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# DEPOSITIONAL ENVIRONMENT OF THE CABLE CANYON SANDSTONE: A MID-ORDOVICIAN SANDWAVE COMPLEX FROM SOUTHERN NEW MEXICO

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**Abstract**—The Cable Canyon Sandstone was deposited as a sandwave complex that began during the initial stages of a marine transgression. The sandstone forms a roughly symmetrical "teardrop" or lobe that is eight to 13 m thick along its northwest-southeast-trending axis which extends for nearly 150 km; away from this axis, the sandstone gradually thins to less than one meter over a distance of about 120 km. The unit has a conspicuous marine fauna and consists primarily of medium-grained quartz sandstone with a carbonate (mostly dolomite) matrix. In general, the Cable Canyon is coarsest where thickest, and in most cases grain size increases from the base to the middle of the unit, and then decreases from the middle to the top. These coarse siliciclastics must have been deposited by traction transport processes; however, pervasive bioturbation has destroyed most primary sedimentary structures. Where these primary sedimentary structures have been preserved, they display, from bottom to top: (1) a burrowed zone, 0.6 to 1.0 m thick, with beds and lenses of quartzarenite intercalated with dolomicrite, (2) 0.5 m of medium-scale, trough cross-stratified, coarse-grained sandstone, (3) large-scale, 1.0 to 1.8 m high, lenticular foresets that have small-scale, tabular foresets (which dip in the opposite direction) near their base and (4) 0.5 m of poorly preserved, thin, planar(?), horizontal bedding. This sequence of sedimentary structures indicates that the sandstone was deposited by strong, persistent, highly asymmetrical currents, in waters at least five to 15 m deep. The currents formed subaqueous dunes of quartz sand, analogous to modern sandwave complexes.

## INTRODUCTION

This paper deals with the depositional environment of the Cable Canyon Sandstone, which is the lowermost formation of the Ordovician Montoya Group of southern New Mexico. The unit is underlain by the El Paso Group and gradationally overlain by the Upham Dolomite (Fig. 1). Most earlier work on the Cable Canyon Sandstone has focused on general descriptions, paleontology and stratigraphic nomenclature. While the Cable Canyon's diverse, distinctly marine, fauna has been studied in the past (Flower, 1961), the depositional environment of the unit has not been examined in detail. This study provides a sedimentological description of the Cable Canyon Sandstone and an interpretation of the depositional setting and hydrodynamic processes under which it accumulated. Particular attention is paid to textural parameters, primary sedimentary structures, patterns of deposition and stratigraphic relationships.

The Cable Canyon was examined in the Silver City Range, at Lone Mountain and in the Caballo, Sacramento, Big Hatchet and Florida mountains (Fig. 2). Nine stratigraphic sections were measured. At these locations, samples were generally taken no more than one meter apart; this was sufficient to establish grain-size trends and variations in rock composition.

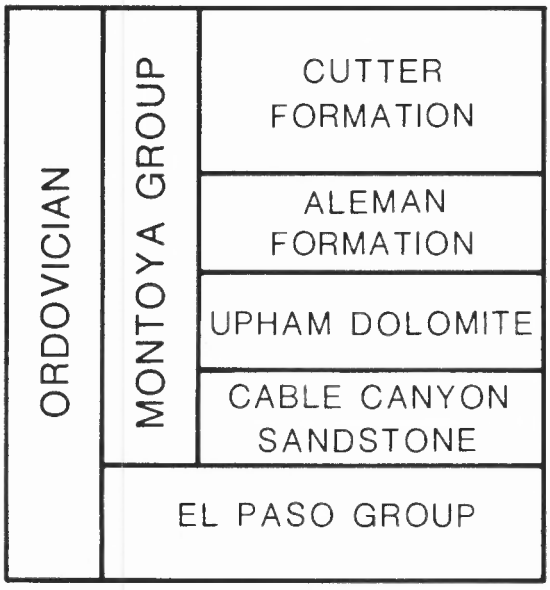



FIGURE 1. Stratigraphic classification used in this study.

