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PALEOBATHYMETRIC ANALYSIS IN PALEOZOIC SEQUENCES AND ITS GEODYNAMIC SIGNIFICANCE

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ABSTRACT. This paper demonstrates the importance of paleobathymetry to an understanding of basin tectonics and presents our approach to bathymetric analysis of Paleozoic sequences. Previous studies of Paleozoic sequences have treated subsidence or bathymetry separately. For an understanding of basin tectonics, the two must be combined. By using chemical, physical, biotic, and stratigraphic bathymetric indicators within an ecostratigraphic framework, we are able to infer absolute as well as relative bathymetric gradients in a Paleozoic sequence in East Tennessee. By combining cumulative sediment thickness and concurrent changes in bathymetry at several points within this basinal and peribasinal sequence, we have calculated subsidence rates for a Middle Ordovician basin and adjacent shelf. Maximum subsidence rates in the basin exceed those of the shelf by a factor of 8.

Paleobathymetric data are used to construct "bathystratigraphic" profiles and paleobathymetric contour maps at four different times during basin evolution. The profiles suggest a polybathic origin for most lithologic units within the sequence. The paleobathymetric maps illustrate changes in basin geometry through time and indicate that the basin "closed" by filling from the south and southwest.

This analysis documents a major Middle Ordovician subsidence event with rates of subsidence greater than 40 cm per 1000 yrs. The timing of this event, in view of inferred rates of sedimentation, suggests a significant time elapsed between subsidence and arrival of sediments from a southern source.

INTRODUCTION

Basinal and peribasinal sediment sequences represent a detailed log of crustal response to sediment loading and other tectonic forces associated with subsidence and basin evolution, as well as a record of deformation and erosion in orogenic source regions. Far too frequently, though, sediment thickness alone has been equated with amount of subsidence in Paleozoic sequences. This approach has been adopted because of the lack of well documented Paleozoic bathymetric indicators. Accurate knowledge of bathymetric changes through time is prerequisite to an understanding of shelf, shelf margin, or basin tectonics. Consequently, geodynamic research on Paleozoic sequences lags behind that on Cenozoic and Mesozoic sequences.

Only by knowing changes in water depth can we analyze subsidence in detail (fig. 1). Despite the importance of bathymetry to tectonics, water depth in Paleozoic sequences remains difficult to quantify, because depth *per se* does not exert any easily recognizable direct influence on sediments or biotas. Paleobathymetric inferences must be based on factors that are indirectly correlated with depth. Many workers have concluded that bathymetric inferences derived from depth correlative factors (for example, based on primary sedimentary structures, grain size, et cetera) are so tenuous that absolute bathymetric data are beyond reach. While we agree that absolute depth in ancient sediments is difficult to determine, establishment of relative depth relationships is feasible. Furthermore, it is a premise of this paper that conclusions reached by using multiple lines of evidence within an ecostratigraphic framework have greater resolution than those derived by using either technique singly.

Cenozoic and Mesozoic bathymetric determination has been more successful than Paleozoic bathymetric analysis. Mesozoic analysis, however, is almost completely dependent on the use of benthic and planktic foraminifera as indices of specific depth ranges (see, however, Eicher, 1969). Without the work of Bandy, Ingle, Arnal, and others, Cenozoic and Mesozoic bathymetric analysis would be quite as difficult as similar analysis of Paleozoic sequences.

In contrast to Cenozoic strata, Paleozoic sediments have no counterpart to the foraminiferal depth indices. Attempts at Paleozoic bathymetric analysis have demonstrated repeatedly that any single criterion contains ambiguities or uncertainties. We advocate a multipartite approach based on suites of bathymetric indicators interpreted within an ecostratigraphic framework. The difficulties of Paleozoic bathymetric analysis do not diminish the need or the inherent utility of such studies. Only by understanding changes in water depth through time can we hope to understand the dynamic evolution of Paleozoic basins.

PREVIOUS WORK RELATED TO PALEOZOIC BATHYMETRIC ANALYSIS AND SUBSIDENCE HISTORIES

Despite the intimate relationship between paleobathymetric development and tectonics of basins, few subsidence studies of Paleozoic sequences have taken advantage of paleobathymetric data. Similarly, few paleobathymetric studies have considered the broader tectonic significance of their conclusions. Most studies involving Paleozoic bathymetric analysis have centered around paleoenvironmental reconstruction or paleoecology. Several studies dealing with specific techniques of determining bathymetry will be discussed subsequently. At this point, however, we wish to con-

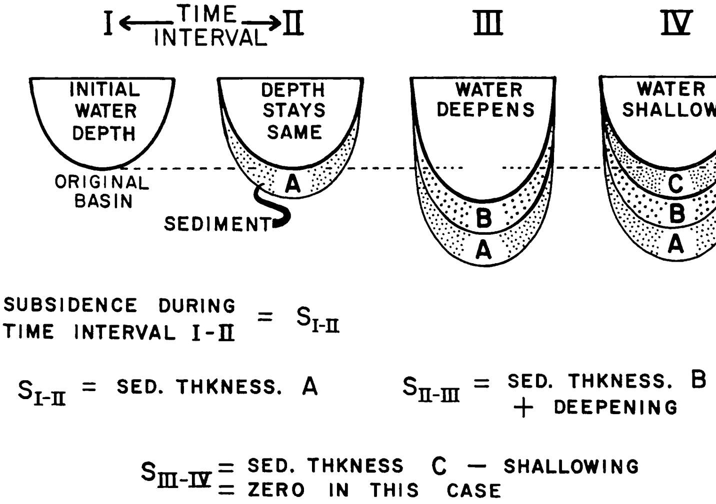


Fig. 1. Subsidence as a function of the interplay between sediment accumulation and changes in bathymetry.

sider five papers dealing in a more general way with Paleozoic subsidence analysis.

Barrell (1917) discussed the controlling influence of subsidence on the development of stratigraphic sequences. Although his treatment was entirely theoretical, he clearly recognized the geodynamic significance of subsidence. He did not mention the need for information on changes in water depth during subsidence for accurate analysis.

Kay (1955) pointed out the important distinction between rates of deposition and rates of subsidence. Subsidence "controls" deposition since total thickness of sediments cannot much exceed subsidence prior to or during deposition. Subsidence can, however, greatly exceed deposition to produce deep-water deposits. Although great sediment thickness requires great subsidence, great subsidence need not result in great sediment thickness.

Acknowledging the importance of bathymetric variation to understanding subsidence, Kay chose to ignore water depth and assumed such changes were insignificant when compared to the total thickness of the sequence studied. This assumption, though reasonable for long term (more than 100 m.y.) subsidence analysis (Burshtar and others, 1970) obscures short term subsidence events that can differ from long term rates by orders of magnitude. The determination of changes in water depth through time will allow recognition of these short term events which may be of great tectonic significance. Kay's data gathered from a variety of stratigraphic sections show long term subsidence rates for Paleozoic sequences ranging from 6 cm per 1000 yrs (Carboniferous of Colorado) to a maximum of 75 cm per 1000 yrs (Lower Devonian of Western New Hampshire). His average rate for Paleozoic sequences is 20 cm per 1000 yrs with eugeosynclinal subsidence rates averaging 30 cm per 1000 yrs and miogeosynclinal rates averaging 13 cm per 1000 yrs.

Multiple lines of evidence and analogy with modern environments allowed Elias (1937) to construct paleobathymetric curves for late Paleozoic strata in Kansas. His interpretations show highly variable water depths with several cycles of change from 0 to 55 m of depth in less than 110 m of section. Elias noted that "isostatic subsidence" due to sediment loading could counterbalance only a fraction of the thickness of sediment deposited (a principle first recognized by Barrell, 1917). Subsequently, he explained the variability of water depth by "nonisostatic epeirogenic" subsidence and possible eustatic sealevel changes.

If we assume that overall subsidence for Elias's sequence was 10 cm per 1000 yrs (20 percent less than Kay's 1955 average for comparable sequences), Elias's bathymetric data imply that the shorter term subsidence events approached rates of 100 cm per 1000 yrs. By this example, we wish to underscore the magnitude of tectonic events obscured, if bathymetry is not considered for shorter term subsidence analysis.

Roeder and Walker (unpub. ms) and Briggs and Roeder (1975), in general discussions of Paleozoic subsidence and sedimentation, point out the resemblance of long term subsidence curves for several parts of the

Ouachitas and Southern Appalachians to empirically derived lithogenetic subsidence curves of Sclater, Anderson, and Bell (1971). Roeder ascribes this congruence of subsidence histories to a "drag effect" imparted upon the continental edge by aging (hence subsiding) oceanic crust.

Briggs and Roeder (1975) calculated Paleozoic subsidence rates for the Southern Appalachians assuming the strata were deposited "near sea level". Hence, they neglected paleobathymetric changes. As demonstrated earlier, this assumption can obscure significant details of subsidence history, even though the long term subsidence rate may be reasonably accurate. Their average rate for the entire Paleozoic at Wildwood Quadrangle, east Tenn. is approx 2 cm per 1000 yrs with an anomalous surge during the Middle Ordovician with averaged rates approaching 22 cm per 1000 yrs. They noted that this anomalously high rate over a period of about 20 m.y. is matched in the modern oceans in the vicinity of subduction zones. We will demonstrate below that short term rates in this region during the Middle Ordovician actually exceeded 40 cm per 1000 yrs.

