The practicality of vertical cephalopod shells as paleobathymetric markers

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ABSTRACT

The depth to which an intact coiled cephalopod shell will sink with its plane of symmetry vertical is related to shell geometry. Equations that relate shell geometry to physical constants of pressure, sea-water density, and gravity yield the maximum depth of stable verticality of a shell. Water depths calculated from the geometries of vertical shells of *Cymatoceras hilli* (Shattuck), *Drakeoceras drakei* Young, and *Mortoniceras wintoni* (Adkins) from the Fort Worth Formation (Upper Cretaceous, Albian) of north-central Texas are used to reconstruct a portion of the paleobathymetry of the East Texas Embayment during late Fort Worth time. The maximum water depth to which shells with these geometries would have sunk with the plane of symmetry vertical range from 1.6 m for the least stable shell geometry (*D. drakei*) to 2.6 m for the most stable shell geometry (*C. hilli*). Water depths were deeper than 2.6 m at localities where no vertical shells were observed and shells with the plane of symmetry horizontal showed no evidence of being reworked from the vertical orientation.

INTRODUCTION

For most shell-bearing animals, death is followed by a fairly mundane set of events, but post-mortem history of the chambered cephalopod *Nautilus* is far more spectacular than that of other important marine invertebrates. After death, gases released during decay of the visceral mass (including the siphuncular cord) often increase the buoyancy of the shells (if not already of positive buoyancy) so that they rise to the surface of the water, where they float until stranded near a shoreline or become waterlogged and sink. Due to the relationships between acceleration of gravity, buoyancy, mass of

the shell, total volume of the shell, density of sea water, and shell geometry, the observed sinking behavior of *Nautilus* can be duplicated experimentally using equations developed by Weaver and Chamberlain (1976) and Chamberlain and Weaver (1978). Given that the earliest coiled cephalopods had shell construction similar to that of *Nautilus* (Flower, 1964; Mutvei, 1972) and assuming that constants such as atmospheric pressure, acceleration of gravity, and density of sea water have not changed significantly during the Phanerozoic, the necessary parameters (total volume of the shell and shell geometry) can be measured or estimated with sufficient precision to allow for the description of the sinking behavior of the coiled shells of fossil cephalopods. In their experimental work, Weaver and Chamberlain (1976) and Chamberlain and Weaver (1978) placed emphasis on the behavior of the shell during actual sinking because it is during this portion of the post-mortem history that shell geometry determines the attitude of a shell at the time of burial. This statement assumes that other physical constants were invariable or nearly so. Thus, a coiled shell of a given geometry, mass, and volume will, if the shell maintains its integrity, pass through a series of events that can be described using equations of motion in sinking. If, during its descent through the water column, the shell reaches bottom in a vertical position and remains in this position long enough to be preserved, reasonable estimates of maximum water depth can be calculated.

Weaver and Chamberlain (1976) tested ideas put forth by Reyment (1958, 1970) and Raup (1973) concerning the presinking and postsinking history of coiled shells and did so by using shells of *Nautilus* to describe the sinking behavior of chambered shells. They were able to derive equations for

motion to describe the sinking behavior of the shells of *Nautilus* by applying the physics of the sinking of hollow, rigid bodies. Experiments using shells of *Nautilus* yielded sinking velocities in agreement with their calculated values and also showed that the orientation of a sinking *Nautilus* shell varies as the phragmocone fills with water. With a small negative buoyancy, the shell sinks with its plane of symmetry upright (vertical), but as the phragmocone fills, the shell begins to rock from side to side until the phragmocone is about 55% full, at which point the shell leans over and sinks with its plane of symmetry horizontal. Weaver and Chamberlain were also able to refute the common argument that vertical shells may result from embedding upon impact with the bottom. The observed and calculated sinking velocity of a *Nautilus* shell was shown to be approximately 30 cm/sec, a velocity too slow to cause embedding upon impact. They were able to show empirically that the maximum depth to which *Nautilus* sinks in a vertical position ranges from less than 7 m for rapidly filling shells to as much as 600 m for slowly filling shells. In the latter case, however, the shell will quickly assume a horizontal orientation because it will continue to fill after reaching bottom and the stability of the vertical shell will be removed within a few hours or a few days, depending on depth. Chamberlain and Weaver (1978) modified the equations introduced in their 1976 paper to allow for variations in shell geometry, the mass of the shell, and the total volume of the shell (shell material plus camerae). By incorporating the effects of hydrodynamic stability and loss of buoyancy during sinking, they were able to calculate sinking velocity and pressure across the shell wall as a function of depth for shells of any size and shape. The results of this analysis indicated that the largest single source of variation in the

observed and calculated depth limits of shells is the geometry of the shell. Although the mass and total volume of the shell may vary from shell to shell and from taxon to taxon, these differences are so slight that they do not noticeably affect the depth limit. Thus, as Raup (1973) suggested, shell geometry as it describes the stability of the shell is the key to estimating water depth from a vertical shell.

Aside from occasional published reports prior to 1958 of coiled cephalopod shells found preserved in a vertical position, Reyment (1958) was the first to report on the phenomenon as it relates to the distribution and buoyancy of fossil cephalopods. Although Reyment made no prediction of water depth, he did recognize that all occurrences were in facies he believed to be shallow-water and which quite possibly represented strandline deposits. Reyment (1970) later examined a number of cephalopod-bearing localities, unrelated in space and time for the presence of vertical shells. At each locality, he was able to document that at least a few coiled ammonites or nautiloids were in a vertical orientation as a result of the shell coming to rest on the bottom under conditions whereby verticality was sustained either by rapid burial or prolonged buoyancy plus a rate of sedimentation sufficient to anchor the shell in a vertical position. However, Reyment's hypothesis that "almost any ammonite locality will sooner or later yield vertically imbedded ammonite shells, likewise for nautiloids" (Reyment, 1970, p. 110) must be rejected in light of what is now known about the post-mortem history of the coiled shell.