## SANDBODY GEOMETRY AND FORMATION THICKNESS VARIATIONS

In map view, the sandbody defined by the Cable Canyon Sandstone is a roughly symmetrical teardrop or lobe (Fig. 3). This lobe is thickest, typically exceeding nine meters, along its northwest-southeast-trending axis, gradually thinning both away from this line of symmetry and to

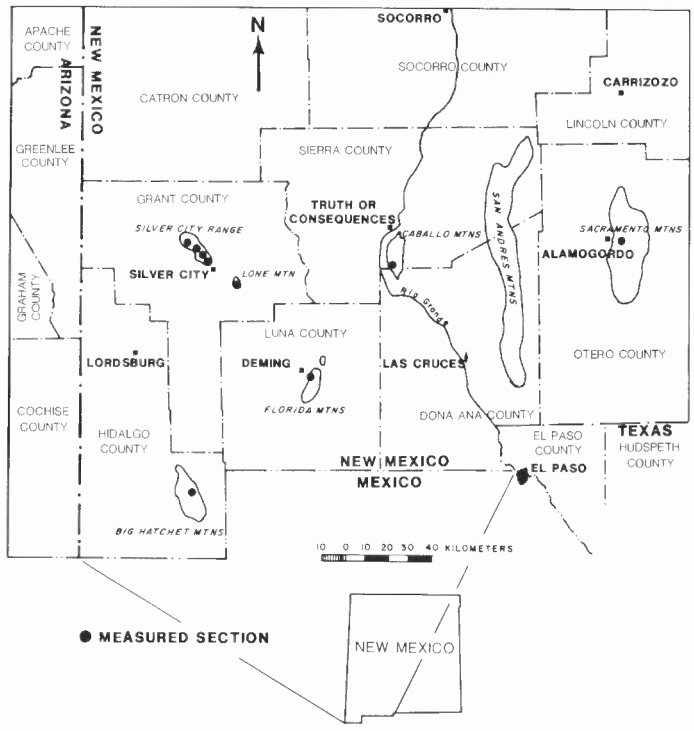



FIGURE 2. Study area showing locations of detailed measured sections.

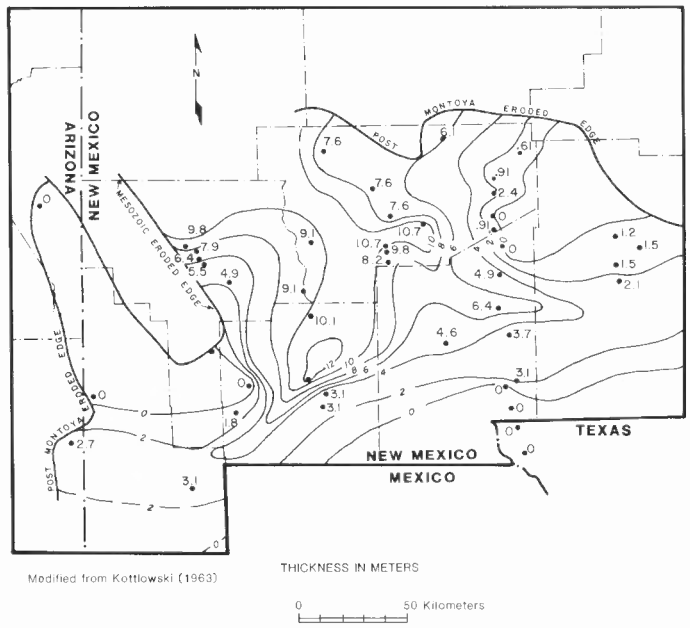



FIGURE 3. Isopach map of the Cable Canyon Sandstone modified from Kottlowski (1963) to include data obtained during this study.

the southeast. During this study, the Cable Canyon was found to be thickest along the northwest side of the Florida Mountains (13.1 m) and thinnest at Alamo Canyon in the Sacramento Mountains (1.0 m). In addition, on a local scale, the Cable Canyon Sandstone can range two meters in thickness over lateral distances of several hundred meters. Thus, superimposed over the regional changes are more localized thickness variations.

The Upham Dolomite gradationally overlies the Cable Canyon Sandstone. Therefore, the lobate shape of the sandstone and the observed regional and local thickness variations must be related to depositional processes and are not an artifact of post-Cable Canyon Sandstone erosion. Unfortunately, the up-dip limit or "depositional zero edge" of the Cable Canyon is poorly defined due to post-Montoya erosion and cover by overlying Tertiary volcanic strata.

## ROCK COMPOSITION

The Cable Canyon Sandstone consists primarily of well-rounded to subrounded quartz sand in a carbonate (mostly dolomite) matrix. Modal analyses further reveal that quartz accounts for 96% or more of the siliciclastic component of the rock; minor amounts of feldspar, heavy minerals, chert and quartzose metamorphic rock fragments were also noted. Intraclasts and bioclastic debris, predominantly crinoid ossicles, combine to form a small percentage of the framework constituents.