Subsidence in the Sverdrup Basin (Canadian Arctic Islands) has been investigated by Sweeney (1977). The sequences studied are late Paleozoic to Tertiary in age without a stratigraphic gap greater than 5 m.y. The absence of any "deep water deposits" (Thorsteinsson and Tozer, 1970) and the total thicknesses of the sequences influenced Sweeney to disregard paleobathymetric variation. He also disregards compaction although Burshtar and others (1970) warn against this except when relative subsidence rates are considered on a regional scale (as done in the present paper). Sweeney assumes (from the work of Thorsteinsson, 1961, and Thorsteinsson and Tozer, 1970) that relief in the depositional surface was insignificant, that deposition "kept pace" with subsidence, and that deposition was continuous. With these simplifying assumptions, Sweeney inferred 3 major phases of synchronous subsidence and sedimentation with initial rates of up to 10 cm per 1000 yrs subsequently decreasing exponentially. Such close synchroneity in variable sedimentation and subsidence rates without a time lag has not been documented in other studies known to us. It is possible that shorter term more rapid subsidence events occurred but are obscured by lack of detailed paleobathymetric and chronostratigraphic control.

Unlike the previously discussed papers, this paper will examine a relatively short period of geologic time (less than 20 m.y.), and with paleobathymetric data we will interpret the subsidence history and evolution of an Ordovician basin and basin marginal areas.

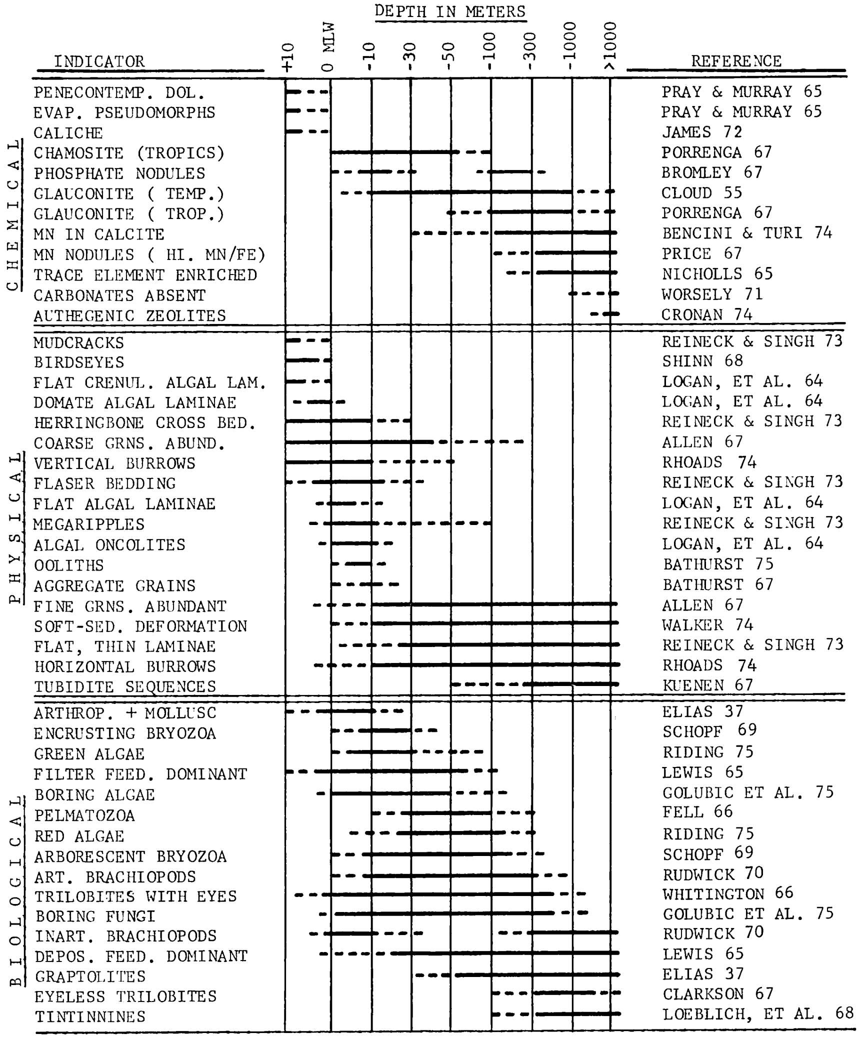
PALEOBATHYMETRIC DATA SOURCES

General Discussion

Paleozoic bathymetric analysis requires not only a system of bathymetric indicators (see table 1 for examples) but also an ecostratigraphic framework for the area of interest. Ecostratigraphic knowledge implies a knowledge of litho-, bio-, and chronostratigraphic relationships in terms of environments of deposition (Hedberg, 1958). Our approach uses bathy-

TABLE 1

Depth ranges of chemical, physical, and biological paleobathymetric indicators used by us in analysis of Paleozoic sequences. The solid part of the bar indicates most common ranges of depth, and the dashed part shows less common depths. More controversial indicators are discussed in the text. No single indicator is valid alone but should be used as a part of a suite. The use of detailed ecostratigraphic analysis is not included in this table but is considered prerequisite to any paleobathymetric study



	INDICATOR	REFERENCE
CHEMICAL	PENECONTEMP. DOL.	PRAY & MURRAY 65
	EVAP. PSEUDOMORPHS	PRAY & MURRAY 65
	CALICHE	JAMES 72
	CHAMOSITE (TROPICS)	PORRENGA 67
	PHOSPHATE NODULES	BROMLEY 67
	GLAUCONITE (TEMP.)	CLOUD 55
	GLAUCONITE (TROP.)	PORRENGA 67
	MN IN CALCITE	BENCINI & TURI 74
	MN NODULES (HI. MN/FE)	PRICE 67
	TRACE ELEMENT ENRICHED	NICHOLLS 65
	CARBONATES ABSENT	WORSELY 71
	AUTHEGENIC ZEOLITES	CRONAN 74
PHYSICAL	MUDCRACKS	REINECK & SINGH 73
	BIRDSEYES	SHINN 68
	FLAT CRENUL. ALGAL LAM.	LOGAN, ET AL. 64
	DOMATE ALGAL LAMINAE	LOGAN, ET AL. 64
	HERRINGBONE CROSS BED.	REINECK & SINGH 73
	COARSE GRNS. ABUND.	ALLEN 67
	VERTICAL BURROWS	RHOADS 74
	FLASER BEDDING	REINECK & SINGH 73
	FLAT ALGAL LAMINAE	LOGAN, ET AL. 64
	MEGARIPPLES	REINECK & SINGH 73
	ALGAL ONCOLITES	LOGAN, ET AL. 64
	OOLITHS	BATHURST 75
	AGGREGATE GRAINS	BATHURST 67
	FINE GRNS. ABUNDANT	ALLEN 67
	SOFT-SED. DEFORMATION	WALKER 74
	FLAT, THIN LAMINAE	REINECK & SINGH 73
	HORIZONTAL BURROWS	RHOADS 74
	TUBIDITE SEQUENCES	KUENEN 67
BIOLOGICAL	ARTHROP. + MOLLUSC	ELIAS 37
	ENCRUSTING BRYOZOA	SCHOPF 69
	GREEN ALGAE	RIDING 75
	FILTER FEED. DOMINANT	LEWIS 65
	BORING ALGAE	GOLUBIC ET AL. 75
	PELMATOZOA	FELL 66
	RED ALGAE	RIDING 75
	ARBORESCENT BRYOZOA	SCHOPF 69
	ART. BRACHIOPODS	RUDWICK 70
	TRILOBITES WITH EYES	WHITINGTON 66
	BORING FUNGI	GOLUBIC ET AL. 75
	INART. BRACHIOPODS	RUDWICK 70
	DEPOS. FEED. DOMINANT	LEWIS 65
	GRAPTOLITES	ELIAS 37
	EYELESS TRILOBITES	CLARKSON 67
	TINTINNINES	LOEBLICH, ET AL. 68

metric indicators to yield probable absolute depth ranges (or relative depths) which are refined by reference to the ecostratigraphy. Implicit in this approach are the constraints imposed by modern oceanographic research such as the JOIDES, Deep Sea Drilling Project.

Lack of knowledge of time stratigraphic relationships are very frequently one of the greatest deterrents to calculating rates of sedimentation or subsidence. Reasonably accurate time relationships must be known to calculate relative rates of sedimentation. Calculation of absolute rates of subsidence, of course, requires some knowledge of absolute chronology, but this can be approximated in certain instances with simplifying assumptions (see, for instance, Sweeney, 1977). Time relationships in this paper are derived primarily from lithostratigraphic observations (Walker, 1977), conodont biostratigraphy (Bergstrom and Carnes, 1976; Bergstrom, 1973), bryozoan faunas (Walker and Ferrigno, 1973), and to a lesser degree brachiopod faunas (Cooper, 1956). Our experience with this Ordovician sequence indicates that the sort of accurate knowledge of local time relationships needed can best be obtained by using physical criteria such as progradational tongues, transgressive-regressive cycles, and bentonites (see Fischer, 1964). Careful field mapping and detailed petrographic study of critical sections (some shown in fig. 2) by several workers have facilitated lithostratigraphic interpretations (Walker, in preparation). These lithostratigraphic relationships provide important geometric constraints on the ecostratigraphic model and help to establish contemporaneity of lithologies. Biostratigraphic data provide a basis for environmental interpretations as well as time-stratigraphic relationships. Studies

