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Wallace W. Hagan, Director and State Geologist

TIDAL-FLAT CARBONATE ENVIRONMENTS IN THE HIGH BRIDGE GROUP (MIDDLE ORDOVICIAN) OF CENTRAL KENTUCKY

E. R. Cressman, *U. S. Geological Survey*
M. C. Noger, *Kentucky Geological Survey*

REPORT OF INVESTIGATIONS 18

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Findings are based on results of the cooperative geologic mapping program between the Kentucky Geological Survey and the U. S. Geological Survey

REPORT OF INVESTIGATIONS 18

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LETTER OF TRANSMITTAL

May 5, 1976

Dr. Wimberly C. Royster
Dean of Graduate School
and Coordinator of Research
University of Kentucky

Dear Dean Royster:

Report of Investigations 18 is based upon information acquired in the cooperative geologic mapping program between the Kentucky Geological Survey and the United States Geological Survey.

This technical geological report is a key to the paleogeography at the time of deposition of these Middle Ordovician sediments. An understanding of the depositional environments that existed at that time may become a useful tool for the professional in search of oil and gas, mineral deposits, and building stones.

Sincerely,

Wallace W. Hagan

Wallace W. Hagan
Director and State Geologist
Kentucky Geological Survey

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TIDAL-FLAT CARBONATE ENVIRONMENTS IN THE HIGH BRIDGE GROUP (MIDDLE ORDOVICIAN) OF CENTRAL KENTUCKY

E. R. Cressman and M. C. Noger

ABSTRACT

Detailed study of surface exposures indicates that carbonates of the High Bridge Group (Middle Ordovician) in central Kentucky were deposited in tidal-flat environments analogous to those of the Bahamas and Florida Bay. Criteria for distinguishing these environments include sedimentary structures, vertical sequence, textures, and composition.

Comparison with other published studies of carbonates of approximately the same age in Alabama, Arkansas, New York, and Ontario indicates that the High Bridge Group of Kentucky is part of a vast complex of carbonate tidal flats that extended over much of the craton of the eastern United States.

INTRODUCTION

In recent years, complexes of supratidal, intertidal, and shallow subtidal carbonate rocks deposited in environments analogous to those of Florida Bay, the Bahamas, and the Persian Gulf have been recognized in many parts of the geologic column. In central Kentucky, much of the upper part of the High Bridge Group (Wilderness Stage of the Middle Ordovician) shows features of tidal-flat deposition. This paper, an outgrowth of the cooperative U. S. Geological Survey-Kentucky Geological Survey geologic mapping program, consists of a description of these features and an interpretation of the depositional environments of late Wilderness time. The area involved is shown in Figure 1. The basic data are from megascopic descriptions of eight measured surface sections (Plates 1 and 2). Locations of the sections are given in the appendix.

We gratefully acknowledge the thoughtful and constructive reviews by G. R. Dever, Jr., of the Kentucky Geological Survey, W. C. MacQuown of the Department of Geology, University of Kentucky, and W. J. Sander of the U. S. Geological Survey.

STRATIGRAPHY

Limestones and dolomites of the High Bridge Group of Middle Ordovician age are the oldest strata exposed in Kentucky. The High Bridge crops out in the gorge of the Kentucky River and the lower part of its tributaries in the southern part of the Inner Blue Grass region where the Kentucky River has entrenched its course across the Cincinnati arch (Fig. 1). The thickest section is near Camp Nelson, where 440 feet (134 m)[1] is exposed above river level (Wolcott, 1969). The base of the High Bridge is not exposed in Kentucky, but information from cores indicates that the entire group ranges from about 550 to 700 feet (198 to 213 m) in thickness in the report area (Wolcott and others, 1972).

The High Bridge Group as exposed at the surface consists of three formations. These are, in ascending order, the Camp Nelson Limestone, the Oregon Formation, and the Tyrone Limestone. The Camp Nelson is dominantly micrite, pelmicrite, and biopelmicrite, all containing abundant dolomite-

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[1] Measurements shown in parentheses are equivalent values expressed in metric units. Abbreviations are: cm, centimetres; km, kilometres; m, metres; and mm, millimetres.

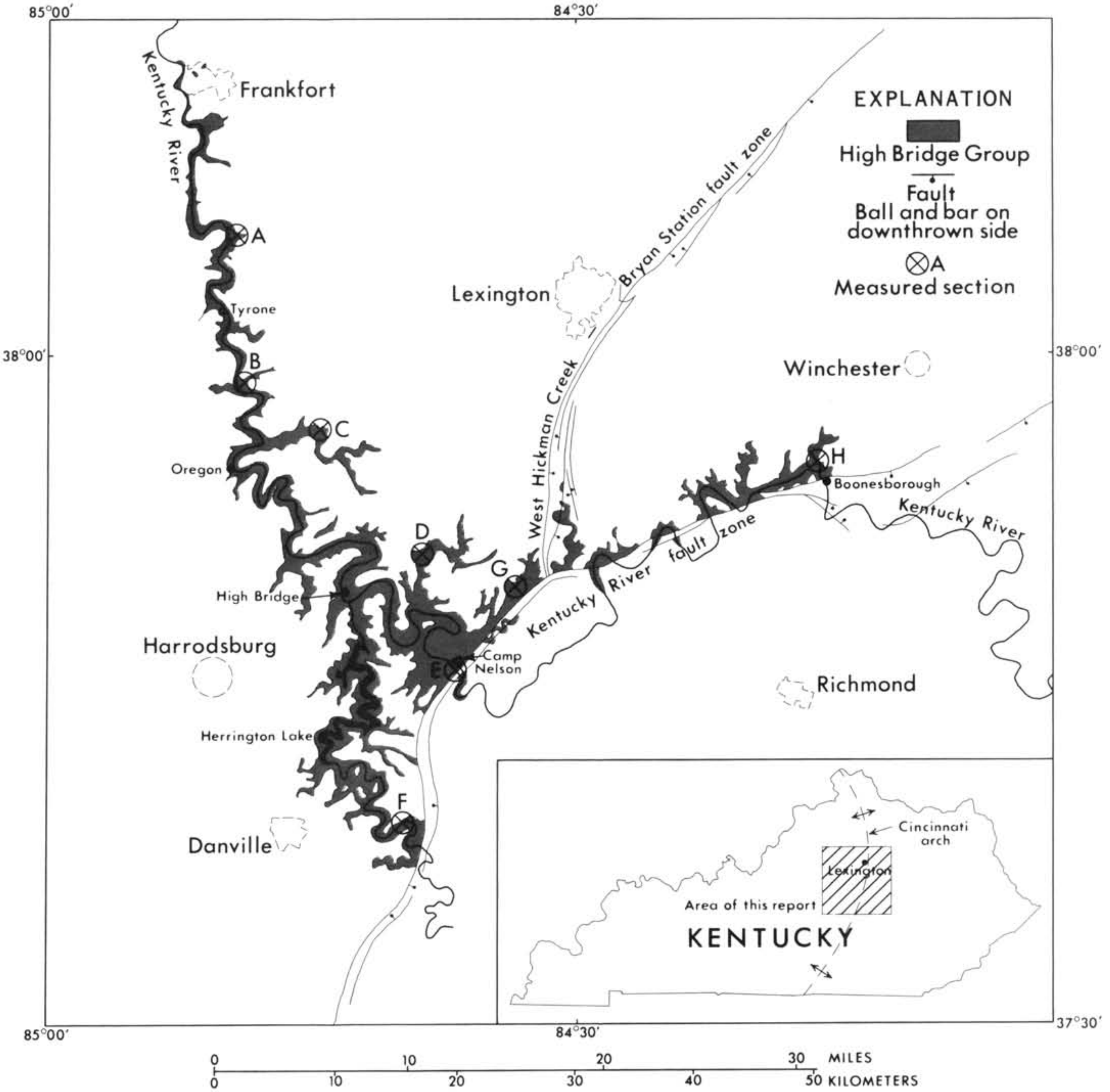

Figure 1. Index map showing outcrop area of the High Bridge Group and locations of measured sections.

filled burrows. Near the village of Camp Nelson, 320 feet (98 m) is exposed above drainage (Wolcott, 1969). The Camp Nelson crops out mostly in cliffs along the Kentucky River, and accessible well-exposed sections are rare; therefore, except for the uppermost few feet, the formation is not considered in this report.