The purpose of this paper is to demonstrate the degree to which the equations of Chamberlain and Weaver (1978) combined with the occurrence of coiled ammonoid and nautiloid shells preserved with their plane of symmetry vertical can be used to describe the paleobathymetry of entombing sediments. The cephalopod fauna of a portion of the Fort Worth Formation (Lower Cretaceous, Comanchean-Albian) of north-central Texas is used to illustrate this point.

CALCULATION OF DEPTH ESTIMATES

The physics necessary to describe the sinking behavior of a coiled and chambered shell has been elegantly related by Weaver and Chamberlain (1976) and Chamberlain and Weaver (1978) through a series of equations derived from equations used by naval architects and others to describe motions in the sinking of hollow, rigid bodies. Only the equations necessary for the calculation of depth estimates are discussed below. The reader is directed to Weaver and Chamberlain (1976) and Chamberlain and Weaver (1978) for the derivation of these equations.

In their experiments, Chamberlain and Weaver (1978) considered an incompressible shell sinking from the surface of a stationary fluid (sea water) of constant density. This was done for convenience, with full knowledge that sea water is not motionless and that its density varies slightly as a function of salinity and temperature. The variation in these factors, however, did not prove large enough to introduce a significant error in their calculations. It was also assumed that the chambers of the shell contained an ideal gas and an amount of external fluid (sea water) that had entered by diffusion through the wall of the siphuncular tube.
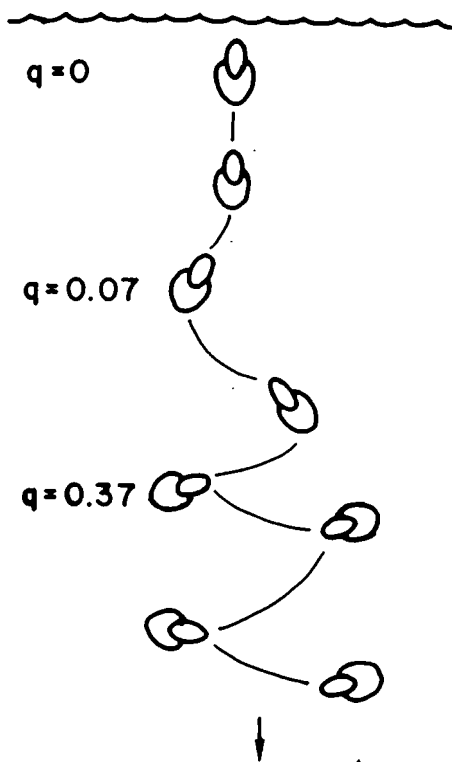

Figure 1. Sinking behavior of a *Nautilus* shell due to the loss of stability from the influx of water entering the shell through the siphuncular tube. At $q = 0$, the shell is stable and the plane of symmetry is vertical. The onset of rocking begins at $q = 0.07$, and at $q = 0.37$ the plane of symmetry is horizontal. From Figure 1 of Chamberlain and Weaver (1978).

Filling of the Shell

If the integrity of a shell has not been lost as it sinks (no breakage of the phragmocone), filling will occur in one of two ways: *rapid* or *slow*. During *rapid filling*, the gas contained in the shell will be trapped and the influx of fluid into the camerae will be proportional to the pressure difference between the external fluid (sea water) and the internal gas. If the siphuncular tube has deteriorated, leaving a conduit for the entrance of sea water through the open septal necks, the pressure difference will be small and the shell can be said to fill rapidly. Sinking by rapid filling was probably a rare event because well-preserved shells commonly show that the siphuncle was intact at the time of fossilization. *Slow filling*, whereby sea water moves slowly through the wall of the siphuncular tube by diffusion, was probably the common mode of filling for most shells (Collins and Minton, 1967). Owing to the slow addition of weight as the shell sank, stability would have been prolonged to a much greater depth. However, if a shell reached the bottom under conditions of slow filling in water deeper than the lower limit of its vertical stability, filling would have continued and the vertical stability of the shell would have been lost within hours or days (Chamberlain and Weaver, 1978).

Chamberlain and Weaver (1978) found it convenient to describe the filling of a shell as it sinks by a dimensionless parameter (q) that describes the fill fraction of the shell and is an index of the extent to which the phragmocone is filled in excess of that required to produce neutral buoyancy. The parameter ranges from $q = 0$ for neutrally buoyant shells to $q = 1$ for shells completely filled with water (Chamberlain and Weaver, 1978).

Stability

As Raup (1973) suggested and Weaver and Chamberlain (1976) demonstrated, the stability of the shell is the factor that plays the major role in controlling sinking behavior. As a shell of *Nautilus* fills with water during sinking, the accompanying loss of stability causes the shell to begin a rocking sequence at $q = 0.07$ (≈ 0.75 m) and to assume a horizontal position at $q = 0.37$ (≈ 9 m) (Fig. 1). The onset of rocking and horizontality results in significant, but predictable, departures from a calculated sinking velocity because the general equation of
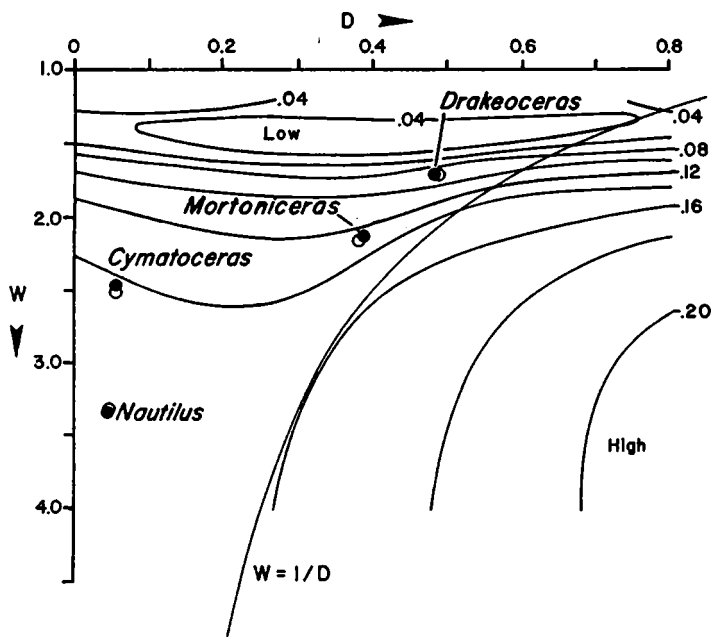
motion (Chamberlain and Weaver, 1978, p. 676) assumes no change in orientation during sinking.

