 to 0	0
				Base	33 to 319	64 to 202
Stress field					Using 1+2	Using 2+3
Sigma-1	72 to 123	83 to 108	90		34 to 249	2 to 203
Sigma-2	18 to 292	7 to 294	0 to 293		56 to 56	0 to 293
Sigma-3	3 to 23	1 to 202	0 to 23		6 to 156	88 to 23

Interpretation:

In the main block, there is little difference between rotations for beds or for vertical stress, so the fracturing is inferred to have formed when the beds were horizontal, before tilting. Least stress at that time seems to have been to the ENE, whereas intermediate stress was aligned with the ultimate direction of tilting and sliding, toward 300-320°.

In the adjacent slump block, present attitudes make little sense. However, rotating for bedding makes fracture sets 2 and 3 an opposed conjugate pair, turns the basal slip plane into normal faulting with back rotation down an old conjugate shear fracture toward the axis of the larger slide. The stress fields become aligned, except that horizontal expansion to 023° has now become horizontal compression to 023°, with no change in the axis of intermediate stress.

ing (Fig. 9). Most megaripples here show well-developed scour pools with climbing ripples that formed where currents swept sediment up and out of their troughs. This is typical for outcrops in Elyria. Flow is to the north, and most of the bounding surfaces suggest the descending or lee side of a macroform. The central part of the irregular base is probably some sort of detachment. The most recent faults (F in Fig. 9) indicate downward movement of the whole sandbody. Basal exposures across West Branch also show a topographically high basal contact climbing toward the center of the confluence of the rivers. Confluence appears to occur at the site of an old mudlump, where erosion was easy, once the capping Berea was breached. Although the basal beds have been oversteepened at point C, the capping beds are horizontal, which suggests, but does not prove, tilting during accumulation. (Syndepositional deformation might be expected in analogy with salt diapir histories; e.g., Currie [1956].) In light of the mudlump to the north and rotation of crossbeds toward it, we interpret the basal C-E detachment as a lystric fault (possibly syndepositional) that transported the outcrop block away from the mudlump. There seem to be two distinct sets of conjugate shears (Table 3).

Continue along the Two Falls Trail up the West Branch to the West Falls.

Ascending West Branch, note that the beds are descending steeply from the general direction of West Branch toward Stop 7, which from this angle resembles Stop 3.

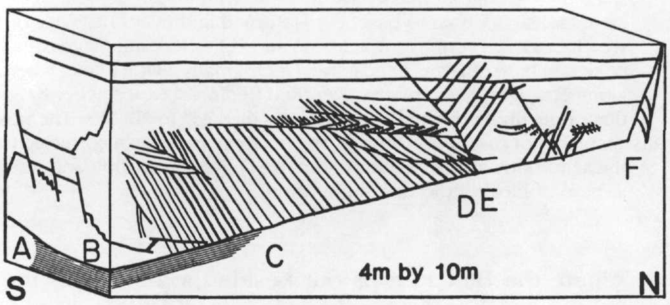

FIGURE 9. Caricature sketch of Stop 7. A: Bedford shale exposed under a finely broken section of Berea, which includes an early planar overthrust that has suffered many small offsets along conjugate shears. (Note similarities with J at Stop 5 and B at Stop 3.) B: Complex basal shearing and trough crossbedding. C: Very high crossbeds (higher than bedforms at B and D), clearly oversteepened. D: Climbing ripples at toe of megaripple scour pool. E: Asymmetrical breakage of conjugate shears. F: Major post-conjugate-shearing fault.

Continue along Two Falls Trail up the West Branch.

STOP 8. West Branch Falls

The macroform at eye height at the end of the trail is interpreted as an abandoned distributary mouth bar, whose many megaripples and ripples accumulated in the order shown in Fig. 10. Unlike the macroform at Stop 3, this one seems to have accumulated steadily, with essentially