The Oregon Formation is dominantly a finely crystalline dolomite that is interbedded with micritic limestone in much of the area. In sections with interbedded limestone, the contacts of the Oregon are placed at the top of the highest and base of the lowest dolomite bed. The thickness of the formation ranges from 6 feet (1.9 m) near the south end of Herrington Lake (Wolcott and Cressman, 1971) to 65 feet (19.8 m) near Boonesborough (Black, 1968). The base of the Oregon is at about the same stratigraphic position throughout the area, and the thickening results from dolomites occurring higher in the section to the northeast.

The Tyrone Limestone consists of a variety of limestone types and ranges from 55 to 155 feet (17 to 47 m) in thickness. The thicknesses of the Tyrone and Oregon are complementary; where the Tyrone thickens, the Oregon thins. The Tyrone contains several bentonites that are useful for correlation. The "Mud Cave" bentonite of drillers is present locally at the top of the formation. The "Pencil Cave" bentonite of drillers occurs 14 to 20 feet (4.2 to 6.1 m) below the top and is present throughout the area; it is used as the datum for correlation of sections (Plates 1 and 2). The occurrence of a layer of the tabulate coral *Tetradium* within the bentonite at section E, measured near Camp Nelson, indicates that the "Pencil Cave" is a composite of at least two ash falls. Several thinner bentonites are present locally in the Tyrone and upper Oregon and are useful for local, but not regional, correlation.

The High Bridge Group is overlain disconformably by the Lexington Limestone, which spans the Middle-Upper Ordovician boundary (Cressman and Karklins, 1970, p. 21).

Cooper (1956, p. 105-106) placed the High Bridge Group in his Wilderness Stage on the basis of brachiopod zonation. He correlated the Camp Nelson Limestone with the Lebanon Limestone and possibly part of the Ridley Limestone of central Tennessee, and correlated the Tyrone Limestone with the upper member of the Carters Limestone of the same region. Cooper correlated the Camp Nelson with the Witten Limestone and possibly part of the Wardell Formation, and he correlated the Tyrone with the Cane Creek Formation of southwestern Virginia and northeastern Tennessee.

DEPOSITIONAL ENVIRONMENTS

Most descriptions of tidal-flat carbonates distinguish between rocks formed in the supratidal, intertidal, and subtidal environments. Young and others (1972) discussed problems of defining these terms and applying them to ancient rocks. Ginsburg and others (1970) discussed their lack of precision and, on the basis of work in the Bahamas, proposed the use of an exposure index based on the time of subaerial exposure of each environment. We have been unable to find criteria in most rocks of the High Bridge Group on which to assign an exposure index, and we therefore follow the practice of other authors in the use of supratidal, intertidal, and subtidal for designating depositional environments.

We have found the single most useful reference in interpreting environments of deposition of ancient carbonate rocks based on modern environmental studies to be the description of the tidal-flat deposits of Andros Island by Shinn and others (1969). Descriptions of the rock types formed in tidal-flat environments follow.

Supratidal Rocks

Laminated Finely Crystalline Dolomite

The laminae, mostly 0.02 to 0.04 inch (0.5 to 1 mm) thick, consist of alternate layers of coarse and fine dolomite rhombs. The laminae (mostly planar, some crinkled), which are not obvious on fresh surfaces, are more conspicuous on weathered surfaces (Fig. 2) and in thin sections. Lenses and layers of breccia are present locally, and shallow mud cracks probably are more abundant than indicated on Plates 1 and 2. The rock is unfossiliferous.

Interlaminated Micrite and Dolomite

The dolomite laminae are yellowish gray and finely crystalline; the micrite laminae are medium gray to light olive gray (Fig. 3). The laminae, mostly one-half to several millimetres thick, are planar to slightly irregular. Micrite beds several centimetres thick probably record occasional

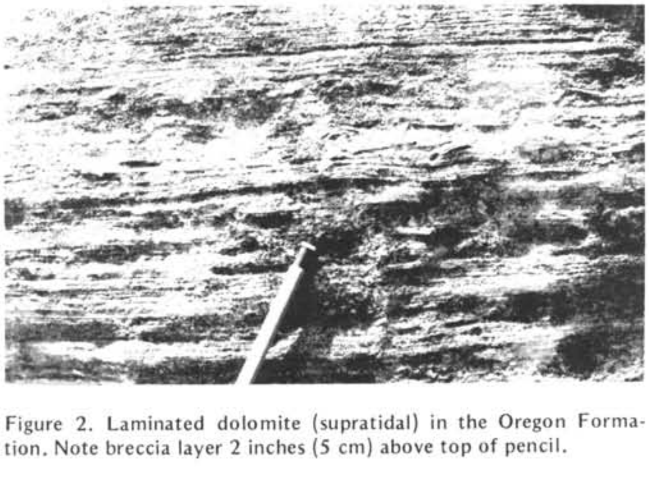

Figure 2. Laminated dolomite (supratidal) in the Oregon Formation. Note breccia layer 2 inches (5 cm) above top of pencil.

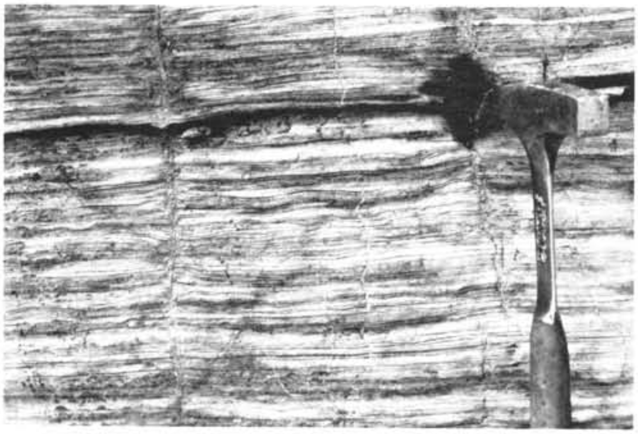

Figure 3. Interlaminated micrite and dolomite (supratidal) in the Tyrone Limestone. Dolomite laminae are dark; micrite laminae are light.

severe storms (Fig. 4). Thin layers and lenses of breccia are common; the breccia lenses fill channels that are mostly less than 5 centimetres deep. Shallow mud cracks are common but not ubiquitous. Mud polygons are mostly 2 to 4 inches (5 to 10 cm) in diameter, but are less than 1.2 inches (3 cm) across on some surfaces (Fig. 5). Vertical tubiform burrows filled with sparry calcite are present in the thicker micrite layers. A few ostracodes may be present, but the rock type is otherwise nearly unfossiliferous. This facies is shown on Plates 1 and 2 as laminated dolomite and micrite.

Laminated Micrite

The micrite is light brownish gray to yellowish gray. The laminae, which range from slightly irregular to crenulated, are defined by slight differences in color. Mud cracks and breccia zones, both similar to those in the interlaminated micrite and dolomite facies, are common. No fossils have been found. Vertical tubiform burrows filled with sparry calcite are present in some layers; fenestral pores (birdseyes) filled with sparry calcite are common locally (Fig. 6).

