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PALEOGEOGRAPHY OF THE EAST BERLIN FORMATION, NEWARK GROUP, CONNECTICUT VALLEY

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ABSTRACT. The East Berlin Formation is a 145- to 450-m terrestrial sequence between the Holyoke and Hampden lava flow units in the Hartford Basin. Conglomerate and sandstone accumulated as alluvial fans along the fault-bounded eastern escarpment. Pale red, cross-bedded channel sandstones interbedded with flood-plain red mudstone record streams that flowed westward from the eastern highlands to meander across low-gradient flood plains. Thin beds of ripple-marked red sandstone and siltstone were deposited in shallow oxidizing lakes in the flood basin. The climate was tropical, probably with a marked dry season and varied from humid to semi-arid. Cycles of gray mudstone-black shale-gray mudstone record perennial lakes of alkaline, hard water that existed during long-term periods of increased rainfall. The larger lakes probably exceeded 4700 km^2 with depths of tens of meters. Couplets of laminated dolomite-black shale or gray mudstone in some of the perennial lake sequences may be varves. Preservation of the fine laminae suggests that the lakes were oligomictic. Shallow-water sandstone is common near the top and bottom of the lake cycles. The dominant paleowinds blew from the northwest over the lake surfaces, generating waves that flowed to the southeast. In central Connecticut the paleocurrents in the perennial lakes flowed northeast, up the southwest-sloping lake floors, which are known independently from slump horizons. In this local area, wave refraction oriented the ripple crests of the nearshore sands parallel to the northwest-southeast-trending strands of the lakes.

INTRODUCTION

The Hartford Basin is one of the fault-bounded basins in eastern North America that form a linear system 2000 km in length (Rodgers, 1970). The terrestrial deposits and basalt flows in the Hartford Basin total about 4 km and can be physically correlated for 140 km from southern Connecticut to central Massachusetts but not to the isolated outcrops of the Deerfield Basin in northern Massachusetts (fig. 1). The rocks in the Hartford Basin have been assigned to the Upper Triassic on the basis of rather variable K-Ar dates (Armstrong and Besancon, 1970, p. 22). The spores and pollen, however, suggest that the transition from the Triassic to Jurassic lies within the Shuttle Meadow Formation or lower and that the East Berlin Formation is of Lower Jurassic age (Cornet, Traverse, and McDonald, 1973, p. 1247; Cornet and Traverse, 1975, p. 26).

The East Berlin Formation is thinnest (145 m) in northern Connecticut in the Avon quadrangle (Schnabel, 1960). It thickens northward to Mountain Park, Mass. (255 m) and The Notch in the Holyoke Range south of Amherst, Mass. (275 m). It also thickens to the south to the

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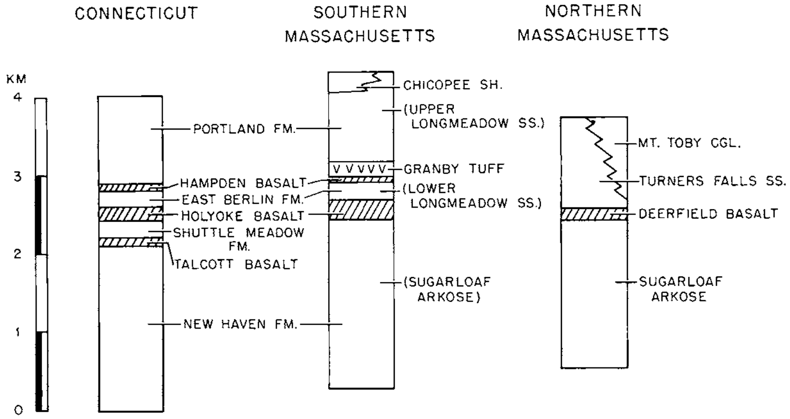


Fig. 1. Stratigraphic nomenclature in the Connecticut Valley. The formations in Connecticut can be traced into southern Massachusetts making unnecessary the formation names shown in brackets (Colton and Hartshorn, 1966). The formations in the Deerfield Basin of Northern Massachusetts cannot at present be correlated with those of southern Massachusetts in the Hartford Basin.

Middletown quadrangle, Conn. (170 m), which includes the type section along Highway 72 (Lehmann, 1959), and the Durham quadrangle (450 m) in the Gaillard Graben (Sanders, 1970).

Our objectives are to use the stratigraphy and primary structures of the sedimentary rocks of the East Berlin Formation to interpret the fluvial and lacustrine environments and map the paleocurrents and paleoslopes. These data are integrated into a paleogeographic map using the Holyoke and Hampden lava flow units as time lines.

Detailed logs were made of the East Berlin Formation at the three best exposed sections. These are: the 105-m section along Connecticut Highway 72 just east of the junction with Connecticut Highway 15 (sec. 1 on fig. 2); the 62-m section at the interchange in Cromwell between I-91 and Connecticut Highway 9 (sec. 5 on fig. 2); and the 58-m section at Mountain Park along I-91, Mass. (fig. 3; pl. 1). The average proportions of rock types for the three sections are 35 percent gray mudstone, black shale, and gray sandstone (perennial lakes), 52 percent red mudstone (flood plains), 10 percent thin, evenly bedded red sandstone and siltstone with abundant ripple marks (shallow oxidized lakes), and 3 percent pale-red channel sandstone (stream channels). These values provide an estimate of the proportions of rock types deposited on the valley floor, omitting conglomerate and sandstone of the alluvial fans along the fault-bounded escarpment on the eastern side of the basin.

ALLUVIAL-FAN CONGLOMERATE AND SANDSTONE

The outcrops close to the eastern border faults are pale-red (Munsell color chart, 10R 6/2) sandstone, pebbly sandstone, and conglomerate, almost entirely horizontally laminated. Angular boulders of igneous and