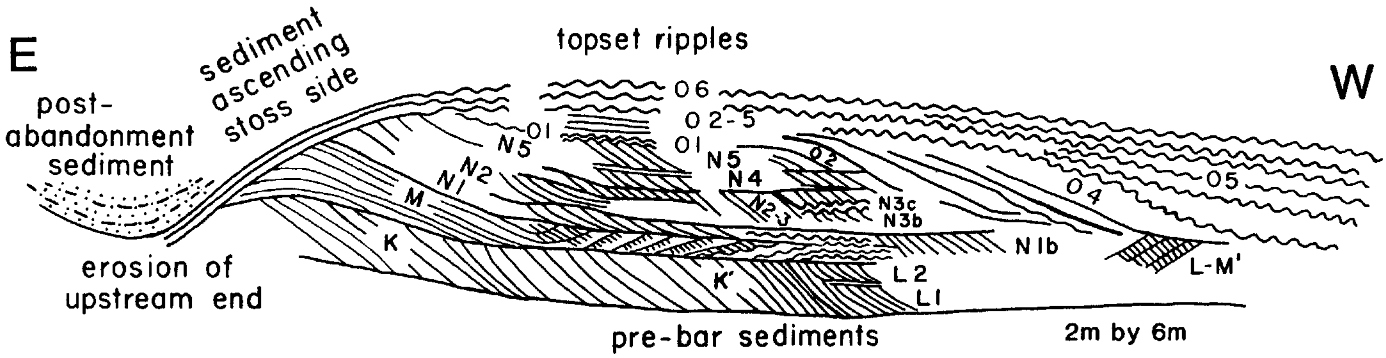

FIGURE 10. River-dominated distributary mouth bar at West Falls. The letters and numbers give the inferred sequence of accumulation (N before O, N2 before N3). Note: a) fine clayey sand deposited in channel-scour upstream of bar after abandonment; b) sediment moving up stoss slope of macroform at time of abandonment; c) megaripples formed during early stages of development of bar; d) climbing ripples at toes of megaripples; e) megaripples coalescing during growth of bar; and, f) late stage accretion, showing climbing ripples, low relief, and gentle slopes. This macroform accumulated from K to O6, with principal upbuilding during M, maximum outbuilding during O4-5, and maximal depositional relief during N1.

TABLE 3

Assessing attitudes and orientations at Stop 7, in degrees.

FEATURE	A Modern Orient'n	B Best horiz. corr. to 0	C Poss. horiz. corr. to 0	D Sigma-1 corr. to 0
SET 1:				
Adjustment factor	0	11 to 48	12 to 342	13 to 307
Dip and Dip Dir.				
A	72 to 59	61 to 60	70 to 63	57 to 54
B	42 to 224	53 to 225	49 to 214	56 to 235
Orig. horiz. beds?	11 to 48	0	12 to 108	13 to 307
	12 to 342	12 to 289	0	26 to 299
Stress field				
Sigma-1	71 to 272	77 to 304	66 to 306	90
Sigma-2	12 to 145	12 to 144	21 to 141	0 to 144
Sigma-3	15 to 52	4 to 51	5 to 48	15 to 52
SET 2:				
Adjustment factor	0	11 to 48	12 to 342	13 to 307
Dip and Dip Dir.				
C	66 to 143	67 to 148	77 to 144	63 to 148
D	60 to 334	58 to 327	48 to 333	62 to 328
Orig. horiz. beds?	11 to 48	0	12 to 108	13 to 307
	12 to 342	12 to 289	0	26 to 299
Stress field				
Sigma-1	78 to 252	85 to 326	74 to 301	90
Sigma-2	11 to 58	1 to 236	7 to 54	0 to 58
Sigma-3	3 to 149	5 to 146	15 to 147	3 to 149

Interpretation:

There seem to be two sets of fractures here, and it is interesting that, no matter what the correction, the two sets seem simply to have exchanged least and intermediate stress directions.

Col. B (correction for bedding at 11° to 48°) seems to provide the best overall orientations, given that correcting sigma-1 to vertical makes beds dip 36°, which is unlikely.

no destructive interference. It built up from flat to steep by coalescence of avalanche faces through stage N, resulting in a large front (O3) that later flattened out during O5. Note the abundant climbing ripples, particularly at the toes of megaripples. The exposure also shows sediment climbing up the stoss slope at the time of abandonment, and post-abandonment fine sediment filling the upstream scour.

Follow the cliff uphill and to the left.

There are relatively few fractures in the macroform, although they are better developed across the falls and they abound where the base of the Berea rises sharply above the surface uphill of the macroform (Table 4). The Berea is completely missing from both walls of the wide part of the valley downstream from the falls, so the wide area is inferred to be another mudlump. The flow directions in the sandstones at the East and West Falls are approximately aligned and might represent a channel axis, but the distributary mouth bar indicates flow coming directly from the mudlump, so the mudlump postdates at least some of the sedimentation. The combination of scouring behind the mouth bar and deposition on it may have precipitated mud movement.

Return down river to boat, and cross to west side of West Branch. If water levels prohibit the use of a boat, return to car park C (Fig. 2), proceed straight ahead (NW) on Lake Avenue to second light (0.8 km or 0.5 miles), turn right (NE) onto Furnace Street for 0.3 km (0.2 miles), and then right on Hillsdale into entrance of Cascade Park. Park near playground at E and walk south to where the old quarry road fords the West Branch, just upstream of the confluence.