Figure 4. Interlaminated micrite and dolomite (supratidal) in the Tyrone Limestone. Thicker micrite layers probably were deposited during severe storms.

Laminated Argillaceous, Dolomitic Micrite

This rock type consists of nearly equal parts of clay minerals, very finely crystalline dolomite, and micrite. It is shaly weathering and is rarely well exposed. The laminae are slightly irregular to crenulated, and mud cracks are common (Fig. 7). In the argillaceous unit near the top of the Camp Nelson Limestone, the mud cracks are commonly deep, and the polygons are stacked. Micrite layers several centimetres thick are intercalated in some units.

Figure 5. Mud cracks in laminated micrite and dolomite (supratidal) in the Tyrone Limestone. Pencil is 5.5 inches (14 cm) long.

Discussion

The supratidal rocks are characterized by thin laminations. Laminations, either sedimentary or algal, or a combination of the two, are commonly destroyed in the intertidal and subtidal environments by infaunal activities and, in the case of algal layers, by browsers (Shinn and others, 1969, p. 1205, 1209; Scoffin, 1970, p. 270). Laminae will be preserved in the intertidal and subtidal zones only if extreme conditions, such as high salinity, inhibit the fauna. Mud cracks and birdseye fabric in these rocks are also indicators of the supratidal environment. Most of the mud cracks are of the type that Ginsburg and others (1970) found typical of the upper intertidal and supratidal environ-

Figure 6. Laminated micrite (supratidal) with birdseye fabric in the Tyrone Limestone.

ments (exposure index >50), but the small mud crack polygons (<3 cm in diameter) and the birdseye fabric are common only in the supratidal zone (Shinn, 1968b; Ginsburg and others, 1970).

Gebelein and Hoffman (1971) found magnesium to be concentrated in the algal sheath material of the blue-green alga *Schizothrix calcicola* and suggested that interlaminated dolomite and limestone in ancient rocks may have originated as alternating algae-rich (high Mg/Ca) and sediment-rich (low Mg/Ca) laminae. Friedman and others (1972) reported that algal mats on the margins of a hypersaline pool on the shore of the Gulf of Aqaba secrete high-magnesium calcite that contains as much as 40 percent molecular $MgCO_3$. Magnesium is also enriched in the algal tissues, and the total molecular $MgCO_3$ in the magnesium-organic complex and the high-magnesium calcite combined may reach 60 percent. Friedman and his coworkers suggested that many dolomitized stromatolitic rocks in the geologic record may therefore be the result of the preferential concentration of magnesium by algae rather than the result of dolomitization of originally calcareous material. Their suggestion, possibly applicable to the laminated dolomite, seems particularly apt as an explanation of the laminated micrite and dolomite of the High Bridge Group. It is difficult to conceive of any diagenetic mechanism that could produce the fine lamination of micrite and dolomite illustrated in Figure 3.

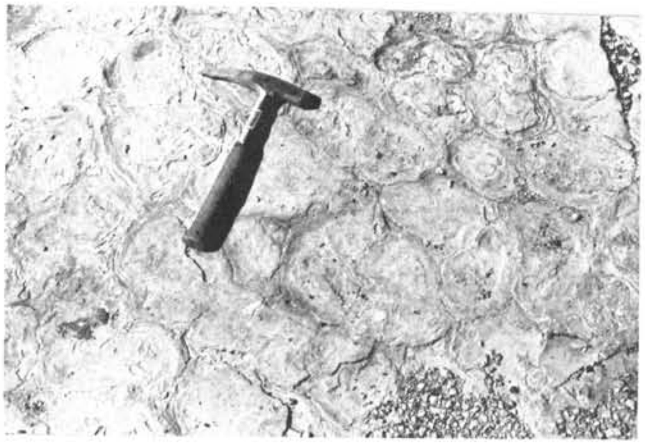

Figure 7. Mud-cracked algal micrite (supratidal) at the top of the Camp Nelson Limestone.

Dolomite in the High Bridge Group commonly occurs as the highest rock type in regressive sequences and is generally underlain by laminated micrite and dolomite. The dolomite seems to have formed on the highest part of the tidal flat; that is, it formed on the part of the flat that was subjected to the longest periods of subaerial exposure. Locally, the micrite laminae in the laminated micrite and dolomite immediately below dolomite beds are partially dolomitized. We suspect, therefore, that the dolomite resulted from dolomitization of laminated micrite and dolomite by the evaporative pumping mechanism discussed by Hsü and Siegenthaler (1971). Dolomite crusts have formed in the supratidal zone of western Andros Island in the Bahamas by replacement of storm-deposited calcium carbonate (Shinn and others, 1965), probably by the evaporative pumping mechanism, but the crusts are only a few centimetres thick, whereas the Oregon contains in places as much as 20 feet (6 m) of dolomite with no interbedded limestone.

Gypsum, anhydrite, and halite are absent from the supratidal rocks of the High Bridge, and there is no evidence that they were ever present. The sedimentary features are more similar to those in sediments of Florida Bay and the Bahamas than to the sabkha of the Persian Gulf. The climate, therefore, was humid rather than arid.

Intertidal Rocks

Micrite Containing Tubiform Burrows

The rock is a light brownish-gray to very light-gray micrite containing scattered pockets of ostracodes, gastropods, and occasional fragments of the tabulate coral *Tetradium*. The characteristic tubiform burrows are perpendicular, or nearly so, to bedding, about 1 mm in diameter, and as much as

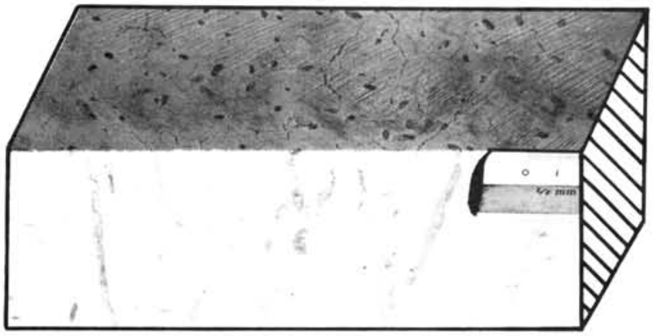

Figure 8. Block of micrite (intertidal) containing tubiform burrows; sample is from the Tyrone Limestone. Lighter colored surface is perpendicular to bedding.

several centimetres long (Fig. 8); they are mostly filled with clear sparry calcite, though some are partly filled with pellets. Some beds are faintly laminated.

Micrite and Interlayered Pelsparite

The micrite, generally light gray, is structureless except for a few vertical tubiform burrows. The rock is largely unfossiliferous except for a few ostracodes. The pelsparite is in discontinuous layers that are generally only a few centimetres thick. A few *Tetradium* fragments and micrite intraclasts as much as several centimetres in diameter may be present in some pelsparite layers (Fig. 9).

Mottled and Interlayered Micrite and Dolomite

The distribution of the micrite and dolomite ranges from irregular alternating layers through seemingly random irregular mixture to aligned flat limestone nodules in dolomite (Fig. 10). Fossils are absent except for a few scattered ostracodes and gastropods. A few bedding surfaces have mud cracks that define polygons 8 inches (20 cm) or more in diameter (Fig. 11).

Figure 9. Pelsparite containing micrite intraclasts (Tyrone Limestone); this lithology may represent a beach deposit. Underlying laminated micrite bed is of supratidal origin.

Figure 10. Oregon Formation consisting of intertidal mottled and interlayered micrite and dolomite (upper two-thirds), and subtidal micrite containing dolomite-filled burrows (lower one-third).