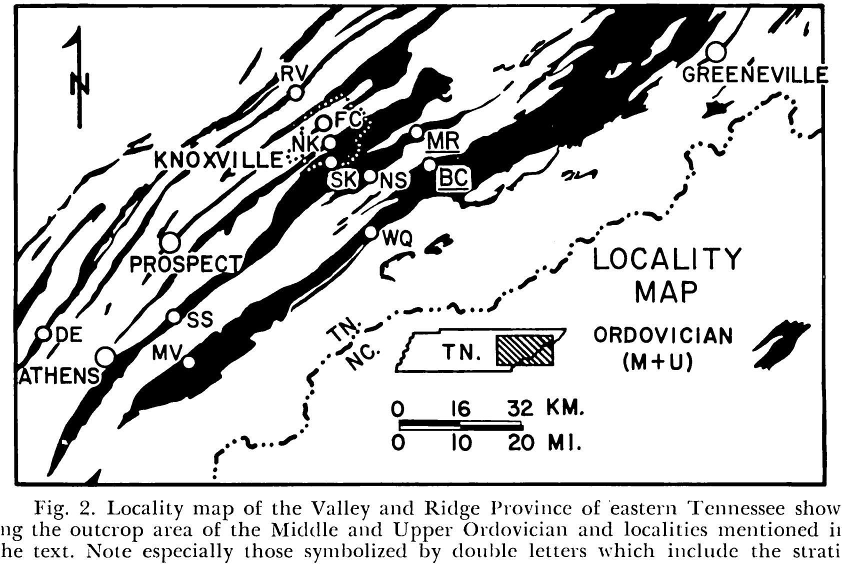


Fig. 2. Locality map of the Valley and Ridge Province of eastern Tennessee showing the outcrop area of the Middle and Upper Ordovician and localities mentioned in the text. Note especially those symbolized by double letters which include the stratigraphic sections shown in figures 5 and 6. *MR* and *BC* are the Midway Road and Boyds Creek stratigraphic sections respectively.

by McLaughlin (1973), Cooper (1956), Bergstrom (1973), Bergstrom and Carnes (1976), Moore (1977), Walker and Ferrigno (1973), Walker and Alberstadt (1973), and Walker (1977) have been valuable in assessing the biostratigraphic complexities of our study area.

Information from the sources above supplemented with unpublished data have been synthesized by one of us (KRW) in the form of stratigraphic cross sections of the Middle Ordovician of east Tennessee. See figure 5 for two of these cross sections and appendix 1 for the evidence on which time lines on these sections are based. The lithologic units shown in these cross sections represent environmental complexes that have been treated by one of us (KRW) elsewhere. The understanding of the stratigraphy in environmental terms has led to a detailed ecostratigraphic framework which provides the constraints within which to cast our paleobathymetric indices.

In any multipartite approach using interrelated conceptual models, the possibility of circular reasoning exists. Our ecostratigraphic framework was developed by constructing an ecologically and environmentally sound model to explain lithotope distributions. Obviously some sense of relative water depths was employed in this modelling. However, we believe that use of supplementary independent bathymetric indicators serves to refine the original ecostratigraphic interpretations rather than amplify mistakes through circular reasoning.

Two sources of error in paleobathymetric analysis remain to be discussed. The first is sediment compaction which may greatly reduce the thickness of sediment sequences after deposition. It has now been demonstrated that lithification of carbonate-rich sediments (such as those analyzed in the present study) occurs very soon after deposition. Because most compaction occurs *shortly* after deposition and before lithification begins, its effects can safely be ignored when dealing with time spans in excess of a few thousand years. In other words, for longer time spans, compaction may be considered essentially contemporaneous with, and therefore a part of, the depositional process. Thus, at any one time, only the uppermost few meters of any developing sequence are in an uncompacted (dilatant) state; the rest have already reached their compacted thickness. For noncarbonate-rich sequences, assumption of very early compaction may not be valid.

The second problem alluded to above is reduction of initial sediment thickness by pressure solution. This aspect of thickness reduction has been discussed in detail by Logan and Semeniuk, 1976. It occurs with greater severity in carbonate sequences but may affect terrigenous clastic sequences to an important degree. In most cases, it is probably reasonable to assume that solutional processes affect most parts of a regional sequence to about the same degree. Thus, the absolute thickness of all parts of a stratigraphic mass would have been reduced, but relative thicknesses and geometric relationships within the sequence would have changed little. Since most solution occurs before lithification, the same argument as noted above for early compaction applies also to solution. In our analyses we ignore the effects of compaction and pressure solution, although we recognize that this may introduce some error.

Bathymetric indicators are of four basic types: (1) chemical, (2) sedimentologic, (3) biologic, and (4) stratigraphic. Each category contains different levels of observations ranging from microscopic observations of single thin sections to regional variations and patterns. In the following sections we will discuss various bathymetric indicators that have been used by previous workers. All are not applicable in every situation, and certainly all were not used in this study. We will emphasize those indicators most useful in Paleozoic bathymetric analysis and, in particular, this study of Middle Ordovician sequences. Any interpretation, to be valid, must be based on suites of indicators viewed within a well understood ecostratigraphic framework. The reader should refer to table 1 in which the inferred depth ranges of many of these indicators are summarized.

Chemical Bathymetric Indicators

Correlation of gross chemical composition and/or trace element geochemistry with depth of deposition have been demonstrated in modern sediments (Ernst, 1970; Degens, 1965; Krumbein and Garrels, 1952; and others). However, as Bathurst (1967) has pointed out, it is easy to think that a particular petrographic or geochemical factor is depth sensitive when we already know the depth. Furthermore, the possible effects of diagenesis are so great that some authors warn that geochemical evidence should never be used to refute contrary evidence from other sources (Nicholls, 1967). Despite diagenesis, certain geochemical criteria, especially if demonstrably primary, are commonly used as indicators.

Numerous studies of sequences of various ages have used phosphate minerals as indicators of particular environmental settings or water depths. Shallow, warm bodies of water, between 30 and 300 m deep represent the most favorable areas for phosphate formation. This is supported by the observation that phosphate-rich interstitial waters in ocean sediments are restricted to depths less than 300 m. Furthermore, organic matter releases almost all phosphate before reaching a depth of 100 m (Bromley, 1967). In modern seas, shallow water environments are typically depleted in phosphate because of phytoplankton activity (Kazakov, 1937; however, see also Bushinski, 1964; and Pevear, 1966).

Abundant phosphate (carbonate fluorapatite) suggests either of two possible environmental settings: (1) very shallow water estuarine environments (Pevear, 1966; Bushinski, 1964), or (2) shelf marginal environments adjacent to zones of oceanic upwelling in warm climates (McKelvey, 1959; Sheldon, 1964; Kazakov, 1937). Thus, the bathymetric implications of phosphate can range from 0 m depth to approx 300 m. If an estuarine environment cannot be demonstrated, phosphate mineralization suggests depths greater than 30 m and, if not transported, less than 300 m. For a general summary and bibliography on bathymetric implications of phosphate refer to Cathcart and Gulbrandsen (1973) or Bromley (1967).

Glauconite and chamosite have also been correlated with specific environmental settings and indirectly to water depth (Porrenga, 1967; Pratt, 1963; Ehlmann, Hulings, and Glover, 1963). Chamosite, in tropical climates, develops in the marine environment to a depth of 150 m though common only above 60 m. Glauconite, though not restricted to tropical climates, develops there only below about 125 m and as shallow as 30 m in cooler climates. It is important to note the temperature sensitivity of these two indicators. Porrenga (1967) has shown that temperatures below 15°C favor the generation of glauconite, whereas warmer temperatures favor chamosite.

In recent years several workers have shown correlations of water depth with trace element geochemistry (Turekian and Wedepohl, 1961; Bolter, Turekian, and Schultz, 1964). However, Nicholls (1967) has shown that pressure changes associated with increasing depth have only a small effect on composition and are inadequate to explain geochemical differences between shallow and deep water sediments. Although Nicholls considers it "unlikely that trace element relationships could be used as absolute depth indicators," the total trace element composition of a sedimentary rock may suggest a deep versus a shallow water origin.

Generally, deepsea sediments are enriched (relative to shallow water sediments) in certain trace elements (notably Cl, Br, Ag, Cd, Mo, Mn, Cu, Co, and Ba). Again, temperature sensitivity plays a significant role in regulating trace element geochemistry as does rate of sedimentation. Nicholls (1967) suggests the possibility of original formation deeper than 250 m, if several of the following concentrations are exceeded in the sediments of interest: Mo greater than 5 ppm, Co greater than 40 ppm, Cu greater than 90 ppm, Ba greater than 1000 ppm, Ce greater than 100 ppm, Pr greater than 10 ppm, Nd greater than 50 ppm, Ni greater than 150 ppm, Pb greater than 40 ppm especially in association with U less than 1 ppm and Sn less than 3 ppm.

Manganese may prove to be another promising geochemical indicator in ancient carbonate sequences. Originally shallow water carbonates rich in aragonite at the time of deposition are likely to be poor in Mn, because Mn is not "tolerated" as a substitute for Ca in the aragonite structure. Friedman (1968) and Thompson (1972) show that marine aragonite contains less than 20 ppm Mn. Deeper water calcite rich carbonate sediments in modern environments can contain several percent Mn substituted for Ca in the calcite lattice (Deer, Howie, and Zussman, 1962; Stehli and Howie, 1961). Thus, Mn content of carbonate sediments should be indicative of relative bathymetry. Bencini and Turi (1974) have applied this reasoning to bathymetric studies of Mesozoic carbonates. Their article gives a thorough discussion of procedure as well as theory for this indicator.