It has been repeatedly demonstrated that the stability of a coiled shell, where stability is measured as the ability of a shell to maintain a vertical orientation in a column of water, is dependent primarily on the distance between the center of mass and the center of buoyancy (approximated by the degree of evoluteness of the shell) and body chamber length (Trueman, 1941; Raup, 1967; Raup and Chamberlain, 1967; Mutvei and Reyment, 1973; Reyment, 1980). If the length of the body chamber is constant (or nearly so) relative to shell diameter (the usual case for related genera from the same stratum), then the degree of evoluteness will be the primary variable determining the relative stability of various genera. That is, if the two centers are close together (an involute shell) and the body chamber is at least one whorl in length, stability is low. An evolute shell (centers more widely separated) with a body chamber of equal length (relative) will be more stable and thus would delay rocking and horizontality to a greater depth than a less stable shell. Therefore, vertical preservation of members of cephalopod populations with the usual variety of shell geometries allows the water depth to be determined for the stratum at the time of entombment.

It also can be demonstrated that for shells of similar shape, sinking behavior is independent of size. This is basic because it establishes that a given amount of filling in shells of equal shape will elicit the same sinking behavior regardless of the size of the shell (Chamberlain and Weaver, 1978).

The stability of Nautilus is known empirically (Weaver and Chamberlain, 1976; Chamberlain and Weaver, 1978), and the stability of any shell can be compared to Nautilus by the equation

$$C_s = K_{sn}/K_{sa}, \qquad (1)$$

where C_s is the stability coefficient, K_{sn} is the stability constant for Nautilus, and K_{sa} is the stability constant for another shell. As Nautilus will be C_s times as stable as the shell being compared, the drag force required to rock this shell will be C_s^{-1} times the drag force necessary to cause rocking in Nautilus, and so forth. The stability constant K_{sa} for any shell can be obtained by first measuring the diameter of the shell and then calculating the center of gravity and buoyancy using equations 8 and 9 of Raup and Chamberlain (1967). K_{sa} is then calculated by E/d, where E is the distance between centers of mass and buoyancy of the shell and d is shell diameter.

Although it may be necessary in some cases to perform these calculations for various shell geometries, another better-known and more easily derived relationship yields the same measure of stability without a loss of accuracy. In 1967, Raup introduced two parameters for describing the geometry of a coiled shell as a function of its linear dimensions: W, which describes the whorl expansion rate of a shell, and D, which describes

the relative distance between the generating curve and the axis of coiling. See Raup (1967, p. 44) for discussion of the calculation of these parameters. Thus, as D increases relative to W (increasing involuteness), the centers of mass and buoyancy are brought closer together and the shell becomes less stable (body-chamber length constant). This relationship is illustrated in Figure 2, where the isopleths record the change in stability with varying values of W and D. Again, stability is expressed as the ratio of the distance between the centers of mass and buoyancy and the total diameter of the shell. Also plotted in Figure 2 are stability values computed from equation 1 (circles) and those from calculations of W and D (dots) for Nautilus and three Cretaceous cephalopods from north-central Texas. Differences between the results of the two methods of determining stability are slight and indicate that W and D are reasonable estimates of shell stability and that their use in this regard will provide accurate stability constants (K_{sa}).

Depth Estimates

Equations 2 and 3 are equations 27 and 28 of Chamberlain and Weaver (1978) and define depths corresponding to the onset of rocking (Z_r) and horizontality (Z_h):

$$Z_r = q_r P_o/[\rho g(C_s - q_r)] \qquad (2)$$

and

$$Z_h = q_h P_o/[\rho g(C_s - q_h)]. \qquad (3)$$

The following parameters are required for calculation: q_r and q_h are the fill parameters of Nautilus (0.07 and 0.37, respectively), P_o is the pressure at the surface (1 bar), ρ is the density of sea water (1.029 g/cm^3), g is the acceleration of gravity (980 cm/sec^2), and C_s is the stability coefficient from equation 1.

At depths less than Z_r, a shell is stable and vertical. At depths greater than Z_h, a shell is unstable and horizontal. In the

strictest sense, Z_r is the maximum depth at which a shell would remain vertical on the sea floor. However, estimates of maximum water depth (Z_e) presented here are one-half of the calculated depth for Z_h for the following reasons. As a shell descends from Z_r to Z_h, its plane of symmetry passes through 90° (from vertical to horizontal) and therefore the plane of symmetry could form any angle between 90° and 0° with the sea floor, depending on the depth at which a shell becomes anchored (if less than Z_h). At angles greater than 45°, possibilities for reworking a shell to the vertical position by organic or physical processes are many. At angles less than 45°, the chances that a shell would be anchored in such a way as to prevent its assuming a horizontal orientation once buoyancy was removed are considerably less. It may be difficult, if not impossible, to differentiate between shells that were anchored in a vertical orientation at depths less than or equal to Z_r and shells that may have come in contact with the sea floor at depths greater than Z_r but less than Z_e and reworked to a vertical orientation. It seems prudent, therefore, to state estimates of maximum water depth in terms of Z_e.