Bulk compositional analyses (Table 1) indicate: (1) throughout much of the field area the unit is composed of less than 50% terrigenous material, and therefore, technically, is not a "sandstone" (Folk, 1980) (this would seem to be of purely academic interest, and it is not suggested that the unit be renamed); (2) the unit contains only small amounts of insoluble (in HCl acid) mud. X-ray diffraction of this fine fraction indicates that it is largely composed of quartz silt; in addition, trace amounts of authigenic illite were identified with a scanning electron microscope in freshly broken rock samples; and (3) the unit, in general, is micrite-rich at the base, gradationally more siliciclastic-rich in the middle and micrite-rich again at the top as it grades into the Upham Dolomite. This indicates that during the initial stages of deposition, carbonate mud accumulation predominated. Gradually, the area became dominated by siliciclastic sand accumulation (although carbonate mud continued to be deposited), and eventually the influx of siliciclastic material waned, and once again carbonate mud accumulation prevailed.

TABLE 1. Bulk composition of the Cable Canyon Sandstone. Relative percentages of carbonate mud, siliciclastic sand and insoluble mud. Sample numbers show height in meters above the base of the Cable Canyon Sandstone. In some suites, the uppermost samples are from the Upham Dolomite.

| HEIGHT ABOVE BASE OF FORMATION (meters) | % CARBONATE | % SILICICLASTIC SAND | % INSOLUABLE MUD |
|---|---|---|---|
| | SILVER CITY RANGE<br>Sec. 14, T. 17 S., R. 15 W. | | |
| 8.69 | 88.4 | 9.5 | 2.1 |
| 6.71 | 60.0 | 37.9 | 2.1 |
| 5.79 | 44.0 | 53.8 | 2.2 |
| 5.03 | 46.2 | 50.7 | 3.1 |
| 3.05 | 46.8 | 50.5 | 2.7 |
| 0.30 | 51.0 | 47.8 | 1.2 |
| | SILVER CITY RANGE<br>Sec. 15, T. 17 S., R. 15 W. | | |
| 8.23 | 91.8 | 6.3 | 1.9 |
| 7.62 | 55.1 | 43.2 | 1.7 |
| 3.96 | 43.0 | 55.2 | 1.8 |
| 2.13 | 42.2 | 56.4 | 1.4 |
| 0.91 | 50.6 | 48.7 | 1.9 |
| 0.00 | 56.0 | 41.8 | 2.2 |
| | SILVER CITY RANGE<br>Sec. 14, T. 17 S., R. 15 W. | | |
| 3.66 | 71.7 | 26.1 | 2.2 |
| 3.05 | 68.2 | 29.5 | 2.3 |
| 2.29 | 68.6 | 29.4 | 2.0 |
| 1.07 | 56.5 | 42.0 | 1.5 |
| 0.00 | 61.0 | 35.4 | 3.6 |
| -0.01 | 94.0 | 2.0 | 4.0 |
| | SILVER CITY RANGE<br>Sec. 16, T. 17 S., R. 15 W. | | |
| 10.96 | 83.2 | 15.0 | 1.8 |
| 10.06 | 83.5 | 14.5 | 2.0 |
| 8.53 | 55.1 | 43.1 | 1.8 |
| 5.33 | 42.1 | 56.6 | 1.3 |
| 2.90 | 52.6 | 45.9 | 1.5 |
| 1.37 | 56.0 | 41.5 | 2.5 |
| 0.76 | 77.4 | 19.7 | 2.9 |
| 0.00 | 89.3 | 8.9 | 1.8 |
| | LONE MOUNTAIN<br>Sec. 28,29, T. 17 S., R. 13 W. | | |
| 5.03 | 92.0 | 5.1 | 2.9 |
| 4.72 | 49.5 | 48.7 | 1.8 |
| 4.42 | 42.9 | 55.0 | 2.1 |
| 3.35 | 59.9 | 38.0 | 2.1 |
| 1.37 | 48.1 | 49.7 | 2.2 |
| 0.15 | 76.4 | 19.5 | 4.1 |
| | FLORIDA MOUNTAINS | | |
| 15.24 | 89.2 | 7.7 | 3.1 |
| 12.50 | 76.2 | 21.9 | 1.9 |
| 10.67 | 62.1 | 35.8 | 2.1 |
| 6.10 | 44.1 | 52.0 | 3.9 |
| 3.66 | 58.4 | 38.8 | 2.8 |
| 2.29 | 67.6 | 29.8 | 2.6 |
| 1.52 | 85.0 | 12.6 | 2.4 |
| 0.61 | 87.0 | 10.0 | 3.0 |
| | BIG HATCHET MOUNTAINS<br>Sec. 29, T. 30 S., R. 15 W. | | |
| 4.57 | 94.3 | 3.1 | 2.9 |
| 3.05 | 96.8 | 0.5 | 2.7 |
| 1.83 | 40.8 | 57.3 | 1.9 |
| 1.22 | 30.7 | 68.8 | 0.5 |
| 0.38 | 87.4 | 6.1 | 6.5 |
| 0.00 | 91.1 | 3.2 | 5.7 |
| | CABALLO MOUNTAINS<br>Sec. 10, T. 16 S., R. 4 W. | | |
| 7.62 | 51.4 | 49.6 | 1.8 |
| 6.40 | 46.0 | 51.9 | 2.1 |
| 5.79 | 41.1 | 57.9 | 1.0 |
| | SACRAMENTO MOUNTAINS<br>Sec. 6, T. 17 S., R. 10 E. | | |
| 1.98 | 95.3 | 2.7 | 2.0 |
| 1.07 | 40.1 | 58.7 | 1.2 |