Discussion

The vertical tubiform burrows are generally considered typical of the high intertidal environment (Walker and Laporte, 1970, p. 935). The vertical sequence of rock types in the High Bridge supports this interpretation; micrite containing abundant tubiform burrows commonly occurs between laminated rocks of the supratidal zone above and rocks of the lower intertidal or subtidal zones below. The isolated pockets of gastropods, ostracodes, and coral fragments probably resulted from entrapment of these organisms in erosional depressions during daily tidal fluctuations.

Figure 11. Mud cracks in mottled and interlayered micrite and dolomite (intertidal) in the Oregon Formation. Pencil is 6.3 inches (16 cm) long.

The micrite with discontinuous layers of pelsparite is suggestive of deposition in the lower intertidal zone. The discontinuous pelsparite layers were probably deposited in shallow runoff channels, though a few of the thicker layers may have formed on beaches (Fig. 9). Again, the vertical sequence of this type–commonly between micrite containing tubiform burrows above and fossiliferous subtidal deposits below–suggests deposition in the lower intertidal zone.

The depositional environment of the mottled micrite and dolomite is more problematic. Some exposures of the mottled and layered micrite resemble the aligned limestone nodules in dolomite described by Shinn (1968a) as forming in the supratidal zone by partial dolomitization of mud-cracked lime mud. However, the large mud-crack polygons in this rock type in the High Bridge seem to be of the intertidal type (exposure index 15 to 75; Ginsburg and others, 1970). Furthermore, this rock type commonly lies between subtidal and supratidal rocks.

The mottled micrite and dolomite rock type closely resembles micrite containing dolomite-filled burrows discussed in the section on subtidal deposits, but there are no obvious burrows and no marine fossils in the mottled micrite and dolomite. Some units of intermixed micrite and dolomite cannot be assigned with confidence to either type, mostly because of inadequate exposure, but the two types may be gradational.

Subtidal Rocks

Micrite Containing Tetradium Fragments

The rock is light gray to yellowish gray and in slightly irregular to wavy beds 0.2 to 0.4 foot (6 to 12 cm) thick. Bedding surfaces are inconspicuous or absent in some exposures. Fragments of the tabulate coral *Tetradium* are abundant (Fig. 12), and a few colonies in growth position have been noted. In the plane of bedding, the fragments have no obvious preferred orientation. Ostracodes are common, and gastropods are present in some beds. Thin discontinuous layers of pelsparite may be present.

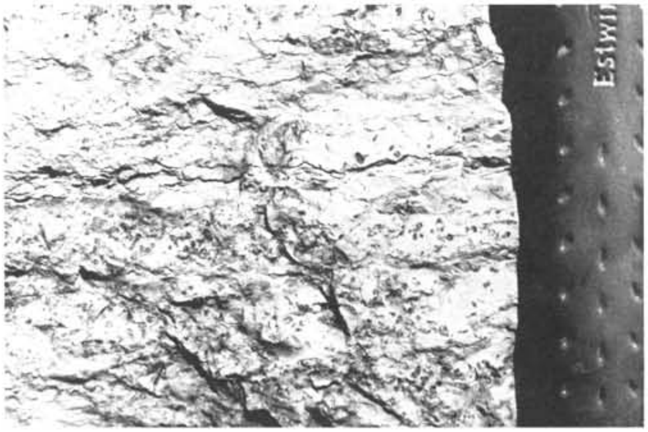

Figure 12. Subtidal micrite containing *Tetradium* fragments (Tyrone Limestone).

Biopelsparite

The fossil fragments in this rock type consist of crinoids, bryozoans, brachiopods, ostracodes, and tabulate corals that may range from a few to half the grains present. The pellets are mostly of coarse-silt to fine-sand size. Glauconite is common in some beds. Most bedding has been destroyed by bioturbation, but crossbedding has been preserved in some units (Fig. 13). The crossbedding is in planar accretion sets less than 6 inches (15 cm) thick. In some exposures the crossbedding appears bimodal.

Micrite Containing Dolomite-Filled Burrows

Dolomite-filled burrows (Figs. 14-16), the striking feature of this rock type, vary considerably in size and shape, but most are about 0.4 inch (1 cm) in diameter and can be classified as full relief feeding burrows (Seilacher, 1964). They are nearly all parallel to bedding. Most have no obvious reg-

Figure 13. Crossbedded biopelsparite (subtidal) in the Tyrone Limestone.

Figure 14. Micrite containing dolomite-filled burrows (subtidal) in the Camp Nelson Limestone.

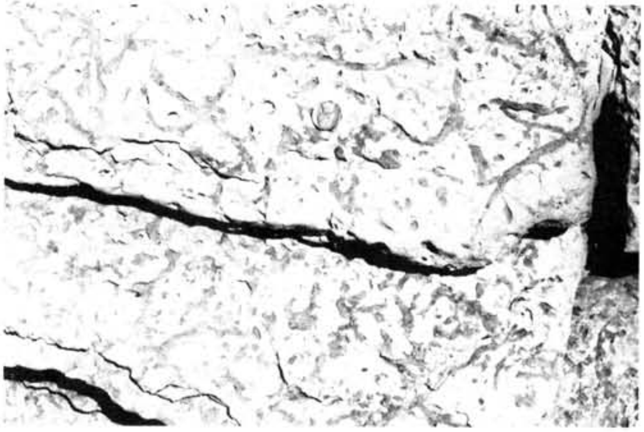

Figure 15. Bedding surface showing dolomite-filled burrows (subtidal) in the Camp Nelson Limestone.

Figure 16. Underside of bed showing dolomite-filled burrows (subtidal) in the Tyrone Limestone.

ular pattern, but some radiate from a common center. The dolomite that fills the burrows is yellowish gray and finely crystalline. The limestone ranges from fossiliferous micrite to packed biopelmicrite; the pellets average about 0.04 mm in diameter. The fossils consist of ostracode valves and fragments of brachiopods, bryozoans, and crinoids; large cephalopods and gastropods are commonly present. In subaerially weathered exposures, the dolomite weathers preferentially, resulting in a deeply pitted surface (Fisher, 1970), but in subaqueously weathered exposures, such as those in stream bottoms, the calcite dissolves preferentially and the dolomite burrow fillings stand out in relief.

Discussion

The fossil content is the basis for assigning most of these rock types to the subtidal environment. The micrite containing *Tetradium* fragments was deposited in a somewhat restricted environment, as shown by the paucity of fossils other than *Tetradium* and ostracodes. *Tetradium* occurs mostly as fragments; the lack of orientation of the fragments indicates quiet water, and the colonies probably disintegrated by biologic processes rather than by water turbulence. Facies relations in the Tyrone Limestone from sections A to E (Plate 1) suggest that at least some of the *Tetradium*-bearing micrite was deposited in the waters on the lee side of a zone of calcarenite bars. We have seen nothing that corresponds to the subtidal wave-baffle community described by Walker (1972, p. 2509). The glauconite, the marine fossils, and the low-angle bimodal crossbedding in the biopelsparite are indicative of subtidal deposition.

The varied fauna in the micrite containing dolomite-filled burrows indicates well-aerated water of approximately normal marine salinity. The predominantly horizontal burrows are also typical of the subtidal environment. We suspect that the burrow fillings are dolomitized because the disrupted sediment in the burrows was more permeable than the surrounding undisturbed material. Wilson (1971), reached the same conclusion for similar rocks in the Chickamauga Limestone of Alabama. The source of the magnesium was probably high-magnesium calcite in the original sediment.

COMPARISON WITH OTHER TIDAL-FLAT CARBONATES

Many features of the High Bridge Group are similar to those of the modern tidal-flat carbonates of the Bahamas, and the similarities indicate a common tidal-flat origin for much of the Oregon Formation and the Tyrone Limestone. The similarities are more remarkable considering the differences between the Ordovician and Holocene biota and the effects of diagenesis and prolonged burial on the Ordovician rocks.