STOP 9. West Branch - Old Quarry Road

This stop is located midway down the west side of West Branch, where old quarry road enters the gorge. Here the Berea reappears on the NW side of the putative mudlump. Bedding that was originally flat is now dipping at about 19° to 020°, away from the mudlump. There is such a variety of fracture orientations in this block (which extends

TABLE 4

Assessing attitudes and orientations at Stop 8, in degrees.

FEATURE	East side of waterfall A Modern Orient'n	 B Av. bed corr. to 0	 C Av. bed corr. to 0	 D Sigma-1 corr. to 0	West side of fall E Modern Orient'n	 F Sigma-1 corr. to 0
Adjustment factor	0	22 to 225	7 to 290	8 to 339	0	5 to 357
Dip and Dip Dir.						
A	60 to 64	81 to 62	65 to 67	60 to 69	60 to 357	56 to 357
B	68 to 253	49 to 260	62 to 251	68 to 250	50 to 178	65 to 178
Orig. horiz. beds?	22 to 225	0	20 to 207	26 to 210	?	?
	7 to 290	20 to 26	0	6 to 216		
Stress field						
Sigma-1	82 to 152	67 to 202	86 to 159	89 to 159	85 to 177	90 to 177
Sigma-2	8 to 339	17 to 335	4 to 339	0 to 340	0 to 266	0 to 266
Sigma-3	1 to 248	16 to 69	0 to 68	1 to 69	5 to 356	0 to 356

Interpretation:
Beds and fractures are not well developed or easily measured here, except for western fractures.
East of the falls, the bed seems to have been tilted toward 290°, probably after fracturing (given the improvement in Col. C). The 22° to 225° surface probably does not represent a paleohorizontal surface.
The stress field seems to have rotated 90° across the falls, but neither orientation agrees with the location of the mudlump downstream.

to Stop 12) that detailed interpretation is uncertain at best (Fig. 11). The beds have clearly been oversteepened by tilting, but correcting them to horizontal does not notably improve the stress field; correcting σ_1 to vertical does not make bedding notably more realistic. Possible interpretations are that fracturing was too variable and complicated for averages to be meaningful, that the maximum confining stress was not precisely vertical, or that fracturing happened during tilting (least stress is toward 020-025° in most calculations, which is not far from the likely direction of tilt). The majority of fractures are antithetical, which is to say that they dip upslope, toward the mudlump. Otherwise, those that permitted lateral movement tend to be oriented NW-SE or N-S, which is not closely related to the Confluence or West Falls mudlumps and is only moderately related to the tilt direction of bedding, which is close to modal paleoflow (see Fig. 2).

Continue downstream toward the confluence of the rivers.

STOP 10. West Branch Trail, Cascade Park, Just Upstream of Confluence

This outcrop shows tilting and erosion at the base of the Berea, as well as a gradation from shale up into sandstone. The shale, the very fine sandstones, the wave-rippled sandstone, and the main Berea are all parallel and titled, which again shows involvement of sub-Berea shales and forbids interpreting the dip of the basal wave-rippled sandstone as a channel. At first glance, the wave-rippled facies here appears to be cut out by a channel at the base of the main-Berea megaripple sandstone, as at Stop 3. Closer inspection reveals not only that the cut descends southward at the south end of the outcrop (2.3 m stepwise down in 20 m), but that the same cut also descends northward at the north end of the outcrop, where it is steeper and has caused a small amount of synsedimentary slumping (Fig. 12). In short, the wave-rippled sand is not the side of a channel but a relict mound eroded from a blanket of rippled sand. The paleocurrent directions in the main Berea share some similarities with those at Stops 2, 3, and 7; but, curiously, the least stress directions are at Site 5 (Fig. 2).

Climb around the nose of the exposure above the confluence to the highest point directly above the confluence.

Note how the base of the Berea climbs dramatically higher, while dipping away from the confluence, where we infer a mudlump (see Stop 7). The shale lies parallel to the base of the sandstone.

Continue around the outcrop; climb on top of it at the first opportunity, between two high rock faces and above a huge fallen block. Go to the back of the ledge where there is a very narrow fenced rock "bridge" to the high ground outside the park.