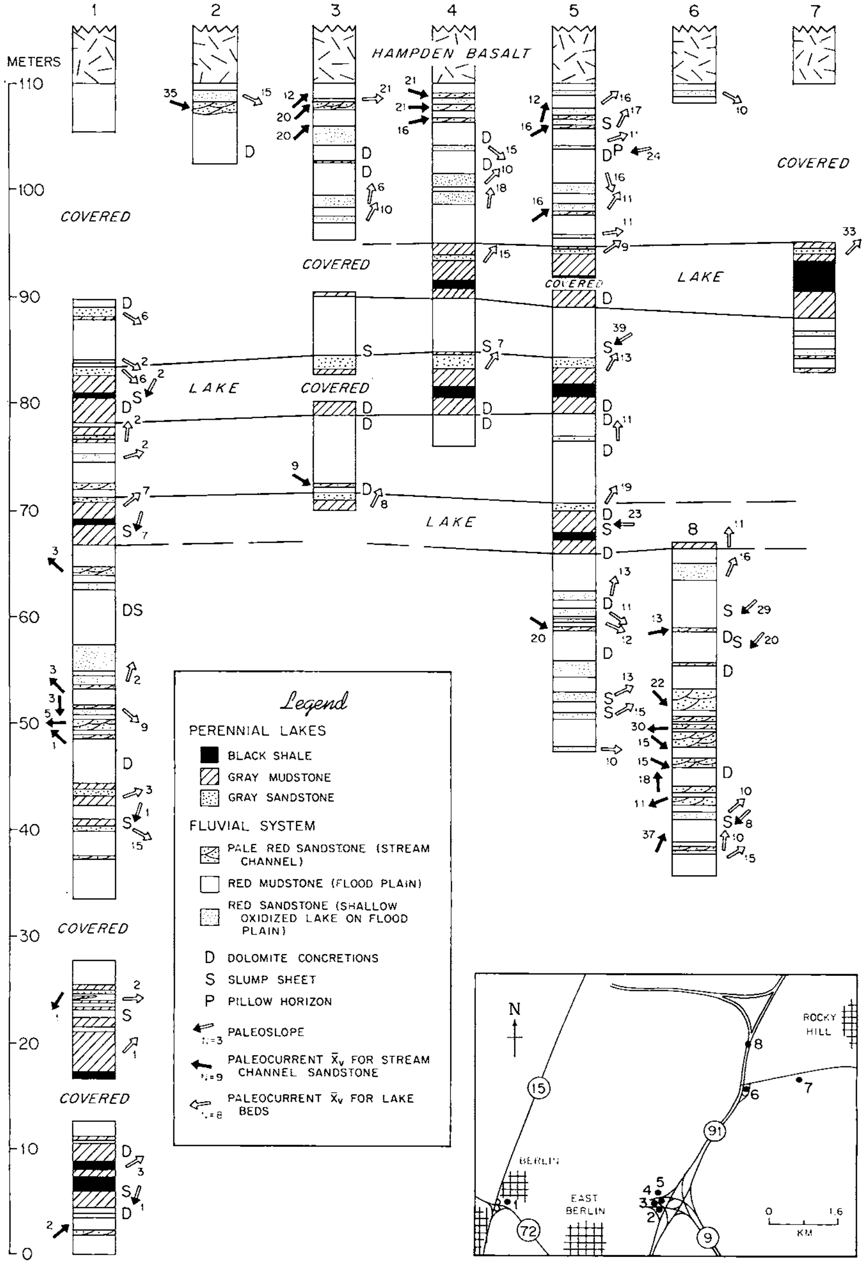


Fig. 2. Stratigraphy, inferred depositional environments, paleoslopes, and paleocurrents for the East Berlin Formation in central Connecticut. Section 1 is the type section, located 16.5 km south of the center of Hartford. Paleoslope directions for lacustrine gray-black beds show the slopes of the floors of perennial lakes. The paleoslopes for the red mudstone with thin sandstone layers are the slopes of the flood plains on the valley floor.

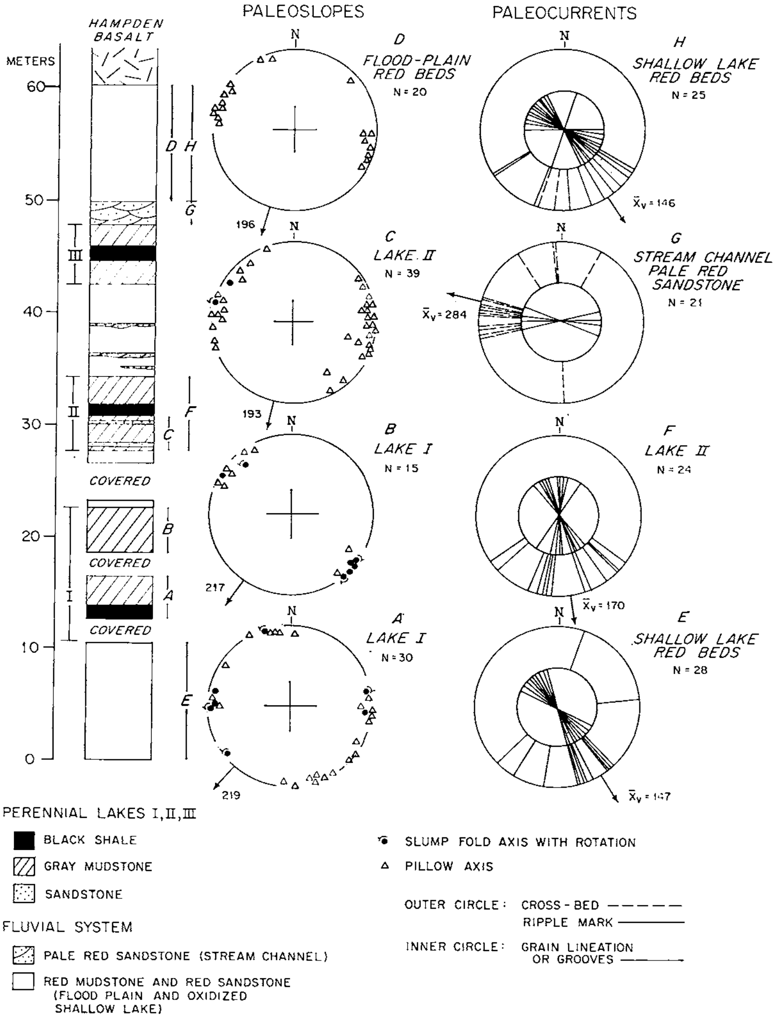
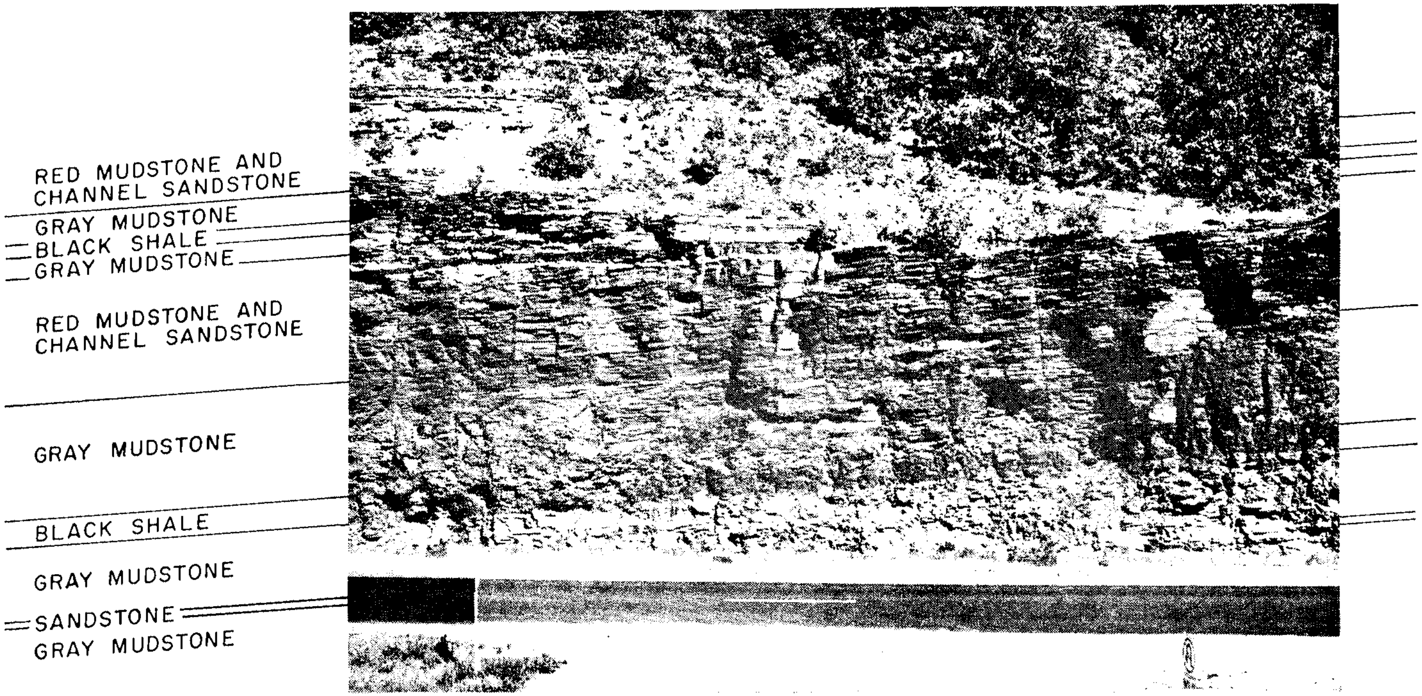


Fig. 3. Rock types and inferred depositional environments in the East Berlin Formation along I-91 at Mountain Park, Mass. The axes of slump folds and pillows are plotted on Schmidt nets with the tectonic dip removed. The southwest paleoslope directions are determined by the sense of rotation of the slump folds. Several 1 to 3 cm lensing beds of algal tufa dolostone occur in red mudstone in the lowest 10 m of the section.

PLATE 1



Lacustrine cycles of gray mudstone-black shale-gray mudstone interbedded with floodplain and shallow lake red beds and pale-red channel sandstone. East Berlin Formation along I-91 at Mountain Park, Mass. The photograph shows the section from 25 to 55 m on figure 3.