Few bathymetric indicators yield depth information for deep oceanic environments (greater than 2000 m). The most frequently mentioned chemical indicator for abyssal depths is the absence of calcium carbonate sediments below the carbonate compensation depth. However, the carbonate compensation depth is a dynamic, indistinct boundary that responds to climatic, biologic, and chemical changes in the hydrospheric-atmospheric system. The CCD is not a "boundary" of calcite solubility but rather a zone within and below which the *rate* of solution increases significantly (Peterson, 1966). The zone has been called the calcium-carbonate lysocline (Berger, 1960). The level of the CCD is controlled by the rate of carbonate supply to and removal from the oceans (Ramsay, 1974). Hay (1970) demonstrated the great variability of the CCD during the Cenozoic. Fluctuations as great as 1000 m occurred several times with one event bringing the CCD into the photic zone nearly to sealevel (see also Worsley, 1974). Furthermore, several authors have shown that the modern CCD is a surface of complex topography influenced by the productivity and fertility of the overlying water column (Tracey and others, 1971; Berger and Winterer, 1974). In areas (or times) of high rate of pelagic calcareous shell production, carbonate "fallout" locally depresses the CCD below regional average (Heezen and others, 1973). However, in the overall oceanic-atmospheric system, a high rate of removal and storage of $CaCO_3$ in sediments leads ultimately to an elevated CCD (Broecker and Broecker, 1974). Therefore, times of maximum transgression and removal of $CaCO_3$ by organisms in Ordovician epeiric seas may have produced an elevated CCD. "Paper-thin" laminated noncarbonate, black shales, such as the Normanskill shale of the New York Ordovician, may owe their lithologic nature to periods of an elevated CCD that allowed $CaCO_3$ dissolution at depths of 2500 to 3500 m.

Sedimentologic Indicators

There are numerous primary sedimentary structures indicative of shallow environments of deposition. Peritidal carbonate deposits in particular are characterized by a suite of primary structures including desiccation cracks, mudcrack polygons, fenestral fabric (birdseyes), caliche deposits, and mudchip conglomerates (we use *peritidal* to indicate the zone ranging from a few meters below mean low tide to a few meters above high tide). Discussion of these and other physical peritidal indicators can be found in Ginsburg (1975) and Reineck and Singh (1973).

Inference of absolute depths below the peritidal zone based on sedimentary structures is quite difficult. In the present state of knowledge, absolute water depths can only be estimated from gross geometric relationships of consanguineous facies (Allen, 1967). Because sedimentary structures and textures are more dependent on the power of fluid flow than on depth, they are generally only guides to relative depths. Nevertheless, suites of sedimentary structures or textures, especially in known depositional systems, can provide probable depth ranges or indicate bathymetric trends.

Allen (1967) has demonstrated the change from coarser grained nearshore marine facies to offshore deeper marine mud facies. This trend can, of course, be modified greatly by local current conditions, submarine slope, and available sediment sizes. Associated with this textural change is a change in sedimentary structures. Evenly laminated clean sands in cross-cutting sets with scoured bases, ripple laminated sands, and ripple marked bedding surfaces are common in Allen's "inshore shallow water facies." His "intermediate depth zone" is characterized by interbedded sand and mud facies with ripple laminations and wave-current ripples. Allen's deepest "mud facies" (silt-clay grain sizes) is relatively barren of macroscopic sedimentary structures.

Organosedimentary structures, especially those of algal origin, are useful for shallow depths. Logan, Rezak, and Ginsburg (1964) have summarized the environmental and bathymetric distribution of algal lamination morphologies in modern environments. Although most forms are abundant only in the tidal zone and allow detailed bathymetric subdivision of ancient supratidal and intertidal deposits, these features extend into the subtidal. Spherically laminated algal structures (oncolites) are abundant today only below the intertidal zone to depths of 10 m. When present in abundance in an ancient sediment, these are probably the most reliable indicator of the shallowest subtidal depths.

The identification of thick turbidite sequences is almost unquestionably an indication of "deeper" water environments. Although absolute depth is equivocal, an understanding of adjacent environments and slope geometry can allow estimation of depth (Taylor and Cook, 1976). In this issue, Shanmugam and Walker discuss complex suites of microscopic sedimentary structures indicative of ultradistal turbidite deposition, probably indicating deep basin.

Biologic Indicators

Autecological indicators.—Many studies reveal that specific modern organisms are associated with certain depth zones of the marine environment (Heezen and Hollister, 1971). It is easy to reach this conclusion concerning a modern taxon, when we *know* the depths from which our samples were taken. It is unfortunate also that the modern distribution of certain taxa has been assumed to be identical to ancient related taxa. To assume that an extinct species of a genus had the same environmental or bathymetric distribution as living members of that genus is a strong test of faith. This approach has been called "transferred ecology" by Lawrence (1971) and is very tenuous at best. We lack a "paleobathymeter" against which to calibrate organismal distributions. There are virtually no known *a priori* depth indicators among organisms. In fact very few studies have dealt with systematic changes in morphology of single species or genera with respect to depth (see, however, Schopf, 1969 and 1976; Golubic, Perkins, and Lukas, 1975).

Perhaps a more promising technique lies in functional morphologic studies similar to those of Rudwick (1970). These studies will be difficult because few morphologic adaptations (except in eurybathic organisms) have been shown to be of advantage to a deep water habit. Exceptions to this observation seem more related to depth of light-penetration than to pressure or absolute depth (Clarkson, 1967; Wells, 1967; Erben, 1958;

Heezen and Hollister, 1971; Clarke and Denton, 1962). Despite these problems, there are several taxonomic groups frequently used as bathymetric indicators. When used in conjunction with other bathymetric evidence, they may constitute corroborative evidence.

Certainly the most commonly used and perhaps the most reliable biotic Paleozoic depth indicator is evidence of algal activity. Despite the criticisms of Riding (1975), abundant algal activity and/or diverse algal assemblages are indicative of the euphotic zone. The depth range of the euphotic zone, however, is dependent on water clarity and is highly variable. Clarke (1933, 1971) and many other workers have shown that the base of the euphotic zone rises to only a few meters depth in turbid water. Environmental analyses of ancient sediments may help to establish the variation of a particular paleoeuphotic zone from the modern clear water maximum value of 100 m.

Fungal and algal boring morphology are correlated with depth in modern environments and show promise for application to Paleozoic sequences (Golubic, Perkins, and Lukas, 1975; Perkins and Halsey, 1971; Perkins and Tsentas, 1976; and Perkins, personal commun.).

Trace fossils have frequently been used as bathymetric indicators (Seilacher, 1964, 1967; Frey, 1975). Burrow and trail "morphology" is not, however, directly depth dependent but is a response to a variety of factors, including a general bathymetric gradient in trophic resource type and location. As water depth increases, organic content of sediment increases and water exchange rate decreases. The increase in sedimented organic material is accompanied by an increase in deposit feeders leading to more sediment feeding burrows (mostly pasichnia of Seilacher, 1964). Conversely in shallower water, agitation reduces the amount of sedimented organic material but increases suspended organic material leading to a predominance of suspension feeder dwelling burrows (mostly domichnia of Seilacher, 1964). The possibility exists, however, that ancient food distribution with depth may have differed from the modern situation and, thus, feeding behavior and consequent burrow distributions may have also differed. Trace fossils do have the advantage that, unlike skeletal remains, they are virtually always autochthonous (Seilacher, 1967).

Abundance of graptolites or tintinnines has been cited as evidence of a "deep water environment." This distribution appears to reflect a preservational bias rather than an ecologic restriction. Graptolites are not uncommon in demonstrably shallow water deposits (Berry, 1960), and modern tintinnines occur in estuaries and other near shore environments as well as the open marine habitat. These two groups do, however, generally occur in much greater abundances relative to other taxa in the deeper portions of ancient environmental complexes, when depth patterns are determined from other lines of evidence. This serves to emphasize the need for multiple lines of evidence in Paleozoic bathymetric analysis.

Synecologic indicators—Community composition and structure have been shown to vary with water depth in modern marine environments (Parker, 1960, 1976; Thorson, 1957). In some cases these changes have been shown to be independent of sediment type (Parker, 1960), but no studies are known to us of communities restricted by specific pressures or absolute depth.

Rhoads (1974) states that increasing depth (and/or distance from shore) produces the following effects on modern marine communities: (1) decreasing standing crop and turnover rate, (2) decreasing average size of individuals, (3) decrease in fluctuation of biological activity, (4) more complete utilization of organic materials, (5) less frequent downgrading of communities due to physical factors. To this list we would add: (6) increase in deposit feeders in dominance position (Lewis, 1965). These effects might be noticed in paleocommunities as trends such as reduction in size of individuals in coeval communities, less frequent cycling of seral successions, or reduction in number of individuals per unit area of substrate (or volume of rock). Diversity would increase with depth, although biomass would probably decrease, provided sufficient sampling is performed (Sanders, 1969; Bretsky and Lorenz, 1969). These trends can only be used as supportive evidence for other indicators of a trend toward relatively deeper (or shallower) water.

Ziegler (1965), using faunal comparisons with modern forms, stratigraphic relations and successions, and paleogeographic considerations, defined five Silurian communities whose distributions are interpreted as "probably coincident with zones of increasing water depth." Ziegler calculated absolute depths for the communities in one area by studying interbedded shell deposits and volcanic flows. Reasoning that each volcanic flow displaced the community and reduced water depth by the thickness of the flow, the community preserved in the sediment above a flow would delimit the bathymetric range of each community. This is exemplary of the multipartite approach advocated here, but we are somewhat alarmed with the indiscriminant transference of such absolute depths to Silurian outcrops of diverse geographic location. While it may be true that Ziegler's Silurian communities represent successively deeper water conditions, absolute water depth determination requires supportive data from several lines of evidence, not just the identification of a particular benthic community.