STOP 11. On "Rock Bridge"

We are on the rim of a Holocene waterfall whose approach has been eroded away after capture of the West Branch by the East Branch and/or after erosion into the top of the mudlump at the modern confluence permitted entrenchment beside the old channel. Bedding dips at 27° to 337°, but horizontal postglacial load-release jointing has

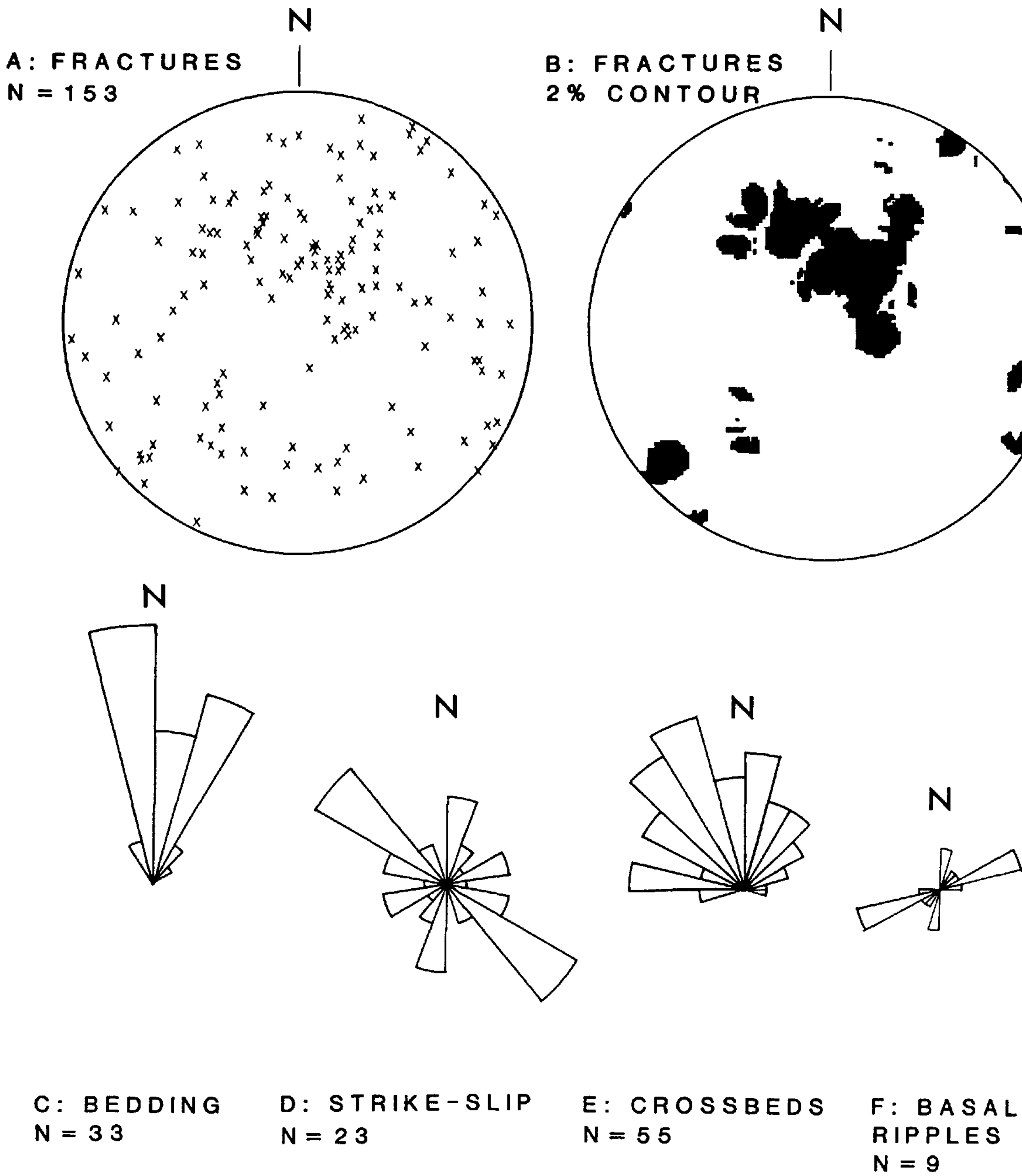

FIGURE 11. Fractures, and so on, in the southern Cascade block. A: Poles to fractures. B: Fracture poles contoured at 2% (using P. Guth's program MICRONET®). C: Bedding dip directions. D: Strike-slip axes. E: Paleocurrents (mostly megaripples) in the main body of the Berea. E: Directions for wave ripples in the basal sands.

mostly obscured it. Stop 10 is below and to the south, and Stop 12 is below to the north.

Cross the bridge, descend steps cut into rock in the bridge's NW corner, and follow trail down to asphalted area, once the site of a bear cage, in the old waterfall's plunge pool.