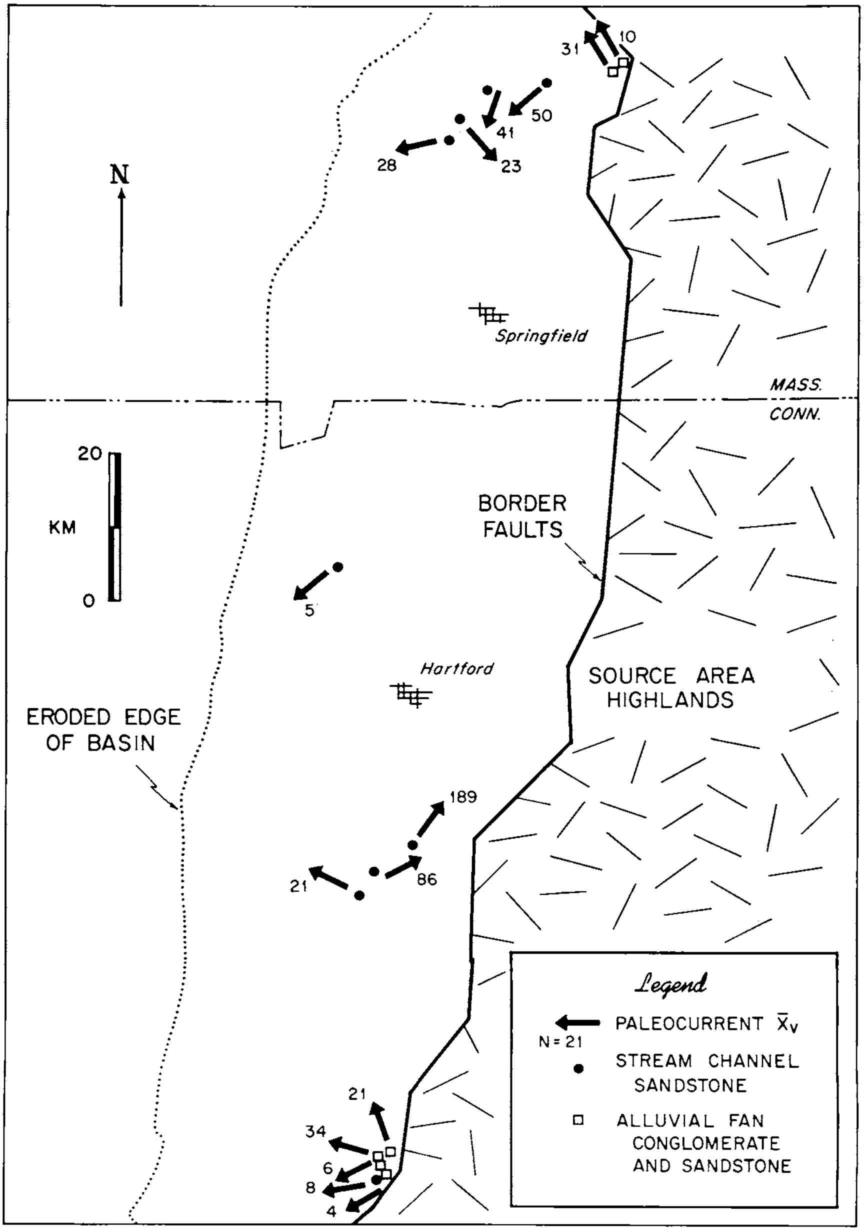


Fig. 4. Paleocurrents and paleoslopes for sandstone and conglomerate deposited in stream channels and alluvial fans of the East Berlin Formation.

metamorphic rocks range up to about 0.5 m in diameter. These coarse-grained sediments were deposited under upper-flow-regime conditions, probably by rapidly flowing, thin sheets of water on alluvial fans that built westward from the fault-bounded eastern escarpment (fig. 4; Krynine, 1950, p. 69; Sanders, 1970, p. 8). Typical outcrops are west of Lake Quonnipaug in southern Connecticut and at the east end of the Holyoke Range in Granby and Belchertown, Mass. Alluvial fans were probably present all along the break in slope between the eastern highlands and the valley floor.

Beds of pebbly sandstone, mostly with horizontal lamination but some with planar cross-beds, are interbedded with red mudstone just west of the alluvial fan deposits. These sections evidently represent braided streams that flowed away from the fans over an alluvial plain. A good exposure is along the power line just east of The Notch in the Holyoke Range, Massachusetts.

STREAM-CHANNEL SANDSTONE

Sandstone bodies with erosional lower surfaces occur throughout the flood-plain sequences of red mudstone. These lensing channel sandstones commonly are about 0.5 m thick, ranging up to 2 m. The pale-red (10R 6/2) sandstones contain intraformational pebbles of red mudstone. A few of the thicker sandstones are interpreted to be point-bar sequences because they fine upward from medium-grained sandstone with festoon cross-bedding to fine sandstone and siltstone with interstratified horizontal lamination and ripples. The thinner sandstone bodies are horizontally laminated with a few festoon or planar cross-bed sets but lack a fining-upward structure.

The paleocurrent vector means of 8 of the 9 outcrops are significant at the 95 percent level when tested by the Rayleigh statistic, demonstrating a preferred orientation. The exception is an outcrop with only 5 readings. The variances within outcrops are large, 1094 to 7544, averaging 3035.

The outcrop vector means for paleocurrents in the channel sandstones generally radiate away from the fault-bounded eastern highlands (fig. 4). The streams flowed northeast at Cromwell and Rocky Hill in central Connecticut; meandering streams are suggested at these localities by the large scatter of azimuth directions.

In general, the streams meandered across the valley floor, as shown by the interbedded red mudstone, fining-upward sandstone sequences, radiating paleocurrent pattern of outcrop vector means, and large variances within outcrops.

FLOOD-PLAIN RED MUDSTONE

Mostly horizontally laminated, grayish-red (5R 4/2 and 10R 4/2) mudstone forms sequences up to 4 m in thickness, the majority being 0.5 to 1 m (figs. 2, 3; pl. 1). The mudstones are interpreted as flood-plain deposits; mudcracks, dinosaur tracks, and raindrop impressions are common. Some horizontally laminated, thin beds graded from sandstone to mudstone evidently reflect sediment that settled from swirling floodwater. Grayish-brown to dusky-brown (5R 2/2 to 3/2) mudstone may have accumulated in organic-rich marshes.

Layers of dolomite nodules are common in the red mudstone (fig. 2). The nodules formed during early diagenesis because mud laminae drape over some of them, others are deformed in slump horizons, and some are reworked as intraformation pebbles in stream channel sandstones. Some of the layers of carbonate nodules seem to be an early stage in the formation of paleosoil horizons where carbonate was precipitated from vadose pore water in the mud. Each layer may have taken a few hundred years to form. At a few localities clusters of gypsum crystals grew in the mud perpendicular to the lamination. The carbonate nodules imply semiaridity with a relatively long dry season and short wet season.

The East Berlin palynoflorule comprises more than 90 percent *Corollina* pollen from conifers that lived most abundantly on sandy areas of the alluvial fans and highlands (Cornet and Traverse, 1975, p. 30). The rarity of xeromorphic cuticular adaptations in the flora, which includes large-leaf forms of *Clathropteris,* plus the many kinds of cryptogams based on spore diversity suggest to these authors a humid savanna climate with a short dry season. The palynoflorule is found in the lacustrine gray mudstone and black shale and records recurring periods of relatively high rainfall that coincided with the existence of large perennial lakes.

The paleoslope directions of the floors of some of the flood plains can be mapped, using slump sheets present in thin sandstones interbedded with the red mudstone. The deformation is not tectonic because the slump folds are bevelled by erosion beneath undeformed strata deposited over them.

Hansen (1966) developed the general solution for determining the slip-line of a slump sheet. He emphasized that an outcrop located anywhere in a slump sheet can be used to determine the direction of movement of the slide. The paleoslope direction is determined by plotting the orientation and sense of rotation of the fold axes on a Schmidt net after the tectonic tilt is removed by rotating the beds to a horizontal position (fig. 5). By convention the clockwise, or counter-clockwise, rotation of each fold axis is plotted looking down the plunge of the axis. The sense of rotation of some folds is indeterminate and only the orientation of the axis is plotted. Although there is substantial scatter in the orientation of the axes, the paleoslope direction is easily determined, if the rotation sense of some of the folds can be recorded. The axes form two groups characterized by clockwise and counter-clockwise rotation of the folds. The axes tend to cluster in two groups which lie along the paleocontour direction. Axes that lie nearly parallel to the slip-line of the slump sheet (paleoslope vector) are especially useful because they more closely define it. The paleoslopes of the flood plains dipped south-