Stratigraphic Indicators

Unlike the previously discussed indicators, stratigraphic indicators are generally of much larger, sometimes even regional, scale. Successful application of stratigraphic indicators requires at least one bathymetric datum to allow extrapolation to other parts of a sequence. Such stratigraphic interpretations range from the simplistic rule that identification of adjacent (coeval) basin and shelf deposits implies an intervening slope facies, to more sophisticated analyses of asymmetric and symmetric lithologic cycles (Coogan, 1972; Vail, Mitchum, and Thompson, 1974; Lohman, 1976) or analysis of geometrical relationships of well exposed time constant surfaces (for example, Capitan Reef, Newell, and others, 1953; or channel depths in clastic sequences, Allen, 1967).

It is imperative in applying this technique that one understand the three-dimensional dynamics and geometry of the paleoenvironmental complex. As stratigraphic, paleoecologic, and paleobathymetric data are analyzed, each bit of information can be reexamined within the larger context of the whole framework. This feedback system (compare Fischer, 1964) can serve to refine both the total ecostratigraphic framework and each component of which the framework is composed.

PALEOBATHYMETRIC ANALYSIS OF A MIDDLE ORDOVICIAN SEQUENCE IN EAST TENNESSEE

In the following sections of this paper we will outline the procedure we have used to analyze bathymetry of shelf, shelf marginal, and basinal deposits in the Middle Ordovician of eastern Tennessee (fig. 2). Hereafter, we will refer to this basin as "The Sevier Basin." We will discuss in detail the paleobathymetric analysis of one stratigraphic section (loc. *MR* of fig. 2), compare two stratigraphic sections (loc. *MR* and *BC* of fig. 2), and use data from several sections (fig. 2) to construct bathystratigraphic profiles and bathymetric maps showing the evolution of the Sevier Basin and adjacent areas.

This study grew out of several earlier projects concerning the stratigraphy of Middle Ordovician strata of Tennessee. One of us (Walker, 1977) has synthesized data from these projects to form an ecostratigraphic framework. Although the framework implies that basinal deposits developed in the eastern part of the study area (figs. 2 and 5), it does not indicate the absolute depths that developed in the Sevier Basin. Nor does it show the dynamic nature of basin evolution in terms of subsidence history or sedimentation rates.

In an effort to understand better the dynamics of this basin's evolution we have reexamined the data of previous projects and collected new data to determine changes in water depths through time at as many exposures as possible. Many of the bathymetric indicators used are tabulated in table 1. Not shown in that table are the stratigraphic "indicators" used and depth inferences derived from the ecostratigraphic framework. Some of these indicators are discussed in the text.

Critical to understanding absolute rates of sedimentation and subsidence is a chronostratigraphic framework. The "time lines" used in this study (shown on the cross sections of fig. 5) were derived from a variety of sources and are discussed in appendix 1.

Bathymetric Analysis of the Midway Road Section

A 300 m thick section of Middle Ordovician strata ranging from the upper Knox Group through the Lenoir, Holston, and lower Chapman Ridge formations is exposed along Interstate 40, 20 km east of Knoxville, Tenn. Our examination of this section for paleobathymetric analysis consisted of measuring, describing, and sampling the outcrop in detail, *noting* any observations indicative of bathymetric gradients or depth ranges. All 61 samples were thin sectioned and examined petrographically to determine biotic and lithic constituents. Careful attention was given to relative abundances of algae and changes in dominant elements of the fauna. These data were augmented with field observations of sedimentary structures, nature of bedding contacts, and lateral relationships of units. Graphs showing the distributions of various bathymetrically important data are shown in figure 3.

Abundant peritidal indicators near the base of the section provide a datum for sealevel. This interpretation, is based on birdseye limestones, vertical burrows, and flat pebble conglomerates (Mosheim member, Lenoir Formation) unconformably overlying the Knox. These tidal deposits are succeeded by algal rich (*Girvanella* and *Nuia* sp.) oncolitic packstones and grainstones (Asbury Member of Lenoir Formation, Walker, in preparation) indicating shallow subtidal deposition. These conclusions are in agreement with the interpretation of the lower Lenoir by Stephenson, Walker, and McLaughlin (1973). Algae decrease upward, (fig. 3) suggesting a deepening environment. This interpretation is also supported by a stratigraphically upward increase in "normal marine" stenohaline taxa (pelmatozoans, articulate brachiopods, sponges, and corals), an increase in wackestone and packstone lithologies, decrease in

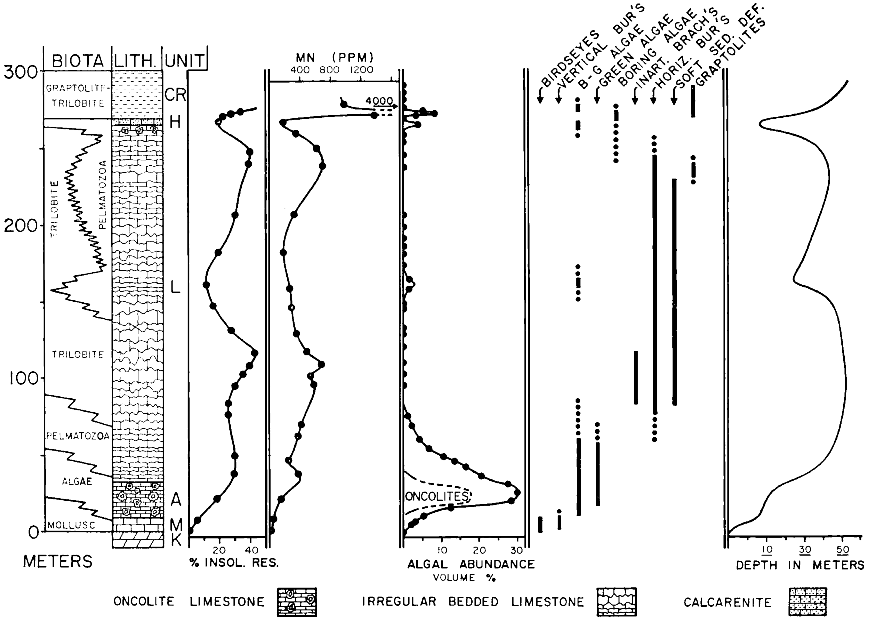


Fig. 3. Midway Road stratigraphic section of the Lenoir Formation showing the variation of several paleobathymetric indicators with stratigraphic position and the position of other indicators in the section. Note that the depth scale is roughly geometric. Stratigraphic unit abbreviations are as follows: K = Knox Group, M = Mosheim Member of Lenoir Formation, A = Asbury Member of Lenoir, L = upper, main body of Lenoir Formation, H = Holston Formation, CR = Chapman Ridge Formation. Selected samples are shown by dots.

sorting and other indications of wave induced sedimentary structures, and increasing abundance of soft sediment deformational features.

Higher in the section at about 160 m (fig. 3) algae are present again; however, only *Girvanella* (blue green alga) lumps have been observed, and no oncolites have been found. *Girvanella* occurs as thin encrustations on pelmatozoan columnals and as small ovoid aggregates of tubules suggesting little transport. We interpret this zone as shallower than the immediately lower parts of the Lenoir but not as shallow as the oncolitic Asbury Member. Water depth increases again above this zone as indicated by disappearance of algae and an increase in pelmatozoans, bryozoans, trilobites, and graptolites in some samples.

The upper part of the Lenoir is also characterized by an increased abundance of *Girvanella* with occasional grains of *Nuia*. The fauna becomes more diverse with abundant pelmatozoan columnals, corals (*Billingsaria* sp.), articulate brachiopods, and trilobites. An abrupt but conformable change in lithology and biota marks the transition to the Holston Formation. The Holston at Midway Road comprises 3 m of gray to pink pelmatozoan grainstones with scattered bryozoan fragments and a conspicuous absence of algae. Some pelmatozoan grains do, however, appear bored by either endolithic algae or fungi.

Overlying the Holston is a thin zone (1 m) of "Lenoir-like" lithologic character with common algae (*Girvanella* and *Nuia* sp.). At the base of this unit and increasing upward are common to abundant dark brown to black phosphatic peloids. These peloids range in size from less than 0.1 mm to as large as 2.0 cm in diameter. In thin section, they frequently display amber colored concentric laminae around nuclei of pelmatozoan grains or euhedral pyrite crystals. Electron microprobe analysis shows the laminae to be calcium fluorapatite. This phosphate rich zone is overlain by mixed terrigenous quartz and calcareous siltstones, graptoliferous shales, and sandstones mapped as Chapman Ridge Formation.

Geochemical analyses were run on selected samples to determine the amount of manganese in the carbonate fraction of lithologies described. Analyses were run using the procedure of Bencini and Turi (1974), except that Mn content was determined using atomic absorption instead of titration.

The data discussed are plotted in figure 3, and the inferred changes in bathymetry are shown by the rightmost curve of that figure. The absolute depth values are derived from integration of all the indicators shown in table 1. The following paleobathymetric history of the Midway Road stratigraphic section is inferred. The desiccation and other peritidal features of the Mosheim Member of the Lenoir indicate deposition of these sediments in the intertidal zone. The overlying Asbury Member contains abundant algal oncolites indicating deposition in water depths from low tide to a maximum of about 10 m. The overlying lower part of the upper Lenoir contains few oncolites, but other algae are present indicating depths between 10 m and the base of the transient euphotic zone. The abundance of carbonate mud (micrite) and fine grained insoluble residue in the Lenoir suggests turbid water, with the depth of the euphotic zone not exceeding 30 to 40 m. Higher in the Lenoir the complete absence of algae indicates deposition below the euphotic zone (greater than about 40 m). One thin zone in the middle part of the upper Lenoir does contain untransported algae and represents a brief shallowing (fig. 3), followed by deepening below the euphotic zone again. Near the upper contact of the Lenoir with the overlying Holston, reappearance of algae and other shoaling indicators suggest another shallowing event. Finally, the Chapman Ridge Formation contains evidence of deepening conditions, including high phosphate and manganese content probably indicating a shelf edge or upper slope environment at a depth of 100 m or more.