STOP 12. Site of Bear Pit

Directions of both dip and paleoflow are more or less out of the outcrop. This exposure is thought to be a transverse cut through the type of mouth-bar macroform of Stops 2F and 8. Note the zones of climbing ripples and the climbing ripples at the toes of megaripple scour pools, including one set with reverse flow toward the bedform.

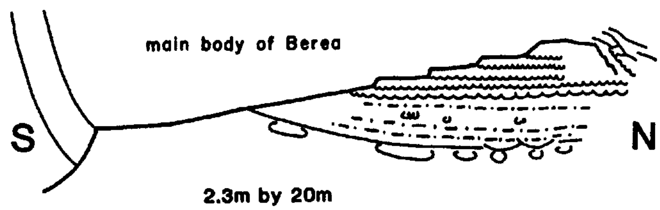

FIGURE 12. Caricature sketch of outcrop at Stop 10 showing wave-rippled sandstones over load-casted fine sandstones at the base of the Berea. The rippled sands are cut by broad and gently incised pre-mid-Berea erosion.

The major bounding surfaces arc across the face of the old waterfall and, therefore, suggest domal accretion of the macroforms, given the upstream and downstream accretion seen at Stops 3 and 8. Distributary mouth bars seem capable of such growth and are well situated to be preserved by slumping into prodelta muds prior to destruction by waves during delta-lobe abandonment.

DISCUSSION

Directions of paleocurrents, slumping, lateral movement, and stress fields are summarized in Fig. 2. Those directions depend on decisions about original orientations, appropriate groupings, whether fractures were active before or after rotation, and the significance of structures. The evidence nevertheless demonstrates major mudlump and slump activity, and calls into question the Pepper et al. (1954) model of Berea channels and valley-fills. These exposures instead suggest mass-wasting on deltas as described by Morgan et al. (1968), Prior et al. (1979), Galloway and Hobday (1983), Coleman and Prior (1988), and Nemec et al. (1988).

The evidence points to complex and changing stress fields and flow directions. Sites 6 and 8 are distinct from the other exposures because of their westerly rather than northerly flow. Evidence for complex changes in stress fields includes: a) multiple directions of slip and/or conjugate fractures, as at sites 3, 7, and 9; b) the poor alignment of stress fields with apparent mudlump locations at the East and West falls; c) the sliding of the Stop 5 slide block in what was previously the intermediate-stress direction; and, d) the abundance of antithetical normal faults (see Morgan et al. [1968] for structural complexities around deltaic mudlumps).

The features seen in Elyria are also present elsewhere in the Berea outcrop belt in northern Ohio. For example, at the falls of the Rocky River in Berea (the type area of the Berea Sandstone [Fig. 4B]), there is a mudlump under the overlook on the Valley Parkway at Barrett Road. The base of the Berea is very irregular (Figs. 54, 55 of Coogan et al. 1981), but the subjacent shales remain parallel to it, proving mass movement rather than erosion. South of the mudlump, the Berea is intensely faulted and tilted south and comprises unidirectional megaripples (flow to N) with some climbing-ripple toes. The Berea to the north is a long block tilted northward and broken into conjugate shears, some of which show complex patterns of movement and rebreakage (Fig. 53 of Coogan et al. 1981). The northern end of that block, together with some underlying shales and siltstones, has been thrust over another block of Berea, which caused faults and recumbent drag folds in the siltstones. Further downstream there is a large overthrust within the "Red Bedford," with overturned dragfolds in the hanging wall (Fig. 20 of Lewis 1988, Fig. 50 of Coogan et al. 1981). This seems to have been a distal result of the Berea sliding off the mudlump. Conjugate shears have become normal faults at several places.

Similarly, the quarries at South Amherst, long critical to the argument that Berea irregularities are best interpreted as channels (Burroughs 1911, Pepper et al. 1954), also contain many Elyria-type features. Several quarries show block tilting and faulting is particularly abundant near their bases. Inclined shaly zones like the one in Quarry 7 (Fig. SA-4 of Potter et al. 1984) contain abundant planed-off, double-crested, and interference ripples indicative of very shallow water and original flat bedding. At Birmingham Quarry (west of the Vermilion River), the tilt of a 23 m section decreases upward from 12° to 6°. Alternation through the section of laterally extensive upper flow regime plane bedding and intercalated beds of ripples *without intervening megaripples* implies persistently shallow depth and requires that each bed was horizontal during deposition. This implies steady tilting during deposition (Nesbit and Wells 1989). Quarry 6 shows a bedform similar to the bar at Stop 3F, except that it is "stretched out" owing to more progradation and less attack (Nesbit and Wells 1989). Unlike the Elyria exposures, however, the South Amherst blocks are too large to be seen and appreciated in a single outcrop, and their bases are not exposed. The exposure of "down-faulted" or "channel" Berea in the Lake Erie cliffs east of Vermilion (Kindle 1912, Burroughs 1914) seems to be another instance of syndepositional or pre-burial slumping.