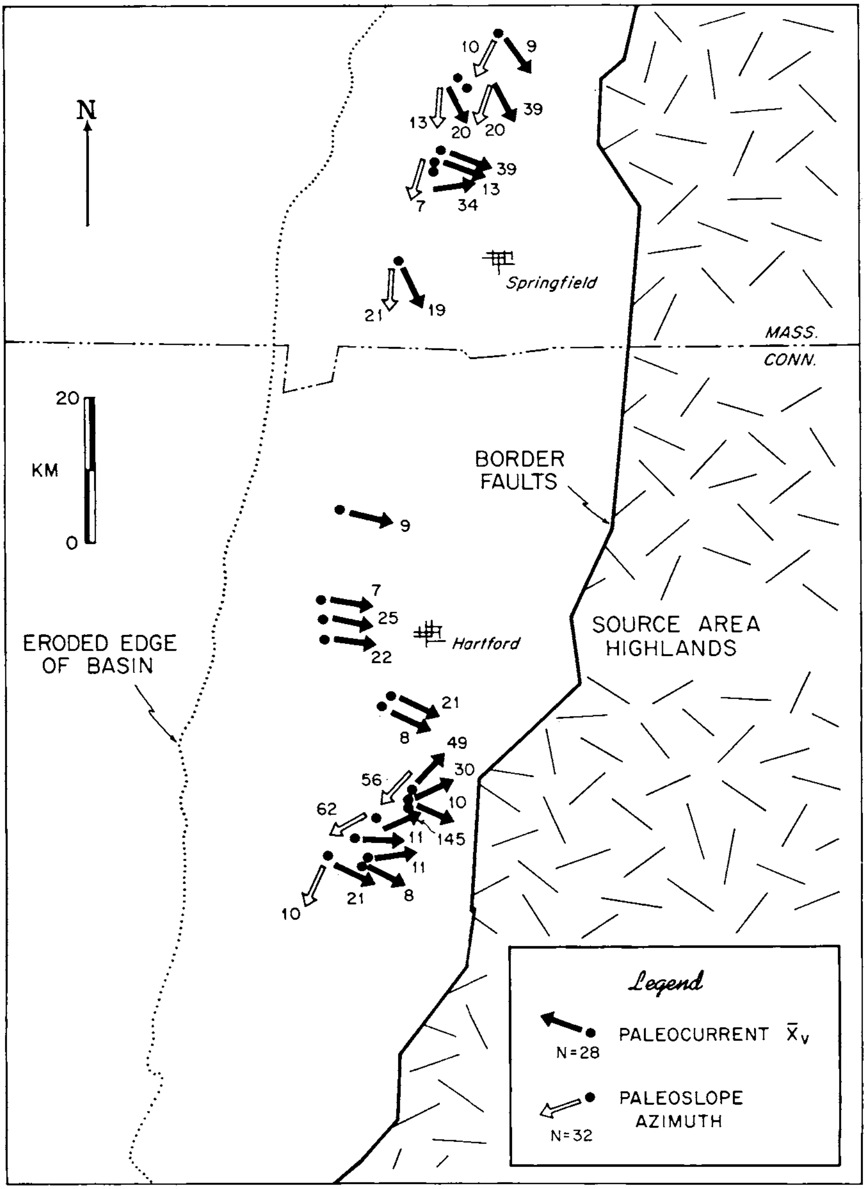


Fig. 5. The paleocurrents are for red sandstone and siltstone deposited in oxidized shallow lakes on flood plains of the East Berlin Formation. The paleoslopes are for flood-plain red mudstone with thin sandstone layers and show the paleoslope of the valley floor.

west, or south, both in central Massachusetts and central Connecticut (figs. 2, 3, and 5).

LACUSTRINE RED BEDS

Thin, even beds of red (pale reddish brown, 10R 4/4; grayish red, 10R 4/2), very fine sandstone and coarse siltstone are interbedded with the flood-plain red mudstone (fig. 2). The tabular bodies contain abundant ripple cross-lamination and vary in thickness from a few centimeters to a meter, with a modal thickness of 0.2 to 0.3 m. The areal extent of the sandstone and siltstone bodies commonly is less than 2 sq km, and they are enclosed within flood-plain red mudstone and stream-channel pale red sandstone (fig. 2). The lower contacts of some of the sandstone and silt-stone bodies are planar surfaces which extend for tens of meters across the outcrops. We interprete the surfaces as the initial lake floors cut into flood-plain mud. Krynine (1950, p. 60) and Sanders (1968, p. 289) also viewed these red beds as having accumulated in shallow oxidized lakes.

Some of the lacustrine bodies show wavy flaser bedding which grades laterally and vertically into starved ripples, making difficult the determination of the boundaries of the lake sequences. Wavy flaser bedding consists of numerous ripple cross-bed sets with discontinuous mud flasers filling troughs and extending as drapes over the ripple crests. With increased mud content, the ripples become isolated to form starved ripples. This suite of structures is characteristic of intertidal and subtidal zones where currents alternate with slack water but is also found in shallow lakes (Reineck and Wunderlich, 1968, p. 104).

Some of the lakes probably persisted for many seasons, but the red color of the sandstone and siltstone implies destruction of organic matter at oxidizing shallow depths and probably lack of permanence. The lakes lay in low areas in the flood basin and were replenished during river flooding.

Grain lineation, grooves, and ripple crests were used to map paleocurrents. With ripple marks cross-lamination indicated the paleocurrent sense. At the outcrop level, the frequency distributions of paleocurrent azimuths tend to be unimodal, with variances from 43 to 6453, averaging 1131. At each of the 21 outcrops the vector mean is statistically significant when tested by the Rayleigh statistic, except for the type section which has only eleven readings.

The paleocurrents that deposited the lacustrine red sand and silt consistently flowed southeast at 18 outcrops in Massachusetts and Connecticut, and northeast at three outcrops near Cromwell and Rocky Hill in central Connecticut (figs. 2, 3, 5, and 6). We interpret the paleocurrents as due to dominant northwest winds that blew over the surfaces of the shallow lakes, generating waves that flowed to the southeast. In central Connecticut, the paleocurrents flowed northeast, east, and southeast, whereas the paleoslopes of the flood plains were to the southwest. Wave refraction evidently oriented ripple crests parallel to arcuate lake shores,

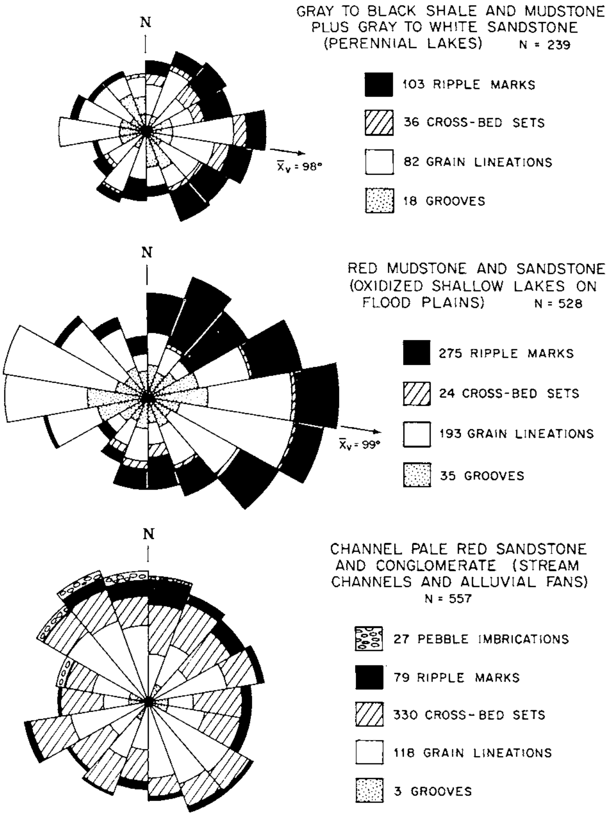


Fig. 6. Summary of paleocurrent data for the East Berlin Formation. No vector mean is calculated for the fluvial sandstone and conglomerate because of the absence of a strong mode in the data.

concave to the northwest, a process commonly observed in modern and ancient lakes (Picard and High, 1972, p. 129).

LACUSTRINE GRAY-BLACK BEDS

Symmetrical lacustrine cycles.—The black shale and gray mudstone are the record of perennial lakes that existed from time to time in the valley during long-term intervals of increased rainfall (Krynine, 1950, p. 35, 60, 160; Sanders, 1968, p. 295; Klein, 1968, p. 14; Byrnes, ms, p. 183). Fossil fish are abundant and large, including representatives of three groups: advanced chondrostean redfieldiids (to 20 cm long), holostean semionotids (to more than 30 cm), and the coelacanth *Diplurus* (to 69 cm) (McDonald, ms, p. 100). At all outcrops, flood-plain red mudstone separates successive lacustrine cycles of gray-black beds.