Using similar integration of multiple paleobathymetric indicators we gam and Walker, this issue, p. 551-578) demonstrates the basinal position of the Boyds Creek Section (BC of fig. 5).

Comparative Subsidence Histories of Shelf and Basinal Sequences

The ecostratigraphic framework indicates the outer shelf position of the Midway Road Section, and our bathymetric analysis supports this interpretation. Paleobathymetric analysis presented elsewhere (Shanmugam and Walker, this issue) demonstrates the basinal position of the Boyds Creek Section (BC of fig. 5).

Time lines of figure 5 (see app 1) allow chronostratigraphic correlation of the two sections as well as calculation of relative rates of sedimentation at the two sites. With these data we have divided each stratigraphic section into approximately equal time intervals and have tabulated cumulative sediment thickness through time at each site. Using the scheme illustrated in figure 1, we have combined water depth through time, derived from paleobathymetric analyses, with cumulative sediment thickness above the Knox to determine subsidence of the Knox surface during the Middle Ordovician. This surface was at sealevel when Middle Ordovician deposition began. The resultant curves are shown in figure 4, showing bathymetric changes, cumulative sediment thickness, and subsidence as a function of time at each of the two sites.

Maximum rates of subsidence in the basinal tectonic setting (Boyds Creek) exceed those of the shelf setting (Midway Road) by a factor of 8. The chronostratigraphic relationships of these two sections suggest that shelf sedimentation rates (Midway Road) were approx 3 to 4 times faster than basinal pelagic sedimentation rates in the lower Blockhouse Shale (Boyds Creek). Higher in the section at Boyds Creek, sedimentation rates increased rapidly as deposition from turbidity currents affected the area (Shanmugam and Walker, this issue). Sediment thickness at each section was proportioned, according to relative sediment rates, into units of variable thickness representing equal lengths of time. We believe a reasonable estimate of time represented by the sections shown is approx 14 m.y. These assumptions yield a maximum shelf rate of subsidence of 5 cm per 1000 yrs and maximum basin subsidence rates in excess of 40 cm per

1000 yrs. These rates are comparable to modern subsidence rates calculated using JOIDES D.S.D.P. data from the Straits of Timor. (That area was chosen as a modern analogue, because the deepwater section there is developing on a formerly shallow water carbonate shelf.)

In addition to helping us understand subsidence rates in various parts of the study area, paleobathymetric analysis allows us to understand changes in basin geometry through time. In order to demonstrate the salient tectonic implications of our paleobathymetric analyses, we

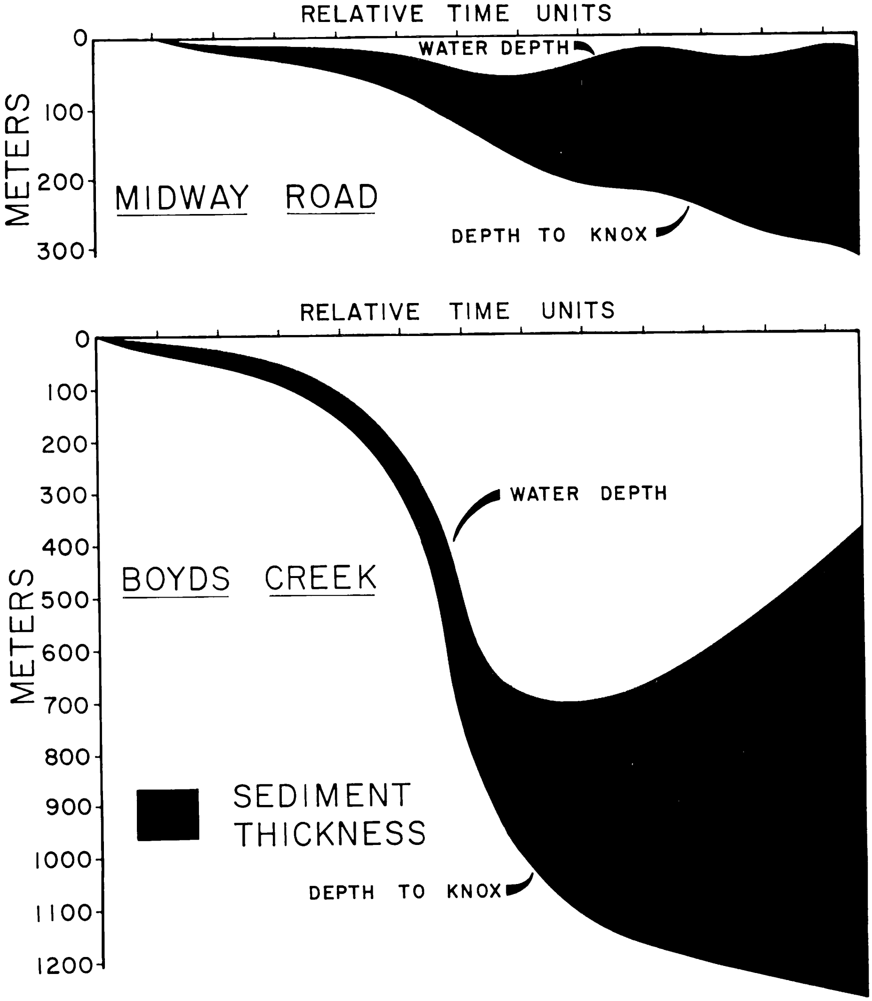


Fig. 4. Comparison of subsidence (depth to Knox), accumulating sediment thickness, and changes in paleobathymetry with time in the Midway Road and Boyds Creek correlative stratigraphic sections.

have chosen two ways of graphically depicting paleobathymetric changes. We first examine the stratigraphic distribution and lateral relationships of isobathic units by developing "bathystratigraphic" profiles (fig. 6) that correspond to ecostratigraphic profiles (fig. 5) constructed by Walker. Because higher paleobathymetric resolution is possible in shallow waters, our depth zone ranges are non-linear and conservatively reflect recognizable paleobathymetric zones.

Examination of the bathystratigraphic profiles (fig. 6) reveals several important features of the basin's development. First, the entire area was initially (but not synchronously) a peritidal complex as shown by the shallow water deposits at the base of each profile (fig. 6). Second, deeper subtidal environments rapidly developed on the previously shallow subtidal shelf east of Fountain City and Prospect (FC and P on fig. 6), whereas areas west of these two points remained dominantly peritidal and shallow subtidal. Third, after the basin was established, pelmatozoan sand banks formed along the deep shelf-shelf marginal areas on the carbonate shelf to the west (Holston of fig. 5) and on the dominantly terrigenous shelf margin to the east (Chota in the upper part of fig. 5). Fourth, after initial basin infilling with pelagic terrigenous sediments (Blockhouse-Sevier-Tellico of fig. 5), the basin was rejuvenated to a lesser degree. This rejuvenation occurs on the RV-WQ profile in the upper part of section BC, and on the DE-MV profile it is inferred to have occurred east of section SS on the basis of shelf edge oolite shoals in exposures of that area. Finally, note that most of the lithologic units in the stratigraphic sequence are polybathic in origin.

The bathystratigraphic profiles give only a limited view of changes in overall basin geometry through time. To construct a regional picture of Sevier basin evolution we derived four sets of time-specific paleobathymetric data from the RV-WQ and DE-MV profiles (figs. 5 and 6) and from other sections (shown as dots in fig. 7). These four paleobathymetric data sets correspond to time lines 1 through 4 of the bathystratigraphic profiles (fig. 6). Data corresponding to each time line were then placed on four equivalent palinspastic base maps (see Roeder and Witherspoon, this issue, p. 543-550) and contoured using the same paleobathymetric range zones shown on figure 6. The resulting paleobathymetric maps are shown in figure 7.

Time 1 paleobathymetry indicates a shelf edge with two recesses of deeper water environments penetrating northwestward onto the shelf. The southwestern recess is recorded by a tongue of deep subtidal (below wave base) Athens Formation within the Lenoir Formation. To the northeast of this recess is a linear, shallow subtidal shelf edge complex of calcarenite bars (Lower Holston Formation) behind which developed the lagoonal lithotope of the main body of the Lenoir Formation. Northeast of the bar complex is a second shelf edge recess. This recess, unlike the southwesterly recess, developed a calcarenite bar complex similar to that developed along the linear part of the shelf edge. This bar complex is roughly coincident with the −10 m contour along the shelf edge.