THE FORT WORTH LIMESTONE: A CASE FOR SHALLOW WATER

The Fort Worth limestone, a member of the Washita Group (Lower Cretaceous, Comanchean-Albian), crops out in a narrow belt that extends from the Red River (Texas-Oklahoma boundary) south toward Waco, Texas (Fig. 3). The outcrop belt approximates the western margin of the East Texas Embayment during late Comanchean-Albian time. This embayment occupied a salient that had formed earlier as the Ouachita Fold System changed from an east-west trend to a north-south trend. The northern margin of the embayment was defined by the remnants of the fold belt, the western margin was defined by the Central Texas Platform and the North Texas Shelf, the eastern margin was the Sabine Uplift, and in the south, the San Marcos Arch or Platform to the southwest and the Stuart City carbonate complex to the southeast. Circulation in the embayment (in some sense, a back-reef environment) alternated between an open and a restricted system, as evidenced by the succession of carbonate build-ups along the shelf margin. Informa-

tion from the subsurface suggests that the embayment opened to the Gulf of Mexico southeasterly between the southern end of the Sabine Uplift and the Stuart City carbonate complex (Cook and Bally, 1975; Murray, 1961).

The Fort Worth limestone varies little in thickness along strike, commonly crops out in planar exposures in stream beds, and contains abundant specimens of the ammonites *Mortoniceras wintoni* (Adkins) 1918 and *Drakeoceras drakei* Young 1957 and the nautiloid *Cymatoceras hilli* (Shattuck) 1903, in addition to a varied bivalved-gastropod-echinoid assemblage.

Working only planar exposures, 336 specimens were observed and collected from 17 localities (see Fig. 7 below for the location of collecting sites). Of these, 51 specimens from 11 localities were vertical. All specimens were taken from the upper 10 to 15 cm of the Fort Worth limestone at the contact with the overlying Denton marl. The orientation of each vertical shell relative to north was recorded before the shell was removed from the outcrop with the aid of a portable rock saw. *Mortoniceras wintoni* (moderately evolute form with a square to rectan-
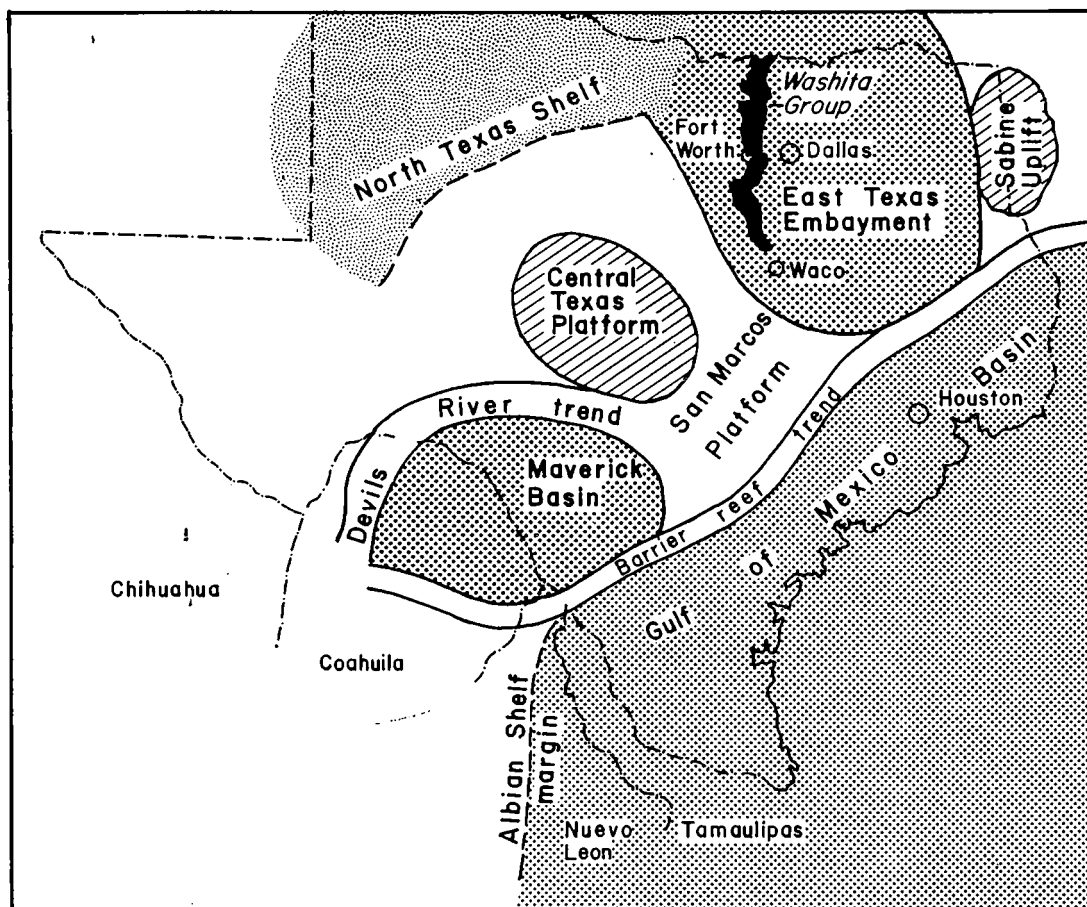

Figure 3. Early Cretaceous (Comanchean-Albian) geography of Texas. Outcrop pattern of Washita Group in north-central Texas shown as solid black. For a description of the major physiographic features, see Murray (1961). Modified from Figure 3 of Young (1972).

gular whorl cross section) was the most abundant, whereas *Drakeoceras drakei* (similar to *M. wintoni* except in aspects of ornamentation and by being more involute) and *Cymatoceras hilli* (involute generally subglobular with a rounded whorl section) occurred in near-equal numbers.

Evidence of Verticality

There is abundant evidence at each sampling locality that the original sediment was extensively bioturbated by the large echinoids *Hemiaster elegans* and *Holaster simplex*. Judging from the size of these echinoids and the density of burrows on the outcrop, it is quite possible that shells with an original orientation other than vertical could have been reworked into a vertical or near-vertical orientation. Fortunately, there are several useful criteria that aid in determining the original orientation of a cephalopod shell at the time of its burial. These are: (1) orientation of the aperture with respect to observed attitude of the shell, (2) a nonrandom orientation of vertical shells presumably reflecting the dominant direction of currents, and (3) geopetal features preserved in the interior of the shell.