Subsurface data (Burrows 1988; Coogan, in progress) has also failed to substantiate the channels of Pepper et al. There are considerable irregularities in the Berea, but their bases do not describe a continuous thalweg at uniform depths. Instead, subsidence of massive blocks of sand and uplift of mud diapirs seem far more consistent with the patterns seen (Fig. 13).

The depth of slumping at Elyria implies that even the Cleveland Shale was still fairly soft and fluid during Berea deposition. The depths attained at South Amherst are more difficult to comprehend, and suggest that the Berea was deposited above some sort of buried shelf-edge or trough in that area (see isopach map in Fig. 5 of Lewis 1988), or possibly growth faults as seen in Fig. 5-7 of Galloway and Hobday (1983) or, in a much smaller example with an 8.4 offset, at the Quarry Rock Picnic Area, 2 km (1.3 m) S of Chagrin Falls. Figures CF1 and 5 of Potter et al. (1984) described the latter as a channel (see also Prosser 1912), but the detailed work they recommended shows that the "channel" is one-sided and consists of thickened units of crossbeds dipping ENE away from an ENE-facing fault scarp. Examples of thrust faults rising through Bedford shales (e.g., Stop 5) and rotation of Bedford shales together with Berea sands (stop 10 and Berea Falls) show that many detachments occur well down in the shale, where they may be unrecognizable.

The outcrops at Berea and in Elyria indicate strong components of flow to the north and to the west, with slumping indicating paleoslopes in those directions. This is entirely contrary to the south-building deltas inferred by Pepper et al. (1954), Burrows (1988), and Burrows and Coogan (1988). Lewis's (1988) study of outcrops north of Burrows' subsurface study showed generally westerly paleoflow (to the NW, W, and SW), which implies that the Berea deltaic complex built westward from the Appalachian orogen. Our observations of northward delta building could represent locally deviant delta lobes from a river or rivers rising in the Appalachian orogen, but are not as easily reconciled with a northern source.

The presence of mudcracks and shallow-water features below the main Berea indicates that the Berea distributaries built out over a very flat and very shallow sea floor, even though the underlying dark shales appear to represent the

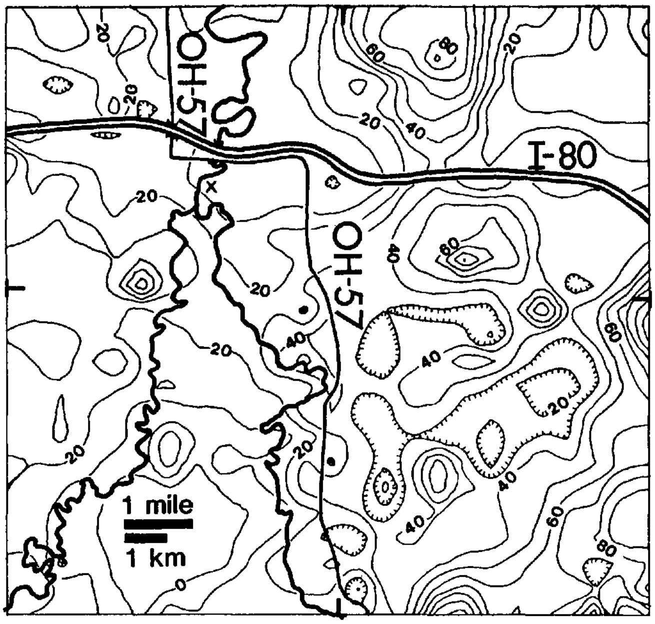

FIGURE 13. Isopach map of the Berea in Elyria and three adjacent townships (102 mi² area), based on 400 well records, contoured in feet. Irregularities are in very small part the result of buried preglacial valleys and modern topography, but most strongly suggest slumps and diapirs. X marks the site of point C on Fig. 2; tick marks indicate township boundaries.