Nearly all sediments of the Andros Island subtidal, intertidal, and supratidal environments consist largely of pellets, most of which are presumably fecal. In the Oregon and Tyrone, on the other hand, pellets are present in only a few of the rock types. Inasmuch as the subtidal rocks of the High Bridge Group bear ample evidence of both an epifauna and an active infauna, we assume that most of the micrites were originally pelleted muds but that the pellets were destroyed during diagenesis. In general, the pelleted texture has been preserved largely in rocks subjected to current action which would have removed the softer, less durable pellets, leaving more indurated ones more likely to survive subsequent consolidation and diagenesis.

The outer portion (1 to 2 miles) (1.5 to 3 km) of the tidal flats of Andros Island is incised by a network of meandering tidal channels that distribute water inland during flood tide and drain the flats during ebb tide. The channels migrate, leaving in their wake regressive sequences consisting of coarse-grained channel sediment overlain by intertidal muds capped by laminated and mud-cracked supratidal deposits (Shinn and others, 1969, p. 1221). Lateral migration of channels is limited to a few hundred feet.

We have not identified any channels in the High Bridge comparable with those of Andros. There are two possible explanations. First, channels may have been present, but we have not recognized their sedimentary fingerprint. A possible example of channel-fill sediments might be the sequence beginning 10 feet (3.1 m) below the top of section F (Plate 1). The basal 0.6 foot (0.18 m) consists of pelsparite with abundant subrounded micrite intraclasts. This bed is overlain by 0.6 foot (0.18 m) of micrite with pelsparite layers containing a few *Tetradium* fragments and abundant gastropods. The succeeding bed is 1.4 feet (0.42 m) of faintly laminated micrite containing common tubiform burrows. The sequence is capped by micrite containing crinkly algal laminations and flat-pebble breccia. The basal 1.6 feet (0.48 m) might represent tidal-channel deposits, and channel migration might have resulted in a stratiform rather than channel-like shape. However, the sequence could equally well have resulted from seaward progradation.

A second explanation might be that the Ordovician tidal flats had poorly developed ephemeral tidal channels and that most of the time tides ebbed and flowed through many shallow rills. We do not know why channels would not have formed, but perhaps in the absence of mangroves that help stabilize intertidal areas today, the distributary and drainage systems would have been considerably different, particularly if the semidiurnal astronomic tides were small.

In comparison with other tidal-flat carbonates of Middle Ordovician age, those of the High Bridge Group seem most similar to those of the Black River Group of New York described by Walker (1972). The major differences are the absence in the Oregon and Tyrone of rugose corals, stromatoporoids, trilobites, and calcareous algae. Walker identified pond and channel deposits in New York that we have been unable to distinguish in Kentucky, and although *Tetradium* fragments are common in some of the Kentucky rocks, we have found nothing to compare with Walker's *Tetradium* wave-baffle community. On the other hand, Walker did not describe any rock comparable to the micrite and pelmicrite containing dolomite-filled burrows common in the High Bridge, though his level-bottom bioclastic lime-mudstone is somewhat similar.

Many similarities are also apparent between the High Bridge and the Joachim Dolomite and Plattin Limestone of northern Arkansas as described by Young and others (1972). However, the Joachim and Plattin do not have rocks similar to the micrite and pelmicrite containing the dolomite-filled burrows, and a more striking difference is that supratidal dolomites of the Arkansas section contain molds of gypsum and anhydrite.

Supratidal rocks of the Black River Group of Ontario were described by Mukherji (1969) as being laminated dolomites containing flat-pebble conglomerate layers and mud polygons; they thus closely resemble dolomites of the Oregon Formation. However, the Black River rocks also contain anhydrite and celestite in the acid-insoluble fraction and calcite nodules that Mukherji (1969) interpreted as secondary fillings of cavities formed by the solution of sulfate minerals.

The supratidal rocks of the Chickamauga Limestone of Alabama have not been described in sufficient detail to permit comparison.

FACIES RELATIONS AND PALEOGEOGRAPHY

Facies relations in the Oregon Formation and the Tyrone Limestone are illustrated in terms of supratidal, intertidal, and subtidal rocks in Figures 17 and 18. The diagrams incorporate some inaccuracies owing to uncertainty in assigning some rocks to the correct environment and to problems of interpolation between sections. We are confident, however, that the major features are correct.

More detailed facies relations are apparent in parts of the section. An example is the zone 12 to 22 feet (3.6 to 6.5 m) below the "Pencil Cave" bentonite in section A (Plate 1). At section A, this zone consists of laminated micrite and interlaminated micrite and dolomite, both supratidal deposits. The zone passes southward into subtidal micrite containing *Tetradium* fragments in sections B and C, subtidal biopelsparite in section D, and subtidal fossiliferous micrite containing dolomite-filled burrows in section E.

The measured sections are too widely spaced to show many facies changes in more detail than in Figures 17 and 18, but vertical sequences indicate the type of facies changes that might be expected. Accordingly, types of regressive sequences noted in the measured sections are listed in Table 1. The variety of these sequences indicates that the vertical position within each of the major environments—that is, the depth below or above mean low tide or mean high tide—was not the only factor that governed the nature of the sediment. Factors such as position with respect to prevailing winds and storm tracks, the local amplitude of tides, and the direction and velocity of tidal currents determined which lithic subtype was deposited at any one place within each of the major environments.

The exposures of the High Bridge Group are too limited to make any detailed analysis of the paleogeography, but it is clear from Figures 17 and 18 that during Oregon and Tyrone time, central Kentucky consisted of a complex of tidal flats and intervening shallow marine lagoons. The varied fauna indicates that normal marine waters had easy access to the lagoons. The tidal flats shifted position from time to time, and during part of Oregon time and in latest Tyrone time, tidal-flat sediments prograded across the entire area.

It seems extraordinary that so much of the Oregon and Tyrone should consist of intertidal and supratidal rocks, inasmuch as these two environments are of limited vertical and areal extent. The source of all the carbonates was, of course, the subtidal zone, and sediments that were finally deposited on the tidal flats were transported there from the subtidal environment. Under optimum conditions, carbonate sediments can accumulate rapidly in the subtidal zone. Cloud (1962, p. 36) found the average rate of accumulation of carbonate sediments on the Great Bahama Bank west of Andros to be 80 cm (31 inches) per thousand years. This is equivalent to 38 cm (15 inches) per thousand years of limestone with a bulk density of 2.7 (Cloud, 1962, p. 91). Angino and others (1969) reported a rate of 200 cm (6.5 feet) per thousand years on Campeche Bank on the Yucatan Shelf.[1] Under optimum conditions, then, carbonates on a stable to slightly subsiding shelf should be able to build up rapidly to near low-tide level.

Supratidal sediments will accumulate only to the height of the highest storm wave, which is generally only a few feet above average high tide (Shinn and others, 1969, p. 1204). If sea level is stable, the tidal flat will then prograde across the shelf as long as there is sufficient submerged area to supply material to the prograding margin of the flat. Renewed subsidence in any part of the area will result in a renewed cycle of rapid subtidal deposition, accompanied and followed by progradation of the tidal flat. As the subtidal area is reduced, the rate of progradation of the tidal flat should be

---

[1] By comparison, the High Bridge Group accumulated at an average rate of 4 cm per thousand years, assuming a total thickness of 200 m (about 650 feet) to the underlying Knox Group (Wolcott and others, 1972) and an age span of 5 million years. Fisher (1962) inferred that the Ordovician stages were each of about 5 million years duration, and we assume that the High Bridge represents all of Wilderness time.