The body chamber and aperture should be near that of life position if the vertical orientation is primary. In fact, Reyment (1980) has shown the expected position of the aperture would be rotated a few degrees away (upward) from that of the living animal due to a combination of body-chamber length and the distribution within

the phragmocone of sea water required to induce sinking.

Shells near neutral buoyancy coming to rest on the bottom of a shallow body of water might, at first, display a random orientation with respect to the prevailing current directions. It would be expected, however, that the shells would have reoriented their plane of symmetry normal to the direction of the prevailing current (greatest surface area exposed to the force of the strongest current). Unless there were large differences in the coiling geometry of a shell, the aperture would have an equal opportunity of lying to the right or to the left of the force of the current.

Geopetal features within shells provide the most conclusive evidence regarding the original orientation of shells at the time of primary burial. These features, which are related to the sedimentary infilling of the chambers of shells as they sat vertical or lay horizontal on the bottom, have been described and discussed by Seilacher (1968, 1971). Of the nine expected series of events or routes that a shell can follow before final burial (Seilacher, 1971, Fig. 1), routes 3, 5, 6, 7, and 8 are the easiest to detect and are common in the Fort Worth cephalopods. The type of geopetal features that are most useful are laminae that form as sediment is pulled into camerae by draft filling (intra-cameral draft stream created by external turbulence) through constricted siphuncular openings (route 3 of Seilacher, 1971). Although this would seem to be the most uncommon means of infilling, it appears to be the most common (Seilacher, 1971; personal observation). This infilling is related to holes that formed in the shell by solution or by boring organisms and that help to create a small but effective draft. Under conditions of draft filling, a shell would have remained vertical only if it was anchored by sediment within the body chamber or by some other means.

Of the 51 vertical shells (*Mortoniceras wintoni*, 26; *Drakeoceras drakei*, 11; *Cymatoceras hilli*, 14), most were oriented with the plane of symmetry aligned in a north-northwest–south-southeast direction at each locality, suggesting orientation by currents (Fig. 4). Forty-two shells were preserved with living chambers down and slightly rotated so that the apertural margins were located 5° to 15° from the expected life position. Of the remaining nine shells, three were preserved with the living chambers approximately 180° from life position and six were preserved with living chambers at various positions other than those described. There was no preferred position of apertures with respect to the presumed direction of the current flow (Fig. 4). This is the expected situation, because the geometries of the shells of these three genera are such that the aperture would have had an equal opportunity of lying to the right or to the left of current direction.

Examination of the interior of the 51 vertical shells for evidence of original orientation revealed that 42 shells (22 *Mortoniceras wintoni*, 7 *Drakeoceras drakei*, and 13 *Cymatoceras hilli*) had settled to the bottom with the plane of symmetry normal to

Figure 4. An example of the preferred compass orientation of vertical shells. Alignment of the plane of symmetry of 11 of 14 shells in the same general direction on two bedding surfaces at one locality suggests orientation by currents rather than organic activity. Arrows indicate the direction of aperture orientation. C, *Cymatoceras hilli;* D, *Drakeoceras drakei; M, Mortoniceras wintoni*. Locality, Cobb's Park, Fort Worth.
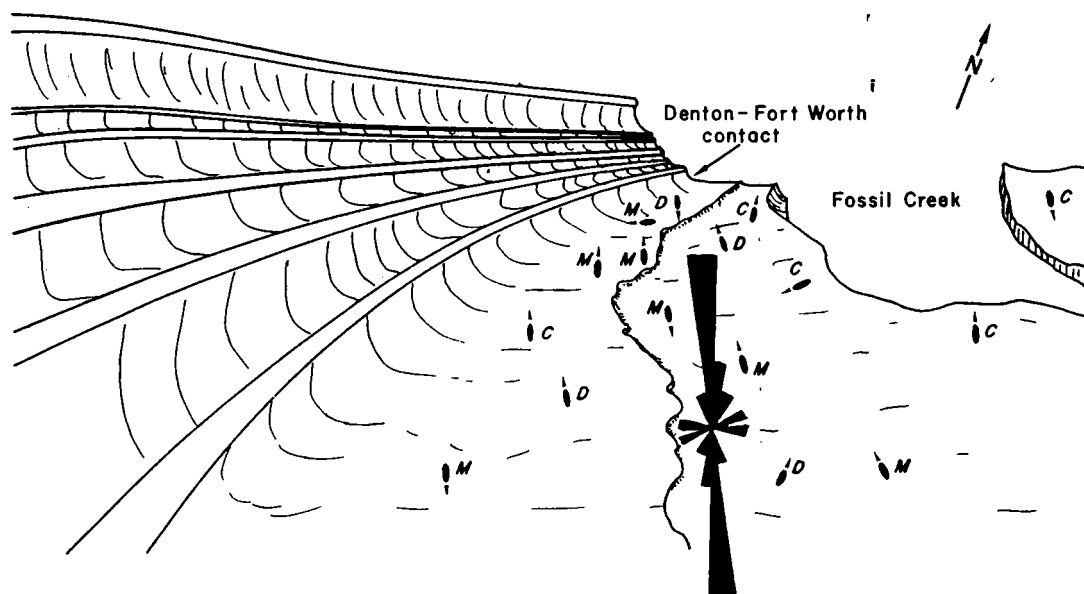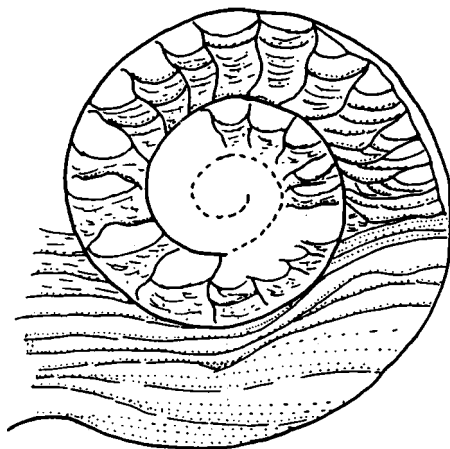
Figure 5. Geopetal features of the type used to determine primary orientation of shells. Diagram of a sectioned *Mortoniceras wintoni* showing the attitude of laminae formed during the infilling of the body chamber and phragmocone of a vertical shell. Cessation of infilling resulted in the absence of laminae in some chambers and in portions of others.