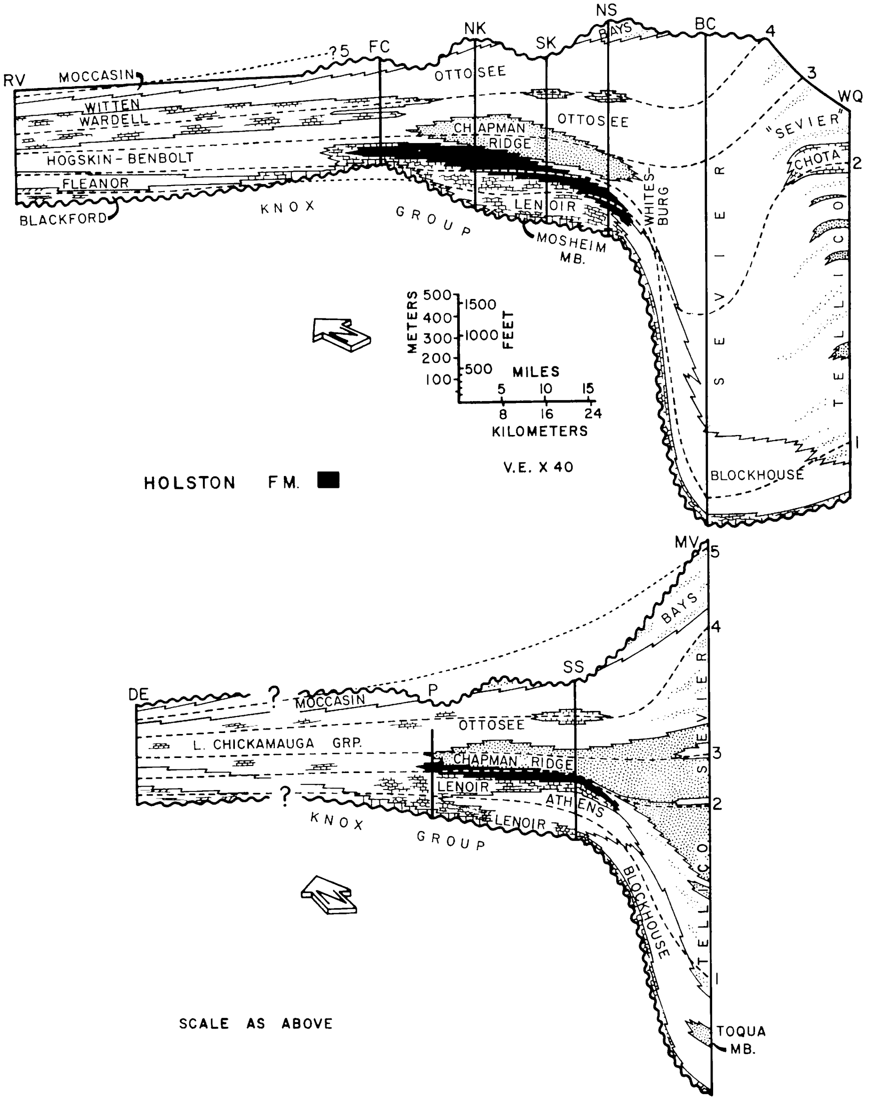


Fig. 5. Northwest to southeast, restored stratigraphic cross sections of the Middle Ordovician of eastern Tennessee on a palinspastic base (see Roeder and Witherspoon in this issue). Note time lines 1, 2, 3, 4, and 5 (see appendix 1). Datum is time-line 2 which is also a paleobathymetric profile. Terrigenous shales and limey shales shown with no pattern, terrigenous sandstones = dot pattern, limestone = brick pattern, dolostone = slanted brick pattern. Calcarenites of the Holston Formation shown in black. See figure 2 for localities of sections shown here as vertical lines. Upper wavy line is present erosion surface, lower wavy line is unconformity on top of Lower Ordovician Knox Group. V.E. = vertical exaggeration = ×40.

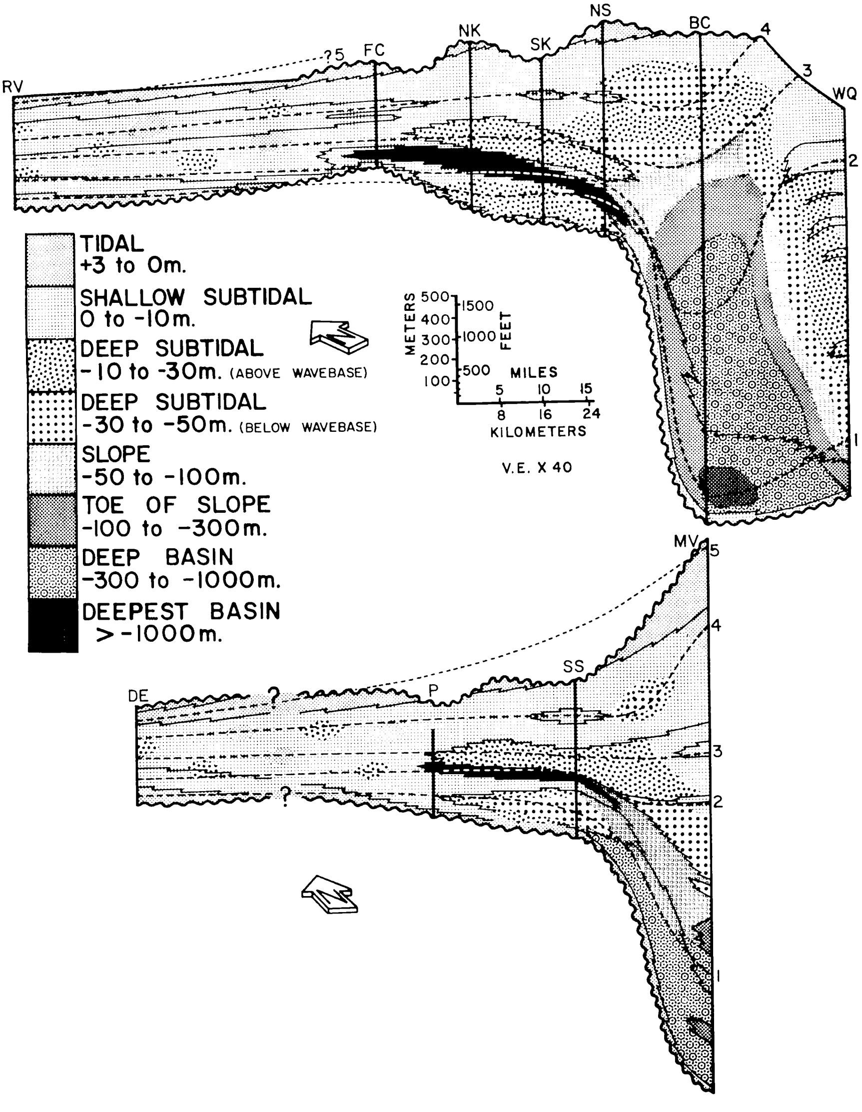


Fig. 6. Bathystratigraphic cross sections corresponding to the stratigraphic cross sections of figure 5. Note that the scale of depth zones is roughly geometric with increasing depth. Boundaries of bathystratigraphic units do not often correspond with lithostratigraphic boundaries.

To the northwest of the shelf edge there existed a complex lagoonal and peritidal array of environments containing exposed low lying Knox islands surrounded by fine micrites of the Mosheim Member of the Lenoir as well as wackestone and packstones of the Lenoir. Insufficient detail in this area prevents us from knowing the exact position of the strand line; therefore, the map pattern of islands and the extent of the sebkah environment are interpretive. The –2000 m contour to the south is based on extrapolation of the regional paleoslope (less than 1.5°) determined from areas of better paleobathymetric control. Major basinal subsidence had already occurred at this time and is not accounted for by sediment loading within this portion of the basin.

Time 2 paleobathymetry (fig. 7) illustrates significant changes in basin geometry especially to the southwest and south. These changes are related to a slowing of tectonic subsidence and an increase in rates of sediment supply producing a net shoaling effect and a reduction of paleoslope. The dotted –5 m contour corresponds approximately to the Holston bryozoan reef and calcarenite bar complex (Walker and Ferrigno, 1973). Note that the southwestward recess in the shelf edge has filled, while the northeastern recess (more distant from the southern terrigenous source) remains. Field evidence in the southern portion of the area (at points not indicated on the map) indicates a shelf edge developing at this time southeastward across the basin from the carbonate platform shelf discussed above.

By time 3 the new shelf edge to the south was well established with oolite shoals and discontinuous "Holston-like" bryozoan reefs. The southwestern end of the basin continued to fill allowing terrigenous sediments to encroach upon the northwestern carbonate shelf edge. This sediment then moved northeasterly along the shelf edge by long shore transport. These terrigenous sediments (the Chapman Ridge Formation) killed off or displaced the Holston bryozoan reefs along much of the shelf edge and reduced the sharpness of the shelf break.

The filling of the basin continued and by time 4 submarine relief of the area had been reduced. Only a narrow northeast-southwest trough existed with scattered patch reefs along its margins (approximated by the –5 m dotted contours). More extensive reefs and skeletal sandbanks still existed along the northeasternmost shelf edge. Subsequent to time 4, but not illustrated here, peritidal fine terrigenous and carbonate sediments prograded westward over the entire area (Bays Formation to the east and Moccasin Formation to the west).