bathymetric axis of the Appalachian basin. That axis would have been a starved basin near the western limit of transport of clastics, but not beyond the zone of tectonic downflexing. A Bedford regression, followed by a Berea transgression to accommodate thick sands, could explain this problematic succession, but a preferable model is analogous with spreading of conglomerate after the end of thrusting and foreland basin subsidence (Heller et al. 1989a,b). Rebounding of the floor of the Appalachian basin following the cessation of Acadian thrusting can explain some long-standing problems. The basin would shrink and sedimentation would shift into whatever remains of the bathymetric axis. The dark shales would be lifted into oxygenated and energetic waters, thus becoming eroded, oxidized, and redeposited as "Red Bedford" in the bathymetric axis. Shelf and coastal sands and mud in Pennsylvania and eastern Ohio might become emergent zones of sediment bypassing, might yield some weathered clastics to be redeposited near the bathymetric axis, and might serve to divert or channelize Berea streams. In this respect, note Burrows' (1988) pattern of northwestward passage from a thin sheet of Berea to irregular slump bodies (Fig. 4C). The rebound model thereby explains the disjunction of the eastern limits of the Red Bedford and the Berea from the western limits of deltas and shorelines further east, and the Gay-Fink and Cabin Creek channels (as discussed by Pepper et al. 1954). It, moreover, fits with earlier authors' models for shallow-subaqueous, oxic, basin-filling with Red Bedford and deformation of the shales where the Red Bedford (Mausser 1982) and the Berea (Lewis 1988) overstep the Euclid Siltstone. The rapidity of progradation of Berea sands (forced by the newly shallow basin), combined with their deposition on the finest, least competent, central-basin, deep-water muds, probably ensured that the muds had not dewatered prior to the arrival of distributary mouth bars, which in turn ensured maximal foundering of the sands.

Some useful analogies for the Bedford-Berea system may be found in aspects of the sediment supply, paleogeography, paleoclimate, and structural setting of the Mesopotamian delta plain in the Persian Gulf (Baltzer and Purser 1990). Constraints of progradation, the shallowness of the receiving basin, and the orientation of the basin and the orogen may be particularly similar. Given the all but complete absence of evidence of animals in the western Berea, it is interesting to note that the Mesopotamian delta plain, its many lakes, and its unusally saline rivers are quite inhospitable.

SUMMARY

While not wishing to deny the presence of channels and scours in the Berea, and while many of the "Berea lows" may be slumps initiated by cutting and/or loading along channel axes, most "Berea channels" at Elyria and elsewhere are primarily mass movements of sand into mud. Therefore, the outcrops at Elyria strongly support Lewis' (1988) view of the Berea rather than the view of Pepper et al. (1954). This has not only considerable paleographic implications, as the latter encompasses both deep erosion along a post-Bedford/pre-Berea unconformity and separate deposition of "Red Bedford" and Berea deltas, but also profound stratigraphic implications, because the Berea should comprise countless small delta lobes, packed tight into a thin zone.

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LITERATURE CITED

Anderson, E. M. and H. Jeffreys 1936 The dynamics of the formation of cone-sheets, ring-dykes and cauldron subsidence (A) with "Note on Fracture" (J). Roy. Soc. Edinburgh Proc. 56: 128–163.

Baltzer, F. and B. H. Purser 1990 Modern alluvial fan and deltaic sedimentation in a foreland tectonic setting: the lower Mesopotamian plain and the Arabian Gulf. Sediment. Geol. 67: 175–197.

Burroughs, W. G. 1911 The unconformity between the Bedford and Berea Formations of northern Ohio. J. Geol. 19: 655–659.

———— 1914 Berea Sandstone in eroded Cleveland Shale. J. Geol. 22: 766–771.

Burrows, V. C. 1988 Subsurface stratigraphy and paleoenvironmental interpretation of the Mississippian Berea Sandstone and Bedford Formation of Medina County, Ohio. Unpubl. M. S. Thesis, Kent State Univ., Kent, OH. 121 p.

———— and A. H. Coogan 1988 Subsurface geology of the Berea Sandstone in Medina County, Ohio. Geol. Soc. Amer. Abstr. w. Progr. 20: 338.

Coleman, J. M. and D. B. Prior 1988 Mass wasting on continental margins. Ann. Rev. Earth Planet. Sci. 16: 101–119.

Coogan, A. H., R. A. Heimlich, R. J. Malcuit, K. B. Bork, and T. L. Lewis 1981 Early Mississippian deltaic sedimentation in central and northeastern Ohio. *In:* T. G. Roberts, Roberts, ed. Geol. Soc. Amer. 1981 Cincinnati Field Trips (no. 13). p. 113–152.

Currie, J. B. 1956 Role of concurrent deposition and deformation of sediments in development of salt-dome graben structures. Amer. Assoc. Petrol. Geol. Bull. 40: 1–16.

de Witt, W. 1970 Age of the Bedford Shale, Berea Sandstone, and Sunbury Shale in the Appalachian and Michigan basins. U.S. Geol. Surv. Bull. 1294–G: 1–11.