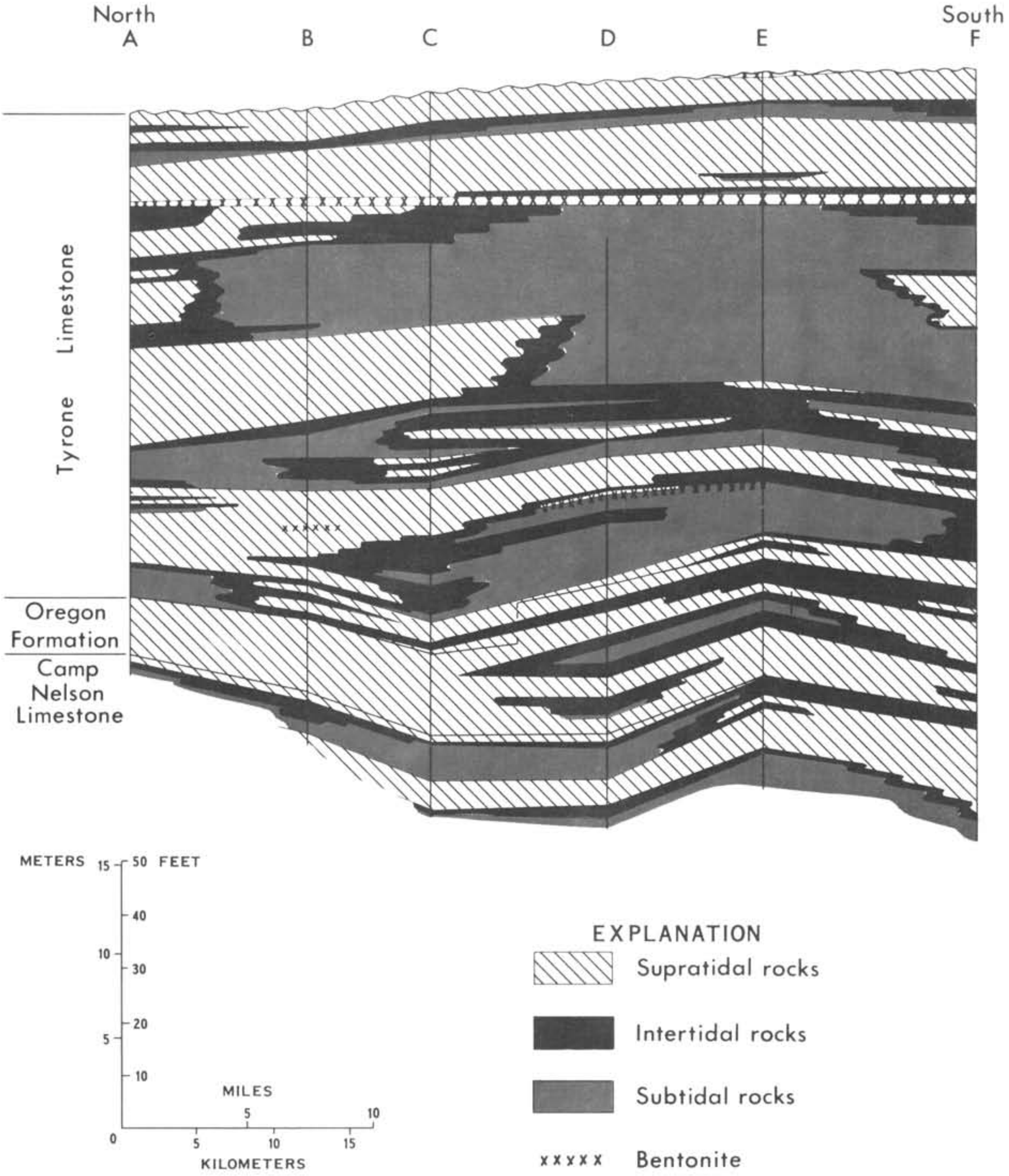

Figure 17. Facies relations in the Oregon Formation and Tyrone Limestone from north to south. Based on columnar sections on Plate 1; locations of sections shown on Figure 1.

reduced. The rate of carbonate deposition will be affected by changes in water circulation and character, which can either be imposed by changed conditions from without the basin or by the changing pattern of tidal flats and basins within. Changing rates of subsidence can be an added complication. All these factors may have combined to produce the complex facies mosaic in the Oregon and Tyrone, and the repeated cycle of rapid subtidal deposition and tidal-flat progradation at least partly explains the abundance of the tidal-flat facies.

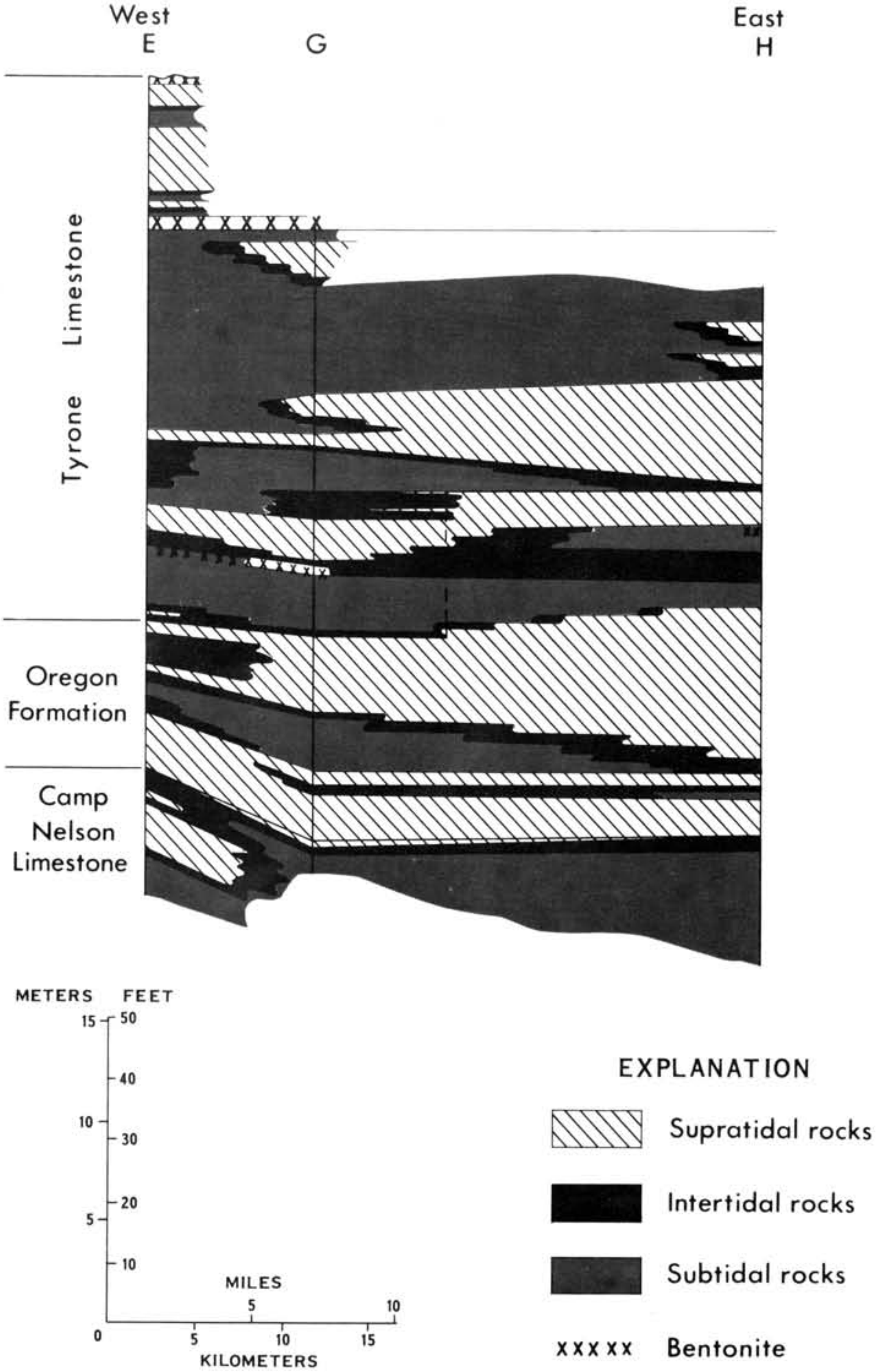

Figure 18. Facies relations in the Oregon Formation and Tyrone Limestone from west to east. Based on columnar sections on Plate 2; locations of sections shown on Figure 1.