SUMMARY AND CONCLUSIONS

Paleobathymetirc analysis, using a variety of bathymetric indicators cast within an ecostratigraphic framework, has allowed us to examine the evolution and tectonic development of a Middle Ordovician basin in east Tennessee. This approach affords a more detailed understanding of basin development and geometry through time than previously used techniques. The analysis has demonstrated a significant early Middle Ordovician

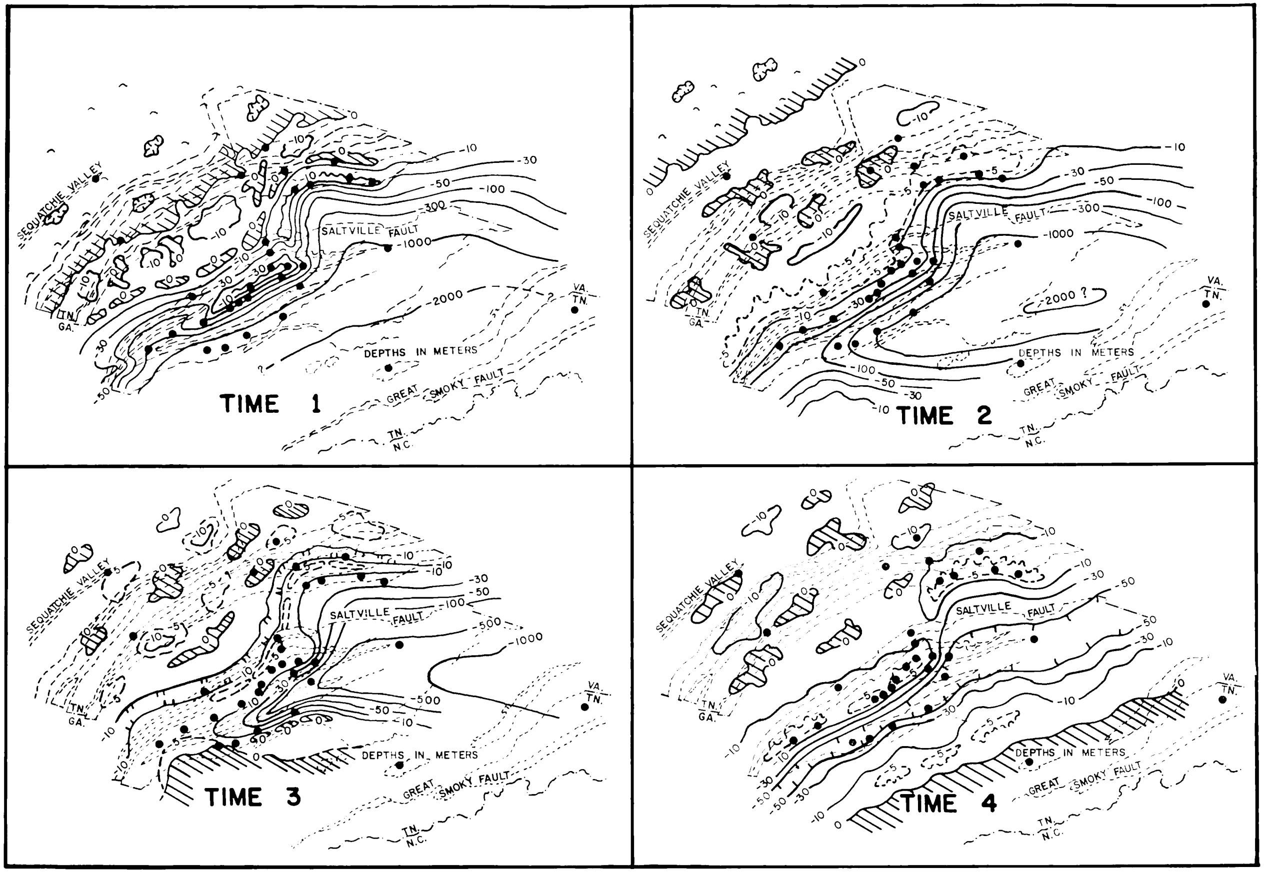


Fig. 7. Paleobathymetric maps of four times during the Middle Ordovician. Time 1 (earliest) corresponds to time-line 1 of figures 5 and 6, time 2 corresponds with time-line 2, time 3 with time-line 3 and time 4 (latest) with time-line 4. The base map is the palinspastic map of Roeder and Witherspoon (this issue). North is toward the top of the figure. Each map represents an area approx. 300 km east to west and 200 km north to south. In general, the extension of the maps into the Virginia area is based on information from J. F. Read (personal comm, 1977).

subsidence event. Unlike the Sverdrup Basin, where sedimentation rates kept pace with subsidence rates (Sweeney, 1977), in the Sevier Basin, a time lag existed between an initial major subsidence event and the arrival of sediments from bordering source areas. The timing of these events suggests that the initial subsidence event was not induced by sediment loading but, rather, by some other tectonic driving force. The nature of this force is equivocal, but it is reasonable to infer a genetic relationship between it and the forces producing relief in the source areas to the south and east. Subsidence may have been accompanied by either flexure or faulting to form the Sevier Basin. We do not presently have clear evidence to choose between these alternative possibilities.

It is clear, however, that the existence of this deep basin controlled for a time the developing environmental pattern and protected the shelf to the west from incursion of terrigenous clastics. Only after the basin was filled (with more than 15,000 cubic km of terrigenous clastics) did sediment from the southerly source region pour in large quantities onto the shelf.

We believe in this study we have demonstrated the value of paleobathymetric analysis in deciphering the developmental history of Paleozoic sequences. Although we have done so by detailing our analysis of a specific sequence, the techniques and many of the specific paleobathymetric indicators we have used could be applied equally well in the study of any Paleozoic sequence. We hope this work will stimulate others to attempt similar analyses.

ACKNOWLEDGMENTS

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APPENDIX 1

The validity of our paleobathymetric analysis of the Ordovician of Tennessee rests on the validity of the time-lines shown in figures 5 and 6. These lines are based on complex evidence. Overall, their correctness hinges on the total ecostratigraphic study of the entire sequence on which one of us (KRW) is now completing a summary article. We feel, however, that it is important to summarize here the basis for each of these correlation lines. Initially, we emphasize that these lines are also paleobathymetric profiles with line 2 being the undistorted profile on which the cross sections of figures 5 and 6 are "hung."

The position of line 1 is based on conodont work done by Bergstrom (1973) and represents the approximate position of the *Pygodus serus*-*Pygodus anserinus* zonal boundary in the Friendsville-South Knoxville belt (SK in fig. 5) and the Lenoir City-North Knoxville belt (NK of fig. 5). This correlation is projected into sections where conodont work has not been done by reference to tongues of the Athens Formation and Blockhouse Formation which extend into the Lenoir Formation from the southwest and southeast respectively, about 60 m below the zonal boundary. This tongue (not shown on figs. 5 and 6) approximately corresponds to the level of first appearance of a primitive type of *Pygodus serus*. The extension of line 1 northwestward onto the shelf in figures 5 and 6 is based on environmental considerations. In these northwestwardly areas, in the line of the two sections shown, a considerable thickness of slowly deposited sebkah sediments (largely dolostone and dolomitic shale) underlies the first conodont bearing limestones. The limestones are probably coeval with the upper Lenoir around Knoxville, and thus the underlying dolostones must be equivalent to the lower and/or middle Lenoir. We must note that the conclusion of Bergstrom and Carnes (1976) that the base of the Middle Ordovician section northwest of the Saltville Fault is considerably younger than the base of the section southeast of that structure is true in the stratigraphic sections they considered but not true in the lines of sections of figures 5 and 6.

The position of time line 2 corresponds to the base of the *Prioniodus gerdae* Subzone of the *Amorphognathus tvaerensis* Zone in the Knoxville area and the area of the Wildwood Quadrangle (WQ of figs. 5 and 6) and Mount Vernon (MV of figs. 5 and 6) (Bergstrom and Carnes, 1976). Between these two areas the position of line 2 is based on environmental considerations, where it falls within slowly deposited pelagic shales and distal turbidites. See Shanmugam and Walker in this issue for a discussion of the depositional environment of these deep water sediments. The approximate position of time line 2 northwest of the Fountain City area (FC of figs. 5 and 6), where it occurs in poorly fossiliferous shales, is based on environmental considerations. Brachiopod (see Cooper, 1956) and bryozoan faunas are in reasonable agreement with the correlation shown. In the southeasternmost sections (WQ and MV of figs. 5 and 6) the positioning of this line near the bottom of the Chota is based on conodonts (see Bergstrom and Carnes, 1976), brachiopods (Neuman, 1955), and bryozoan faunas.

Time line 3 of figures 5 and 6 is based on the progradational-retrogradational Chapman Ridge shallow-water, sand body and the coeval flood of finer grained terrigenous clastic material onto the shelf to the northwest. These shales represent the first arrival of terrigenous clastics from a southeasterly source into the area northwest of the Athens-Knoxville belt (sections SS, NK, and SK of figures 5 and 6).

Time line 4 of figures 5 and 6 is based on the time of maximum extent of a resurgence of limestone deposition on the carbonate shelf that extends from the Athens-Knoxville belt (SS, SK, and NS of figs. 5 and 6) northwestward. This time corresponds to a deepening of the basin at BC and a cut-off of supply to the shelf of terrigenous clastics from the southeasterly source. At SS, SK, and NS of figures 5 and 6, this reduction in terrigenous material allowed the growth of patch reefs in some areas and oolite shoals in others. On the shelf farther to the northwest relatively clean carbonate muds and bioclastic sands accumulated in a complex peritidal regime. Southeastward from the basin in the WQ and MV stratigraphic sections, the position of line 4 is less certain. It is interpolated in the sections between lines 3 and 5 based on consideration of relative rates of deposition.

Finally, time line 5 is based on altered volcanic ash beds which occur in the southeasternmost and northwesternmost stratigraphic sections. The ash (now bentonite) occurs as a single 3 m thick unit high in the Bays Formation near section MV (fig. 5) and as a series of thinner beds (T3 and T4 of Wilson, 1956) intercalated with carbonates near the RV and DE sections (fig. 5). In the other stratigraphic sections where only the lower part of the Bays is occasionally preserved the ash has been removed by erosion.

The correlations shown in figures 5 and 6 are supported by many other lines of physical stratigraphic evidence which in most cases are on a scale too detailed to show in these cross sections. The reader is referred to the more complete treatment of the ecostratigraphy and chronostratigraphy of this sequence in Walker (1977, and in preparation).

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