Dunne, L. A. and M. R. Hempton 1984 Deltaic sedimentation in the Lake Hazar pull-apart basin, southeastern Turkey. Sedimentol. 31: 401–412.

Galloway, W. E. and D. K. Hobday 1983 Terrigenous clastic depositional systems. Springer-Verlag, New York, NY. 423p.

Heller, P. L., C. L. Angevine, and C. Paola 1989a Comment and reply on "Thrusting and gravel progradation in foreland basins: a test of post-thrusting gravel dispersal." Geology 17: 959–960.

——— 1989b Interpretation of pre., syn., and post orogenic gravels in alluvial basins. Progr. and Abstr., 4th Int. Conf. Fluvial Sedim. p. 151.

Hempton, M. R. and J. F. Dewey 1983 Earthquake-induced deformational structures in young lacustrine sediments. Tectonophys. 98: T7-T14.

Kindle, E. M. 1912 The stratigraphic relations of the Devonian Shales of northern Ohio. Am. J. Sci. 304: 187–213.

Kohout, D. L. and R. J. Malcuit 1969 Environmental analysis of the Bedford Formation and associated strata in the vicinity of Cleveland, Ohio. Compass 46: 192–206.

Lewis, T. L. 1976 Late Devonian and Early Mississippian paleoenvironments, northern Ohio. Geol. Soc. Amer. Abstr. w. Progr. 8: 220.

——— 1986 Dispersal systems and basin accommodation of Late Devonian and Early Mississippian clastic wedges, northern Ohio. Soc. Econ. Paleontol. and Mineral. Abstracts 3: 67–68.

——— 1988 Late Devonian and Early Mississippian distal basin-margin sedimentation of northern Ohio. Ohio J. Sci. 88: 23–39.

Majoras, J. J. and N. A. Wells 1988 Formation of Mississippian Berea Sandstone "channels" by soft-sediment deformation, at Elyria, Lorain County, Ohio. Geol. Soc. Amer. Abstr. w. Progr. 20: 379.

Mausser, H. F. 1982 Stratigraphy and sedimentology of the Cleveland Shale (Devonian) in northeast Ohio. Unpubl. M.Sc. Thesis, Case Western Reserve Univ., Cleveland, OH. 116 p.

Morgan, J. P., J. M. Coleman, and S. M. Gagliano 1968 Mudlumps: diapiric structures in Mississippi delta sediments. *In:* J. Braunstein and G. D. O'Brien, eds. Diapirs and diapirism. Amer. Assoc. Petrol. Geol. Memoir 8: 145–161.

Nemec, W., R. J. Steel, J. Gjelberg, J. D. Collinson, E. Prestholm, and I. E. Oxnevad 1988 Anatomy of collapsed and re-established delta front in Lower Cretaceous of eastern Spitsbergen: gravitational sliding and sedimentation processes. Am. Assoc. Petrol. Geol. Bull. 72: 454–476.

Nesbit, K. L. and N. A. Wells 1989 The Mississippian Berea Sandstone of the South Amherst quarries, Lorain County, Ohio: deposition as valley-fills or oversized loadcasts? Geol. Soc. Amer. Abstr. w. Progr. 22: 40.

Pepper, J. F., W. DeWitt, and D. F. Demarest 1954 Geology of the Bedford Shale and Berea Sandstone in the Appalachian basin. U.S. Geol. Surv. Prof. Paper 259. 111 p.

Potter, P.E., J. H. DeReamer, D. S. Jackson, and J. B. Maynard 1984 Lithologic and environmental atlas of Berea Sandstone (Mississippian) in the Appalachian basin. Appalachian Geol. Soc. Special Pub. 1. 157 p.

Prior, D. B., J. M. Coleman, and L. E. Garrison 1979 Digitally acquired undistorted side-scan sonar images of submarine landslides, Mississippi delta. Geology 7: 423–425.

Prosser, C. S. 1912 The Devonian and Mississippian Formation of northeastern Ohio. Geol. Surv. Ohio Bull. (4th ser.). 15: 1–574.

Underhill, J. R. and N. H. Woodcock 1987 Faulting mechanisms in high-porosity sandstones; New Red Sandstone, Arran, Scotland. *In:* M.E. Jones and R. M. F. Preston, eds. Deformation of sediments and sedimentary rocks. Geol. Soc. Special Pub. 29: 91–105.

Wells, N. A. 1988 Working with paleocurrents. J. Geol. Educ. 36: 39–43.