As noted previously, tidal-flat carbonates have been described from rocks of about the same age as the High Bridge Group in northern Arkansas (Young and others, 1972), northeastern Alabama (Wilson, 1971), New York (Textoris, 1968; Walker and Laporte, 1970; Walker, 1972), and Ontario (Mukherji, 1969). During the Middle Ordovician, Kentucky was therefore only a part of a vast complex of carbonate tidal flats and lagoons that extended over much of the craton of the eastern

Table 1.—Types of Regressive Sequences in the Oregon Formation and Tyrone Limestone.

[Each column represents one sequence; O denotes presence of the rock type, and the arrow points to the overlying rock type]

Supratidal rocks								
Laminated finely crystalline dolomite			O			O	O	O
Interlaminated micrite and dolomite					O		O	O
Laminated micrite	O	O						
Laminated argillaceous dolomitic micrite				O				
Intertidal rocks								
Micrite containing tubiform burrows	O	O	O	O	O			O
Mottled and interlayered micrite and dolomite							O	O
Micrite and interlayered pelsparite						O		
Subtidal rocks								
Micrite containing *Tetradium* fragments		O	O	O	O			
Biopelsparite	O							
Micrite containing dolomite-filled burrows				O	O	O	O	O

United States. Conditions were not entirely uniform throughout the shelf. In particular, evidence reported by Young and others (1972) and Mukherji (1969) and summarized in the previous section indicates that the climate was more arid in Arkansas and Ontario than in Kentucky and New York. As evidence accumulates, it should eventually be possible to reconstruct an integrated interpretation of shelf sedimentation during the Middle Ordovician.

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APPENDIX

LOCATIONS OF MEASURED SECTIONS

Section A. Composite measured in three parts:

1. Measured in roadcuts and in small abandoned quarry on road 0.7 mile (1.1 km) southwest of Clifton, Woodford County; Tyrone quadrangle. Carter coordinates: 5-S-57; 150′ FWL, 2600′ FNL.
2. Measured in abandoned quarry at Clifton, Woodford County; Tyrone quadrangle. Carter coordinates: 25-T-57, 2400′ FWL, 50′ FSL.
3. Measured in cuts on county roads 0.75 mile (1.2 km) north of Clifton, Woodford County; Tyrone quadrangle. Carter coordinates: 25-T-57; 800′ FWL, 1600′ FNL.

Section B. Composite measured in three parts:

1. Measured in natural exposures on north side of Gilbert Creek, 0.4 mile (0.6 km) west of its mouth, Anderson County; Salvisa quadrangle. Carter coordinates: 6-R-57; 2200′ FWL, 2900′ FNL.
2. Measured in roadcuts south of bridge across mouth of Craig Creek, Woodford County; Salvisa quadrangle. Carter coordinates: 6-R-57; 900′ FEL, 1660′ FNL.
3. Measured in roadcuts on north side of Gilbert Creek, 0.8 mile (1.3 km) west of its junction with Kentucky River, Anderson County; Salvisa quadrangle. Carter coordinates: 10-R-56; 1100′ FEL, 2600′ FSL.

Section C. Composite measured in three parts:

1. Measured in roadcuts on south and north sides of Clear Creek, 0.9 mile (1.4 km) northeast of Mt. Edwin Church, Woodford County; Salvisa quadrangle. Carter coordinates: 20-R-57; 1000′ FWL, 2500′ FNL.
2. Measured in roadcuts and abandoned quarry along Fords Mill Road on east side of Clear Creek, Woodford County; Keene quadrangle. Carter coordinates: 16-R-58; 1450′ FWL, 1450′ FNL.
3. Measured in roadcut 1900 feet (579 m) N. 32° E. of Mt. Edwin Church, Woodford County; Salvisa quadrangle. Carter coordinates: 19-R-57; 300′ FEL, 1100′ FSL.

Section D. Composite measured in two parts:

1. Measured in quarry at High Bridge, Jessamine County; Wilmore quadrangle. Carter coordinates: 3-P-56; 300′ FWL, 2600′ FSL.
2. Measured in two quarries and intervening roadcuts on west side of Jessamine Creek, 1.25 miles (2 km) south-southeast of Wilmore, Jessamine County; Wilmore quadrangle. Carter coordinates: 24-Q-59; 100′ FWL, 1950′ FNL. Position of section below "Pencil Cave" bentonite of drillers based on measurement in quarry at High Bridge.

Section E. Composite measured in three parts:

1. Part below Oregon Formation measured in gully just north of bridge over White Oak Creek; remainder measured in quarry and in roadcuts west of White Oak Creek, Mercer County; Wilmore quadrangle. Carter coordinates: 25-P-59; 900′ FEL, 1900′ FNL.
2. Measured in quarry on west side of U.S. Highway 27, 0.8 mile (1.3 km) southeast of Camp Nelson Bridge, Garrard County; Little Hickman quadrangle. Carter coordinates: 22-P-59; 1900′ FWL, 2700′ FNL.
3. Measured in roadcut on U.S. Highway 27, 0.7 mile (1.1 km) southeast of Camp Nelson Bridge, Garrard County; Little Hickman quadrangle. Carter coordinates: 2-P-59; 100′ FWL, 1800′ FNL.