TABLE I. DEPTH ESTIMATES AND VALUES REQUIRED TO DESCRIBE SHELL GEOMETRY AND STABILITY

Genus	W	D	K_s	C_s	Z_r	Z_h	Z_e
Drakeoceras drakei	1.71	0.491	0.100	1.50	0.49	3.25	1.63
Mortoniceras wintoni	2.13	0.382	0.125	1.20	0.61	4.42	2.21
Cymatoceras hilli	2.43	0.059	0.140	1.07	0.69	5.23	2.62
Nautilus pompilius	3.33	0.047	0.150	1.00	0.75	5.82	2.91

Note: W = whorl expansion rate; D = a measure of the distance separating generating curve and axis of coiling; K_s = stability constant; C_s = stability coefficient; Z_r = depth for onset of rocking (in metres); Z_h = depth of horizontality (in metres); Z_e = estimated maximum depth of verticality (in metres).

bedding and had remained in this position long enough to be buried and preserved (route 3 of Seilacher, 1971). When sectioned in the plane of symmetry, two of the remaining nine shells, a *M. wintoni* and a *D. dra-*

kei, contained laminae in the interior of the shell. Alignment of these laminae parallel with the original bedding surface (see Fig. 5) placed the shells in an orientation whereby the living chamber was down and the aperture was within 10° of presumed life position. Before reorientation, the living chambers of the shells were 80° and 55° from life position. These secondary orientations presumably were the result of reworking of the surrounding sediment by the bottom fauna. When sectioned in a plane normal to the plane of symmetry, the remaining seven shells contained laminae that indicated that the plane of symmetry was parallel to bedding when infilling occurred (route 8 of Seilacher, 1971). Verticality of these shells was, therefore, secondary and presumably due to reworking of the sediment.

Of the 285 horizontal shells from the 17 localities, 153 were suitable for sectioning. When sectioned in the plane of symmetry, 36 shells from 4 of the 11 localities having vertical shells contained laminae that would have had to have formed while the shell was in the vertical position. The horizontal orientation of these 36 shells was, therefore, secondary (route 7 of Seilacher, 1971). The remaining 117 shells contained either geopetal structures indicating that horizontality was primary (routes 5 and 6 of Seilacher, 1971) or no discernible geopetal structures at all. This suggests that for the six localities where vertical shells were not observed (no sampling bias suspected) the water depth for latest Fort Worth time was deeper than the limit of verticality for the most stable shell geometry present at these localities.
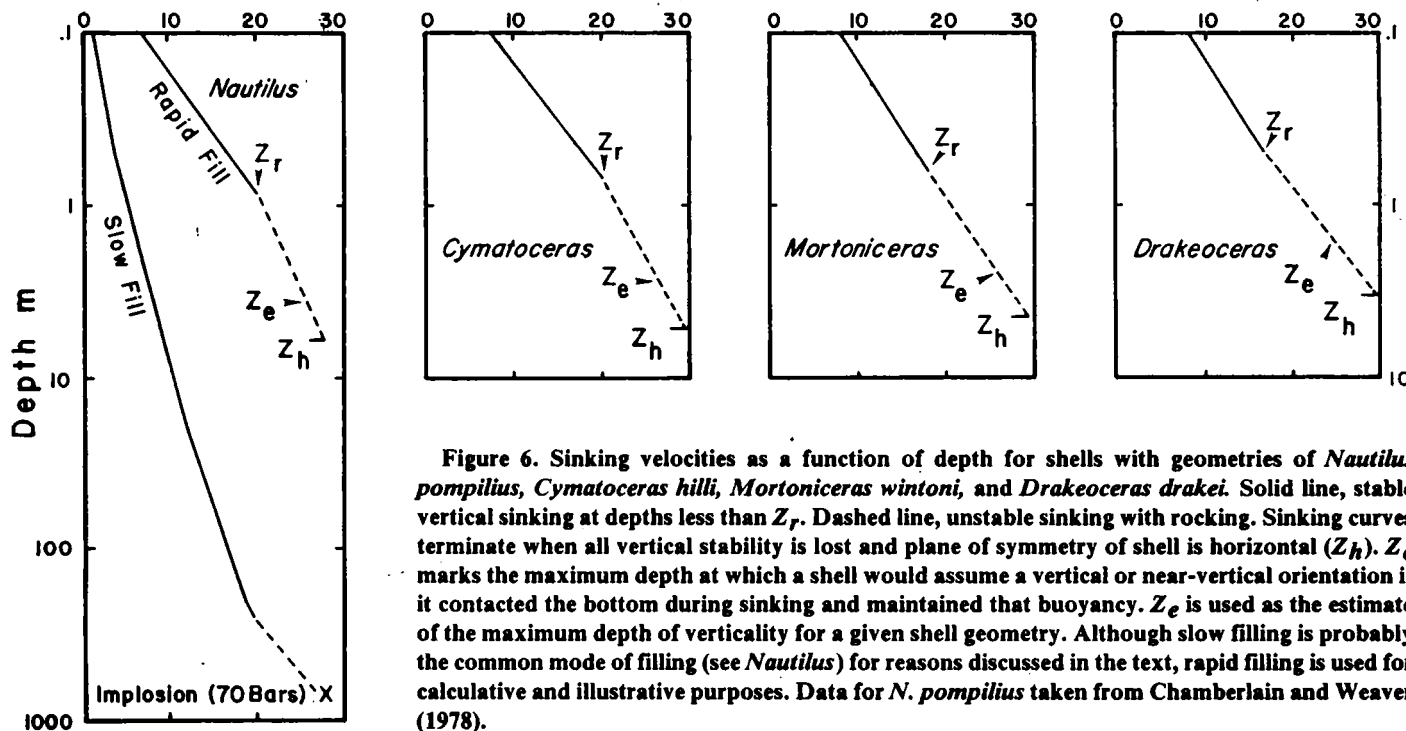
Sinking Velocities cm/sec