The black shale (grayish black, N2; dark gray, N3) and gray mudstone (medium dark gray, N4; medium gray, N5) form symmetrical cycles, mostly 2 to 7 m in thickness (fig. 7). The center of each cycle is pyritic black shale which accumulated in the deeper, more central parts of a lake. Above and below is gray mudstone with structures indicative of shallower water, including dolomite concretions, ripple marks, mudcracks, and dinosaur footprints. Dolomite laminae, commonly ferroan dolomite, are present in some of the black shale and gray mudstone (pl. 2). The terrigenous grains in these drab-colored rocks were originally coated with limonite stains which were removed in solution, evidently as organic-ferrous iron complexes.

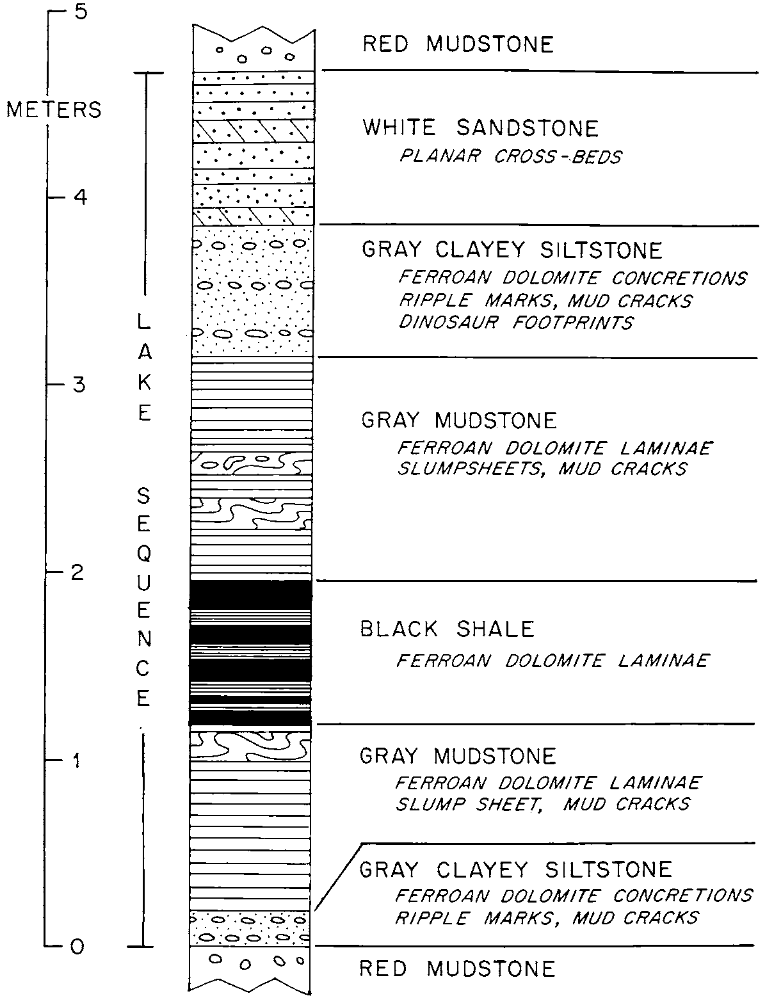


Fig. 7. Perennial lake sequence in the East Berlin Formation at Cromwell, Conn. Fish fossils, spores, and pollen occur in the black shale and gray mudstone.

PLATE 2

Lacustrine black shale and gray mudstone with dolomite laminae, East Berlin Formation, Mountain Park section along I-91, Mass.

Thin beds of gray (medium light gray, N6; light gray, N7) fine- to very fine-grained sandstone occur in the gray mudstone forming intervals of thin-bedded sandstone and gray mudstone that range up to about 1 m in thickness. Most of the sandstone is horizontally laminated, but there are some festoon and planar crossbeds and ripple marks. The sandstones commonly are near the top and bottom of the cycles, implying accumulation in shallow water near the lake shores and in beaches.

The symmetrical cycles of gray mudstone-black shale-gray mudstone require expansion and contraction of perennial lakes. Precipitation on the average exceeded evaporation as each lake initially formed and continued to expand. The larger lakes covered most of the rift valley, nearly filling the tectonic depression. Each lake then contracted to complete the cycle.

Size and depth of the lakes.—The minimum size of one of the lakes can be measured by mapping the areal extent of the horizon of black shale with dolomite laminae that is 28 m below the basal lava flow of the Hampden Basalt in central Massachusetts and central Connecticut (figs. 2 and 3). This black shale also crops out in northern Connecticut southeast of Tariffville in a stratigraphic position 30 m below the Hampden Basalt (Davis and Loper, 1891, p. 427). During construction of the Sugarloaf aqueduct tunnel in southern Connecticut at the northeast end of Lake Gaillard, black shale was encountered 35 m below the Hampden Basalt (Thorpe, 1929, p. 281). Near Long Island Sound at East Haven, the black shale crops out at the south end of Lake Saltonstall, also 30 m below the Hampden Basalt, in a fossil fish locality (Davis and Loper, 1891, p. 427).

The black shale is thus a continuous rock body for at least 108 km in a north-south direction and 20 km east-west. The minimum size of the lake is 2160 km^2. That the lake extended a considerable distance west of the outcrop belt is implied by the consistent west and southwest paleoslopes of the lake floors (fig. 8) and by the west, southwest, and northwest paleocurrents recorded by stream channel sandstone in the westernmost outcrops (fig. 4). Furthermore, the Shuttle Meadow Formation (?) in the Pomperaug Outlier contains beds of fish-bearing black shale (Hobbs, 1898, p. 55; Scott, 1974, p. 34). If the East Berlin lake reached the Pomperaug Outlier, as seems likely, it was at least 44 km wide with an area of 4717 km^2. This is slightly larger than Great Salt Lake. The East Berlin lake was probably substantially larger than 5000 km^2, because it clearly extended beyond existing outcrops into surrounding areas south of East Haven, Conn., north of Mount Tom in Massachusetts, and west of the Pomperaug Outlier.

The depth of the lake can be roughly estimated using an assumed gradient for the lake floor. A gradient of one-quarter of one degree seems a modest value, considering the slope implied by the numerous slump horizons and transgression of the lake over alluvial plain sediments spread away from an active fault scarp. Furthermore, the black shale in