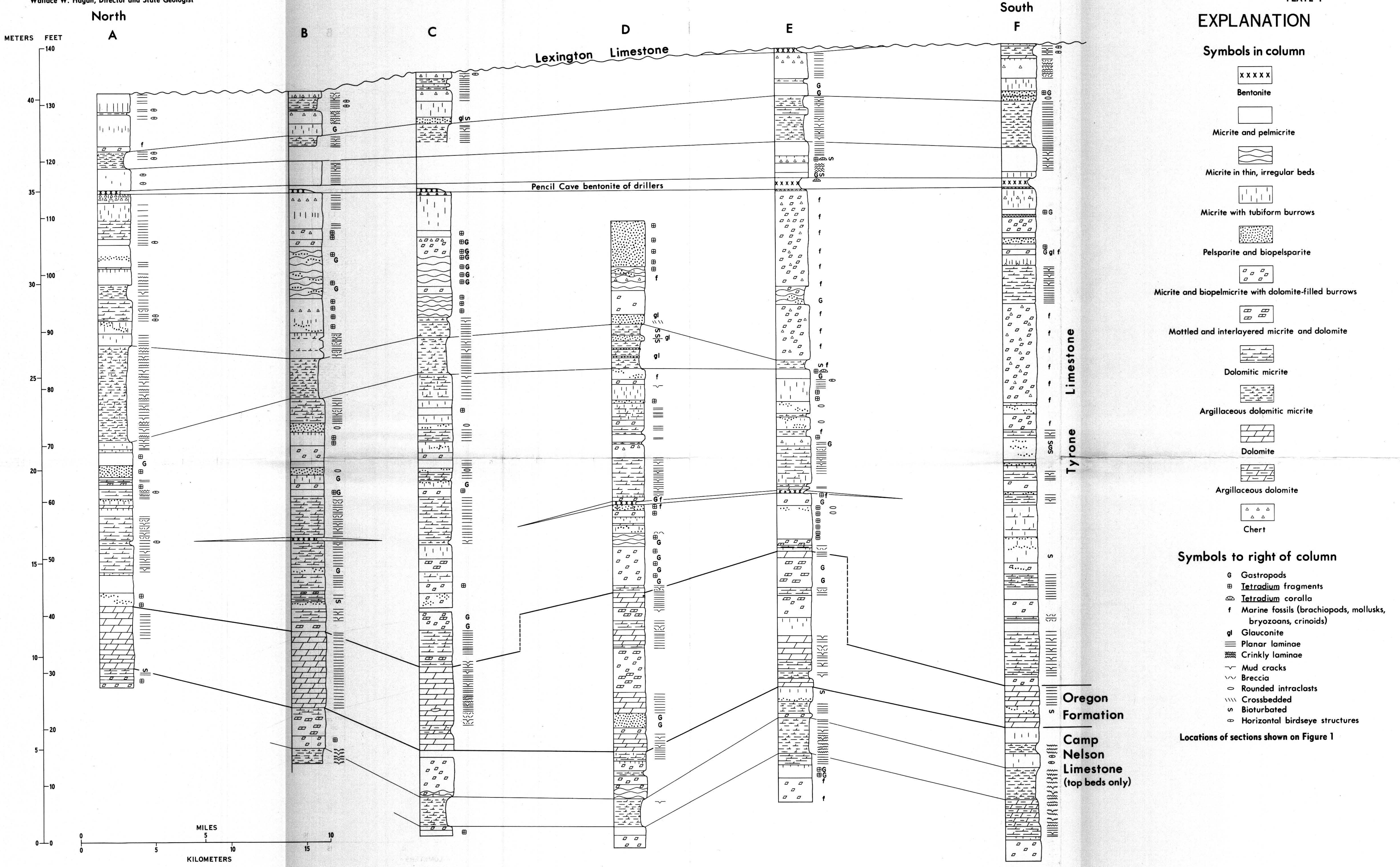
Section F. Composite measured in two parts:

1. Measured from diamond-drill core Humble No. 1 (on file with Kentucky Geological Survey), Boyle County; Bryantsville quadrangle. Carter coordinates: 5-N-59; 700′ FWL, 700′ FSL.
2. Measured in cliff exposures and roadcuts on Ky. Highway 52 on west side of bridge over Dix River, Boyle County; Bryantsville quadrangle. Carter coordinates: 5-N-59; 1500′ FWL, 2800′ FNL.

Section G. Composite measured in roadcuts on Watts Mill Road near intersection with Ky. Highway 39, 0.8 mile (1.3 km) south of Sulphur Well, Jessamine County; Little Hickman quadrangle. Carter coordinates: 4-P-60; 1100′ FEL, 2950′ FNL.

Section H. Composite measured in two parts:

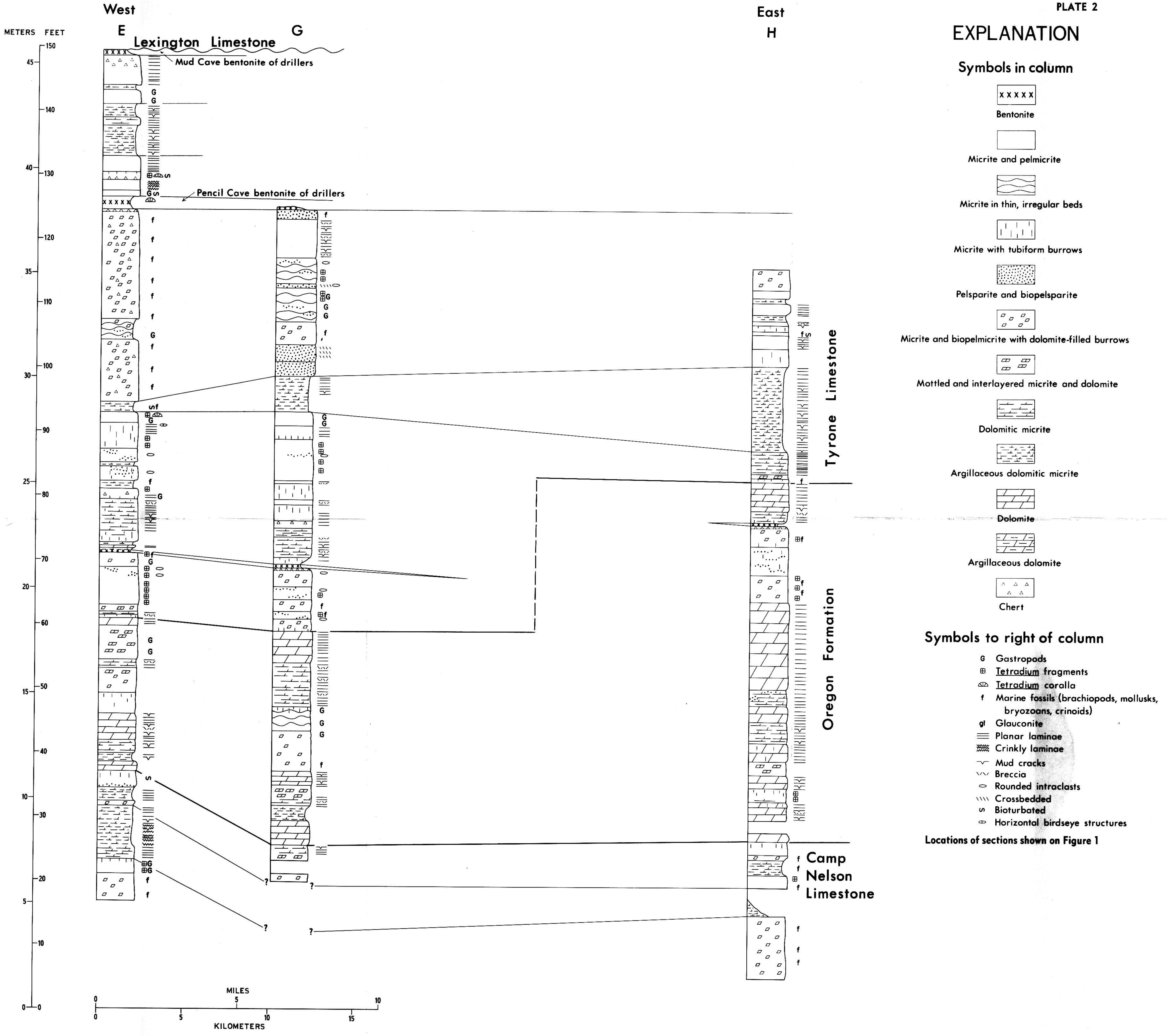
1. Measured in roadcut west of mouth of Howard Creek, Clark County; Ford quadrangle. Carter coordinates: 22-R-63; 2000′ FEL, 700′ FSL.
2. Measured in roadcuts on U.S. Highway 227, 0.25 mile (0.4 km) northeast of bridge over Kentucky River, Clark County; Ford quadrangle. Carter coordinates: 2-Q-63; 100′ FEL, 3100′ FSL. Distance below "Pencil Cave" bentonite of drillers based on diamond-drill core from southwestern part of Winchester quadrangle. Carter coordinates: 5-Q-64; 1720′ FWL, 1720′ FNL.



COLUMNAR SECTIONS OF THE HIGH BRIDGE GROUP (NORTH-SOUTH)

KENTUCKY GEOLOGICAL SURVEY SERIES X
Wallace W. Hagan, Director and State Geologist

REPORT OF INVESTIGATIONS 18
PLATE 2



COLUMNAR SECTIONS OF THE HIGH BRIDGE GROUP (WEST-EAST)