Figure 6. Sinking velocities as a function of depth for shells with geometries of *Nautilus pompilius, Cymatoceras hilli, Mortoniceras wintoni,* and *Drakeoceras drakei.* Solid line, stable vertical sinking at depths less than Z_r. Dashed line, unstable sinking with rocking. Sinking curves terminate when all vertical stability is lost and plane of symmetry of shell is horizontal (Z_h). Z_e marks the maximum depth at which a shell would assume a vertical or near-vertical orientation if it contacted the bottom during sinking and maintained that buoyancy. Z_e is used as the estimate of the maximum depth of verticality for a given shell geometry. Although slow filling is probably the common mode of filling (see *Nautilus*) for reasons discussed in the text, rapid filling is used for calculative and illustrative purposes. Data for *N. pompilius* taken from Chamberlain and Weaver (1978).
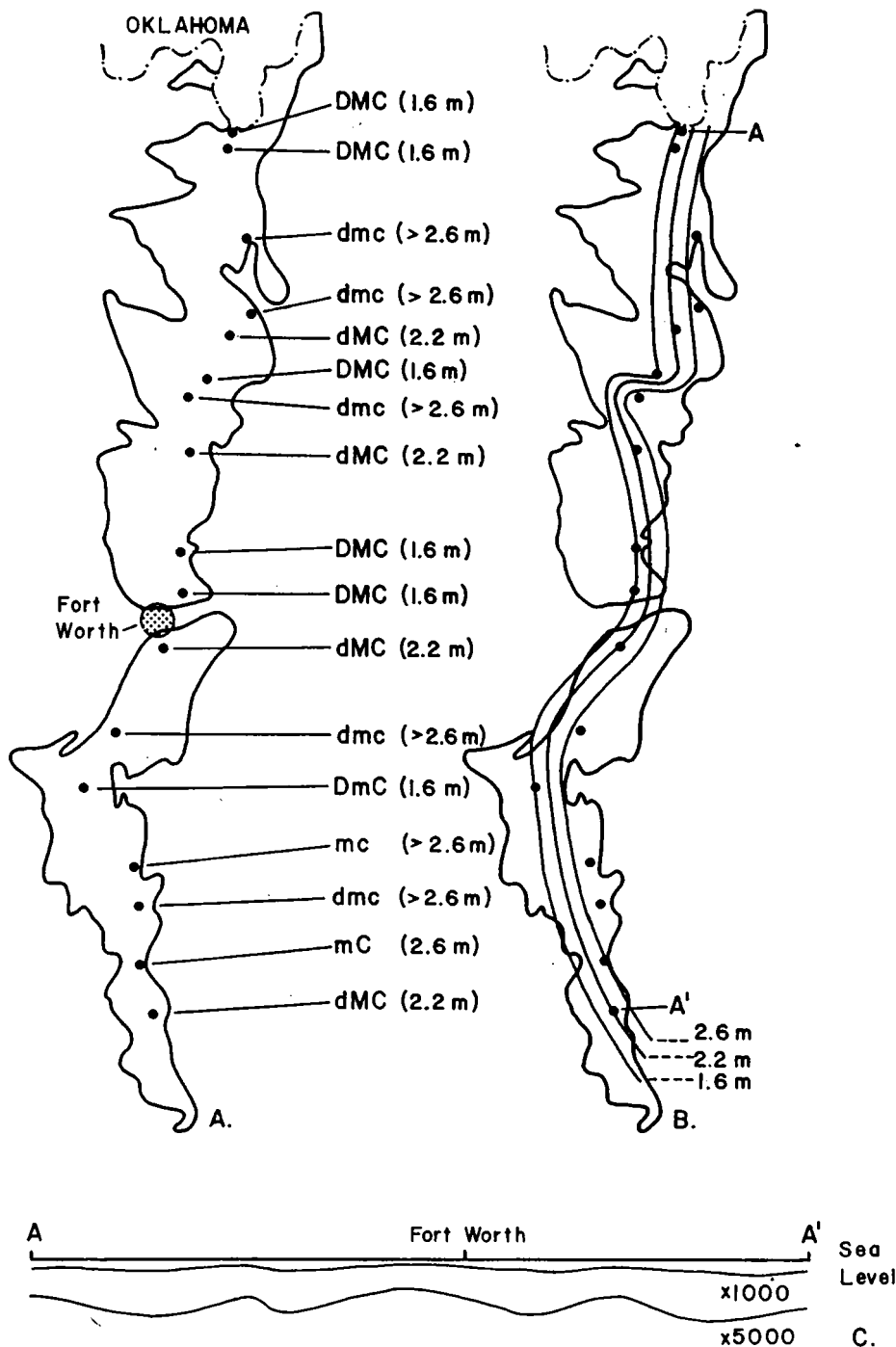
Figure 7. Paleobathymetry along a portion of the western margin of the East Texas Embayment during late Comanchean-Albian time. A. Estimated water depths for 17 sampling localities at the top of the Fort Worth limestone in north-central Texas. Values in parentheses are estimates of water depth (Z_e) for the least stable shell geometry of shells found with the plane of symmetry vertical or nearly vertical. At localities where no vertical shells were found, water depth is given as greater than the estimated depth for the most stable shell geometry present at these localities. B. Resulting paleobathymetric contours. C. Cross section along strike illustrating the relationship of submarine topography to sea level. C, c = *Cymatoceras hilli* (vertical, horizontal); D, d = *Drakeoceras drakei* (vertical, horizontal); M, m = *Mortoniceras wintoni* (vertical, horizontal).