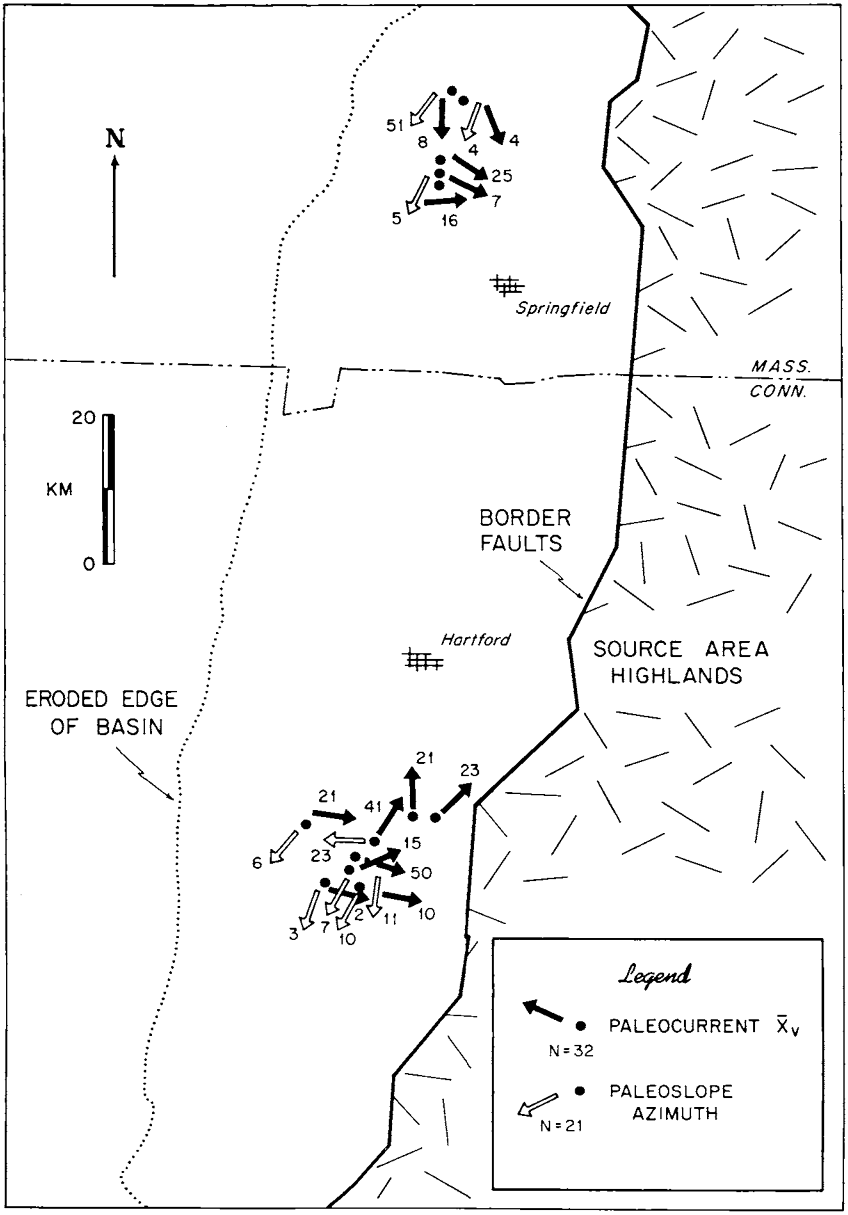


Fig. 8. Paleocurrents and paleoslopes for black shale and gray mudstone and sandstone deposited in perennial lakes of the East Berlin Formation.

the Sugarloaf tunnel is overlain and underlain by coarse gravels with 35-cm boulders, evidently braided stream deposits near, or on, the toe of alluvial fans. The one-quarter of one degree gradient over the minimum of 20 km of southwest-sloping lake floor exposed in central Connecticut implies a depth of 80 m. This value is arbitrary but suggests depths may be conservatively estimated in tens of meters.

Paleoslopes.—The paleoslope directions of the lake floors can be mapped using slump sheets that are common in the lacustrine sequences throughout the Hartford Basin. Similar slump sheets with recumbent folds are found in modern lakes near active faults; some of them can be correlated with specific historical earthquakes (Sims, 1973, p. 163). The outcrops with slump horizons in the East Berlin Formation are within 20 km of the fault-bounded eastern margin of the basin, suggesting that earthquake shocks generated the slides.

A few sandstone beds in the lacustrine sequences are deformed into pillow horizons. The layers of sand foundered into the underlying mud, forming elongate pillows which vary from 2 to 15 cm in width (pl. 3). The laminae are concave upward parallel to the curved exterior of the pillows. Erosion surfaces truncate the curved laminae beneath the overlaying undeformed beds. During sinking of the sand layer, mud flowed upward between the pillows. The pillow axes are subparallel to the axes of slump folds at the same outcrop and thus parallel to the paleocontours of the lake floor (fig. 3).

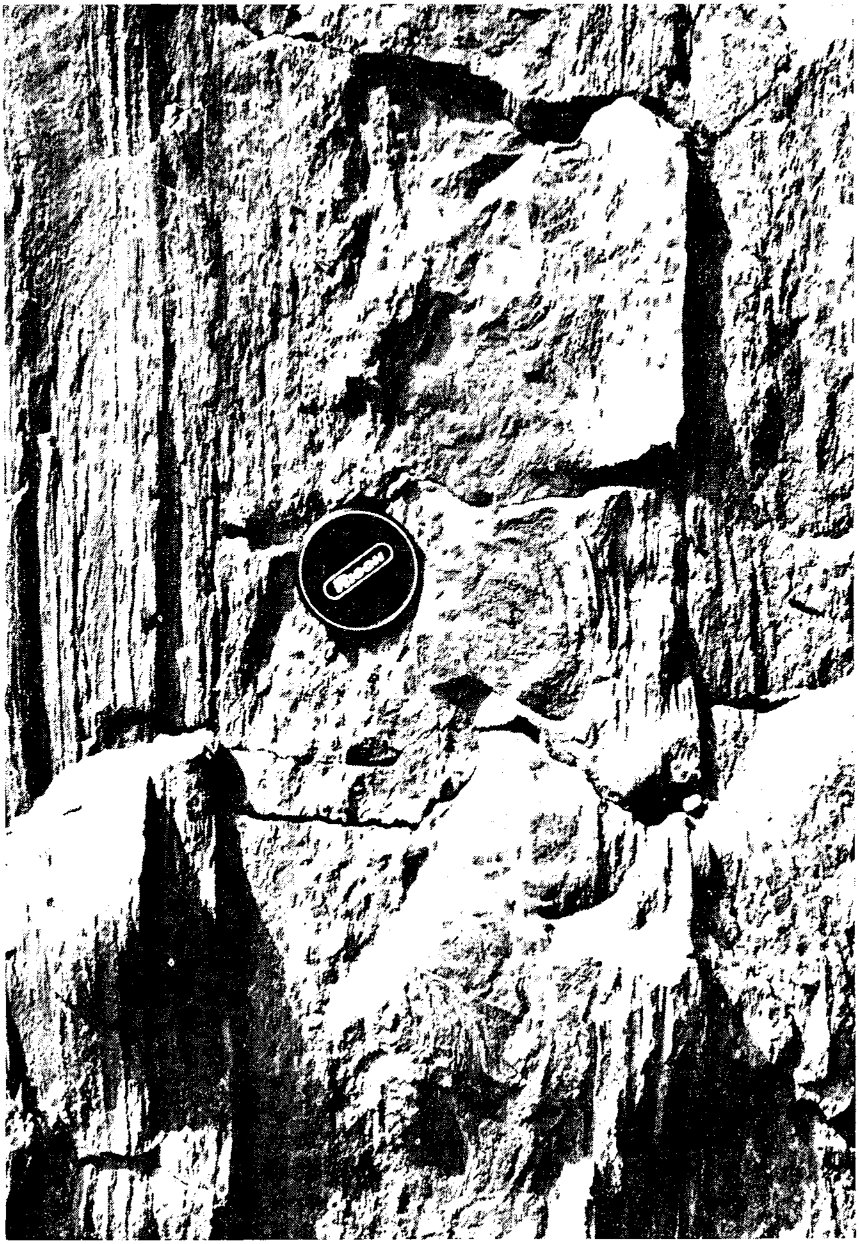
The pillows formed because of downslope tensional stress exerted on the sand layer by the pull of gravity. Pillow formation probably was commonly initiated by earthquakes. Similar pillow structures were used with slump sheets to map paleoslopes in the Cretaceous Cody-Parkman delta of central Wyoming (Hubert, Butera, and Rice, 1972, p. 1656). That paper contains a detailed discussion of pillow horizons.

Where paleoslope data are available for several lake sequences at one outcrop, the paleoslope azimuths are in nearly the same direction (figs. 2 and 3). There is also a striking consistency of paleoslope directions to the southwest for lake floors in Massachusetts and central Connecticut (fig. 8).

Paleocurrents.—The vector mean of the paleocurrents for the gray mudstone and sandstone of the perennial lake sequences at each outcrop were obtained by combining all available readings. The vector mean for each of the thirteen outcrops is statistically significant at greater than the 95 percent level when tested by the Reyleigh statistic, except for one outcrop with only two readings. The paleocurrent readings are mostly from the interbedded gray mudstone and sandstone near the top and bottom of the lake cycles and thus reflect the more shallow, nearshore parts of the lakes.

The paleocurrents in the perennial lakes dominantly flowed to the southeast throughout the valley except locally in central Connecticut where they flowed northeast (fig. 8). We interpret the regional pattern

PLATE 3



Syndepositional pillows in lacustrine sandstone, East Berlin Formation, Mountain Park, Mass.

of southeast paleocurrents as due to paleowinds that blew mostly from the northwest over the surfaces of the lakes. The winds generated wave-driven currents which flowed southeast across the southwest-sloping lake floors.

In Connecticut at Cromwell, Rocky Hill, and Dinosaur State Park, the waves traveled northeast, up the southwest-sloping floors of the lakes. Most of the readings are from shallow-water and shoreline sandstones at the top and bottom of the lake sequences. Wave refraction evidently oriented wave crests parallel to the local northwest-southeast trends of the lake shores (fig. 9).