Estimates of Depth

The stability constants (K_s) and coefficients of stability (C_s) for the Fort Worth cephalopods and *Nautilus pompilius* are listed in Table 1. Based on measurements taken from the shells, *Drakeoceras drakei* is the least stable (higher D, lower W) (see Fig. 2 and Table 1), whereas *Mortoniceras wintoni* and *Cymatoceras hilli* are similar, although their respective D values are considerably different. This emphasizes the importance of W as a better measure of stability because it describes the whorl expansion rate, which is the measure of the separation of the centers of mass and buoyancy. Although *C. hilli* and *N. pompilius* have similar D values, they differ appreciably in values of W.

The maximum depths at which each of the Fort Worth cephalopod genera would have been capable of sustaining a vertical or near-vertical orientation were calculated using equations 1, 3, and $Z_h/2$. These depths are listed in Table 1 and compared in Figure 6. The solid portion of each curve in Figure 6 describes the range of velocity and depth over which each shell would remain vertical without rocking. The dashed portion of each curve describes the range of velocity and depth corresponding to the onset of rocking (Z_r) and horizontality (Z_h).

Using these data, it is possible to state that the depth of water covering the carbonate sediment in which these cephalopods were buried was no deeper than approximately 1.6 m if shells of *Drakeoceras drakei* were preserved in a vertical orientation, 2.2 m if shells of *Mortoniceras wintoni* were preserved in a vertical orientation, and 2.6 m if shells of *Cymatoceras hilli* were preserved in this position. That is, the Z_e for vertical shells with the least stable shell geometry (low K_s) becomes the estimate of the *maximum* water depth for a given locality. This reasoning assumes that the presence of horizontal shells with K_s values smaller than those of vertical shells was due to a water depth greater than the Z_e of the horizontal shells. These conditions were found to exist in the Fort Worth limestone at the localities indicated in Figure 7.

Localities can be used as reference points for contouring estimated water depths at particular horizons, because it is possible to assign an estimated maximum depth of water to a sampling locality if it contains vertical shells and minimum water depth if it does not. Reference points and paleo-

bathymetric contours for the top of the Fort Worth limestone are shown in Figures 7A and 7B. The contours indicate that the water deepened to the east with a general increase in depth from the Red River localities southward. Reversals in the general trend along strike exist and are to be expected, as undoubtedly there were irregularities in the sea floor, as suggested by the cross section of Figure 7C.

The paleobathymetry of Figure 7B agrees with the accepted regional geology of north-central Texas for Albian time (Cook and Bally, 1975; Hendricks, 1967; Murray, 1961; Young, 1972), although it significantly reduces estimates of water depth. From the limited sampling control presented here, it can be said only that along a portion of the western margin of the embayment during latest Fort Worth time the water depth was generally less than 2.6 m. This strongly suggests that waters covering the north Texas Shelf and parts of the central platform (Fig. 3) were exceedingly shallow at this time. Aside from occasional references to the water depth of the Fort Worth sedimentary environment as being "shallow" or "deep," G. Scott (1940) gave a depth range of 15 to 40 m based on what he considered to be the optimum depth of water for the development of what R. W. Scott (1972) considered to be shelly, lime-mud substrate that was part of a level-bottom community. Although R. W. Scott (1970a, 1970b, 1971, 1972) has dealt extensively with the Washita units and their lateral equivalents both from a sedimentological and paleoecological viewpoint, he has been unable to establish satisfactory estimate of water depth. The same can be said of other studies of similar facies. The vertical cephalopod shell is the only means available at present by which estimates of maximum water depth can be stated with reasonable confidence. The only prerequisites are that the unit contain coiled cephalopod shells and that the depth of water during the time interval being investigated did not exceed the maximum depth range of verticality of the most stable shell geometry present in the unit.

SUMMARY

Coiled cephalopod shells that sank to the bottom of a body of water in depths less than or equal to the Z_e for the geometry of these shells will, if preserved, provide a reasonable estimate of the depth of the water at the location at which they became anchored, infilled, and buried. Coiled shells can be used to calculate estimates of water

depths for sedimentary environments beginning with the Early Ordovician (Arenigian) tarphycerids and extending through the early Tertiary (Paleocene-Miocene) aturids because it is reasonable to assume that the physical constants of atmospheric pressure, acceleration of gravity, and density of sea water have not changed significantly during the Phanerozoic. The limited distribution and low diversity of post-Miocene nautiloids reduces the possibilities of using these shells as paleobathymetric markers.

The use of geopetal features to determine the orientation of shells at the time of infilling (their primary position) greatly facilitates the use of coiled shells for determining water depth, because shells with the plane of symmetry either vertical or horizontal to bedding can be used for this purpose. This eliminates potential biases in the estimates for depth that might result from observations of reworked shells.

The 17 planar exposures located at the top of the Fort Worth limestone (Lower Cretaceous, Comanchean-Albian) of north-central Texas provide a fair coverage of the carbonate sedimentary environment that existed at the end of Fort Worth time along the western margin of the East Texas Embayment. The three species of coiled cephalopods present in the Fort Worth Formation at these exposures have shell geometries sufficiently different to provide a range of water depths and to allow the assignment of a water depth to localities where shells of at least one of these genera occur with the plane of symmetry vertical or horizontal to bedding. Estimates of water depth based on shells with a plane of symmetry that was originally vertical at 11 of 17 localities show a gradual increase in water depth from west to east across the width of the Fort Worth outcrop (toward the center of the embayment) and from north to south along the length of the outcrop (the western margin of the embayment). Although the general trend of the paleobathymetry presented is in agreement with the Early Cretaceous geology and geography of north-central Texas, southern Oklahoma, and eastern Louisiana, the estimates of water depth are at least an order of magnitude shallower than previous estimates based on what might be less reliable criteria.

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