The paleowinds were dominantly from the northwest both for successive lake cycles at any one outcrop and also for the 108 km from Massachusetts to Connecticut (figs. 2, 3, 8, and 9). The fetch of the lakes is unknown but was probably much greater than the minimum 20 km demonstrated by the outcrops in Connecticut.

There are no bimodal paleocurrent patterns at the outcrop or regional level interpretable as the record of contrasting summer and winter paleowinds. The paleocurrents at each outcrop tend to have a unimodal distribution. The variances range from 382 to 3492, averaging 1551.

Interpretation of regional paleowind patterns for the Upper Triassic to Lower Jurassic is difficult, because data are very limited and widely separated. Before continental drift, the East Berlin paleowinds consistently blew from the northwest. The partly eolian sandstones in the western United States, including the Nugget, Navajo, and Aztec, also record paleowinds from the northwest in the reconstructed continent (Poole, 1963, p. 402; Stanley, Jordan, and Roberts, 1971, p. 13). In northeastern Scotland, Upper Triassic dune sand was deposited by paleowinds from the southeast (120° azimuth) in today's orientation (Craig, 1965, p. 402) but from the east in pre-drift configuration.

The northwest paleowinds in the East Berlin Formation and the western interior of the United States do not fit a simple system of northeast trade winds. This is so even though the warmer, more uniform climate of the early Mesozoic widened and strengthened the trade wind belt as compared to today. Local mountainous relief on the rifting continental landmass may have strongly influenced the planetary surface winds. To interpret what could be complex paleowind patterns, additional data are needed from lacustrine and eolian rocks in Europe, northwestern Africa, and eastern North America.

ORIGIN OF LAMINATED DOLOMITE-BLACK SHALE OR GRAY MUDSTONE COUPLETS

Couplets of light gray dolomite and black shale or gray mudstone occur in bundles in some of the perennial lake sequences (figs. 3, 7; pl. 2). The couplets reflect rhythmic alternation of two contrasting sets of environmental conditions. We infer that each carbonate lamina was

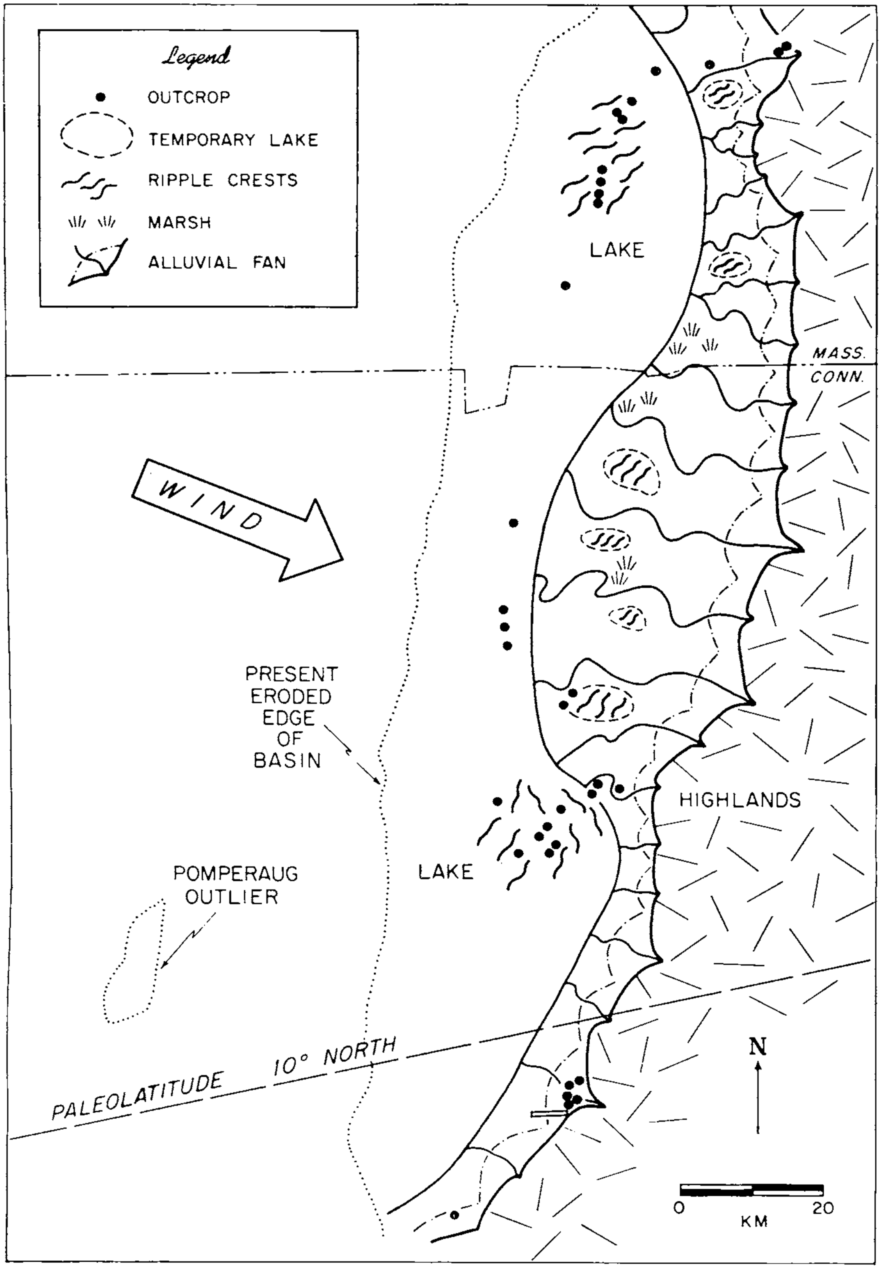


Fig. 9. Paleogeography of the East Berlin Formation at a time of a relatively large perennial lake. At its maximum size, the lake extended eastward to encroach locally on the alluvial fans, as evidenced by the sequence in the Sugarloaf aqueduct tunnel (elongate rectangle).

precipitated during a dry period, when river discharge was low and the lakes received little terrigenous sediment and humus.

The problem of interpretation is whether or not the couplets are varves. The varve hypothesis is suggested by the large size of the lakes, measured in thousands of square kilometers, the inferred depths of some tens of meters, and the less than 1 mm thickness of most of the laminae. In the varve model, each carbonate lamina was precipitated during the dry season of a tropical wet-dry climate, lasting perhaps two to three months. The Hartford Basin at this time was in the tropics at about 10 degrees north latitude (Dott and Batten, 1971, p. 354; Hallam, 1971, p. 139). Counts of couplets indicate a minimum sedimentation rate of 35 to 45 cm of post-compaction sedimentary rock per 1000 yrs. Lacustrine dolomite-black shale couplets in the Shuttle Meadow Formation have been cited as varves by Krynine (1950, p. 161), Cornet, Traverse, and McDonald (1973, p. 1245), and Cornet and Traverse (1975, p. 30).

The alternative hypothesis is that the dolomite laminae, or some of them, are not annual but formed over several consecutive dry years when the rainy season was very short and little detritus reached the lakes. This idea gains support from the observation that the dolomite laminae are poorly defined in places, particularly in the gray mudstone, contain terrigenous clay, and are thicker than 1 mm, suggesting a combination of precipitation and detrital processes. Perhaps some laminae and thin layers of terrigenous clayey dolomite, especially bioturbated layers near the top and bottom of the lake cycles, formed over a span of years in shallow water at or just above the thermocline. Without an independent check on the seasonal origin of the carbonate laminae, such as correlation with tree rings in fossil logs, the rock record unfortunately does not permit the distinction between an annual dry season and a span of drought years. The dolomite laminae in similar rocks ("cementstone") in Carboniferous lacustrine sequences of Nova Scotia have been explained by calcite precipitation during lake contraction in response to prolonged drought (Belt, Freshney, and Read, 1967, p. 720).

Dolomite laminae are not uniformly present in the beds of black shale but form bundles (fig. 7) that may reflect times when the surface waters were relatively more concentrated or a dry season of longer duration. Today in tropical wet-dry climates, a change in annual precipitation is commonly accompanied by a change in length of the dry season.

Couplets of gray to brown, kerogen-rich oil shale-dolomite in the Eocene Green River Formation of Lake Gosiute in Wyoming (Surdam and Wolfbauer, 1975, p. 388) and Lake Uinta in Colorado (Lundell and Surdam, 1975, p. 495) have been explained by a playa-lake model. The playa-lake model is not appropriate for the black shale of the East Berlin Formation because of the absence of typical playa features. Missing are flat-pebble conglomerate of black shale derived by breakup of subaerial mudcracks and interbeds of evaporite minerals, such as trona, nahcolite, halite, and Magadi-type chert. The absence of evaporite beds in the East

Berlin Formation is especially striking and implies that residual brines did not develop with the inevitable filling in and drying up of the lakes.

Whether a varve or not, each nearly pure carbonate lamina in the East Berlin lakes evidently formed during a dry period. At this time there would be a combination of tropical heat, intense evaporation, plant photosynthesis, lack of appreciable rainfall, decrease in terrigenous sediment, and drop in lake level possibly below an outlet if one was present. The elevated surface temperature, high pH, and increased ion concentrations of the surface water would favor precipitation of calcium carbonate. The thickness of a carbonate lamina would vary because of fluctuations in amount of precipitated carbonate and dissolution in the bottom water enriched in CO_2 from decaying plant material.

Mg–calcite was most likely the major carbonate precipitated because of the ease with which the carbonate was dolomitized, leaving no relict calcium carbonate visible in 35 thin sections stained with alizarin red-S. In modern lakes, a Mg/Ca ratio of 2 is adequate to favor precipitation of Mg–calcite with up to 12 mol percent $MgCO_3$ over calcite (Müller, Irion, and Fostner, 1972, p. 161). Calcite and aragonite may have been precipitated at times in some of the lakes.

Rapid dolomitization evidently occurred during burial diagenesis in pore waters with Mg/Ca ratios over 7 and of fairly low salinity, a process known to convert Mg–calcite to dolomite in modern lakes (Müller, Irion, and Fostner, 1972, p. 163; Folk and Land, 1975, p. 63). Precipitation of calcium carbonate from lake water raises the Mg/Ca ratio, so that it is enriched in Mg compared to the inflowing river water. The higher Mg/Ca ratios favor dolomitization of the calcium carbonate in the interstitial pore water during burial diagenesis. Traces of magnesite in black shale of the East Berlin Formation reflect conversion of dolomite when the Mg/Ca ratio exceeded 30, by analogy with modern lakes (Müller, Irion, and Fostner, 1972). Mg-rich pore water is also implied by variable amounts of corrensite (regularly interstratified chlorite–montmorillonite) that formed by post-burial conversion of a detrital expandable clay. The original calcite of ostracod shells is now completely dolomitized.

Some of the gray mudstones have traces of analcime and gypsum plus molds of halite and possibly glauberite. The combined mineral assemblage of the black shale and gray mudstone suggests alkaline, hard-water lakes with abundant Mg^{++}, Ca^{++}, Na^{+} cations and HCO_3^{-} and $SO_4^{=}$ anions. The inferred high Mg/Ca ratios seem reasonable by analogy with the 5.5 to 7.3 Mg/Ca ratios in surface waters of Lakes Tanganyika, Albert, Edward, and Kivu in the Western Rift Valley of East Africa (Beadle, 1974, p. 50).

In the varve model, each black or gray lamina of kerogen-bearing, terrigenous clay accumulated during the rainy season, when swollen rivers brought detrital sediment and humus to the lakes. This is also the time of greatest nutrient availability and lake productivity, yielding the annual maximum of autochthonous organic matter. The thicknesses of the laminae vary, reflecting magnitude of river discharge, availability of detritus, and distance from entering rivers. The absence of grasses on the highland slopes and valleys would promote high rates of runoff, resulting in flash floods and serve erosion of unconsolidated sediment when the first storms announced the start of the rainy season. The initial storms in the wet-dry tropics commonly are violent cloudbursts (Critchfield, 1974, p. 166).

Alternating fine laminae of carbonate and terrigenous clay are best preserved from burrowing organisms in oligomictic and meromictic lakes (Ludlam, 1969, p. 849). The laminae tend to be restricted to depths below the thermocline where the anaerobic hypolimnion prevents destruction by burrowing organisms. With a fetch of more than 40 km, the thermoclines in the East Berlin lakes would be a few tens of meters deep in response to wind mixing. Tropical lowland lakes, unless a few hundreds of meters deep, are mostly oligomictic, the thermally stratified water mixing at infrequent intervals. Mixing commonly occurs either during very high winds accompanying an unusually severe storm or because of warm steady winds blowing over the lake surface in the dry season (Beadle, 1974, p. 73). The wind causes rapid evaporation and cooling of the surface water, so that it is able to mix with the cooler bottom water. After mixing, the tropical heat soon reestablishes a pronounced thermocline, and in a few weeks the hypolimnion is again depleted in oxygen. The brief, infrequent intervals when the bottom water is oxygenated are inadequate for a bottom fauna to become established. The East Berlin lakes were perhaps at times meromictic if deeper than a few hundred meters.

The East Berlin black shale accumulated in stagnant, anaerobic bottom water rich in hydrogen sulphide, as shown by the high organic content, abundant fossil fish, authigenic pyrite, and absence of burrows and fossils of scavenging animals. The fish skeletons commonly are articulated and restricted to certain laminae, suggesting fish kills caused by overturning of stratified water (McDonald, ms, p. 107). The black shale contains about 1 percent organic matter, including aromatic and saturated hydrocarbons (Lawlor, Murphy, and Chapman, 1967, p. 128).

ADDITIONAL FEATURES OF THE PERENNIAL LAKES

Each sequence of black shale and gray mudstone and sandstone records the formation and expansion of a perennial lake followed by its contraction and disappearance. In the tectonic setting of the rift valley, the major control of the cycles seems to have been climatic fluctuations on the order of some tens of thousands of years due to shifting of the transitional boundary between the tropical humid wet-dry and tropical semi-arid climatic belts.

It is not known whether the perennial lakes were closed or throughflowing with spillways because the sequences of gray mudstone and black shale are truncated by Long Island Sound. Also the lakes may have varied from open exit to closed. The available evidence suggests they commonly were closed with waters that were alkaline, of variable salinity and with substantial dissolved Mg^{++}, Ca^{++}, Na^{+}, HCO_3^{-} and $SO_4^{=}$. Especially suggestive are the large volume of carbonate precipitated, extensive dolomitization, traces of analcime, gypsum and halite, abundant authigenic albite and dolomite cements in the sandstones, absence of fragments of gastropods and pelecypods and scarcity of ostracods in thin sections, and the presence of the lacustrine symmetrical cycles.

Some of the dolomitic gray mudstones that enclose the deeper water black shale in the center of the cycles contain traces of analcime and gypsum, plus molds of halite and possible glauberite. These minerals may record concentration of ions in shallow bays or isolated pools during falling lake levels. Prolonged periods of drought may at times have caused lake levels to fall below a spillway, if the lake was not already closed. With no outlet, a drought of even a few years will cause a lake strand to withdraw many kilometers. The absence of beds of evaporite minerals suggests that the main lake bodies were never hypersaline, unlike the large playa lakes with brines that generated analcime-rich mudstone at the top of the lacustrine asymmetrical cycles in the Upper Triassic Lockatong Formation in New Jersey (Van Houten, 1964, p. 509).

During burial diagenesis, the lake and river sands were everywhere cemented by large amounts of pure albite overgrowths on grains of detrital plagioclase. The albite was followed by abundant ferroan and non-ferroan dolomite cement. The albite and dolomite were precipited from the Na- and Mg-rich pore water during burial diagenesis. The petrography of the albite cement is well described by Heald (1956, p. 1148). The youngest cement is calcite, which is mostly confined to faults and joints and is rare in the sandstones.

CONCLUSIONS

Channel sandstones interbedded with flood-plain red mudstone in the East Berlin Formation record streams that flowed westward from alluvial fans along the fault-bounded eastern highlands to meander across low-gradient flood plains. Thin sequences of ripple-marked red sandstone and siltstone accumulated in shallow oxidizing lakes that formed in the flood basin during the rainy season of a tropical wet-dry climate. Cycles of gray mudstone-black shale-gray mudstone record perennial lakes of alkaline, hard water that existed in the valley during long-term periods of increased rainfall. Dominant paleowinds blew from the northwest over the surfaces of the lakes, generating paleocurrents that flowed southeast. Laminated dolomite-black shale or gray mudstone couplets may be varves that accumulated when the perennial lakes were oligomictic.

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