## TEXTURAL QUALITIES OF THE SILICICLASTIC CONSTITUENTS

Primary textural characteristics (mean grain size, sorting, skewness and kurtosis) were determined from sieve data. All of the sieved samples were taken from the suites of specimens collected in conjunction with the nine measured sections; this permitted the measured textural pa-

rameters to be related to vertical position above the base of the Cable Canyon Sandstone (Table 2). These measured parameters provide a basis for delineating trends that relate to the depositional processes that influenced sediment accumulation.

The siliciclastic component of the Cable Canyon Sandstone can be characterized as mostly having: (1) mean grain size in the range of medium sand (250–500 microns, 1 to 2 phi), (2) moderate to poor sorting, (3) nearly normal skewness (close to zero) with some tendency toward an excess of coarse material and (4) generally normal kurtosis (mesokurtic distribution).

TABLE 2. Primary textural parameters of the siliciclastic component of the Cable Canyon Sandstone. Parameters derived from sieve data according to Folk (1980). In some suites, the uppermost samples are from the Upham Dolomite.

| HEIGHT ABOVE BASE OF FORMATION (meters) | MEAN SIZE (phi) | SORTING | SKEWNESS | KURTOSIS |
|---|---|---|---|---|
| | Silver City Range Sec.14, T.17 S., R.15 W. | | | |
| 8.69 | 2.00 | 0.73 | 0.05 | 1.09 |
| 6.71 | 1.88 | 0.73 | -0.15 | 1.15 |
| 5.79 | 1.63 | 0.83 | 0.02 | 0.77 |
| 5.03 | 1.80 | 0.87 | -0.24 | 0.93 |
| 3.05 | 1.47 | 0.75 | 0.07 | 1.14 |
| 0.30 | 1.56 | 0.72 | 0.06 | 0.99 |
| | Silver City Range Sec.15, T.17 S., R.15 W. | | | |
| 8.23 | 1.78 | 0.98 | -0.13 | 1.22 |
| 7.62 | 1.66 | 0.77 | -0.13 | 1.15 |
| 3.96 | 1.37 | 0.86 | -0.05 | 1.05 |
| 2.13 | 1.66 | 0.77 | -0.13 | 1.10 |
| 0.91 | 1.67 | 0.73 | 0.00 | 0.90 |
| 0.00 | 1.60 | 1.01 | -0.08 | 0.97 |
| | Silver City Range Sec.14, T.17 S., R.15 W. | | | |
| 3.66 | 2.02 | 0.74 | -0.02 | 1.08 |
| 3.05 | 1.92 | 0.72 | 0.02 | 1.08 |
| 2.29 | 2.03 | 0.77 | -0.16 | 1.01 |
| 1.07 | 1.72 | 0.68 | 0.01 | 1.08 |
| 0.00 | 1.78 | 0.72 | -0.09 | 0.92 |
| -0.01 | 1.97 | 0.89 | -0.05 | 1.00 |
| | Silver City Range Sec.16, T.17 S., R.15 W. | | | |
| 10.97 | 1.86 | 0.61 | 0.26 | 1.12 |
| 10.06 | 1.74 | 0.85 | 0.11 | 1.04 |
| 8.53 | 1.72 | 0.81 | -0.10 | 1.03 |
| 5.33 | 1.42 | 0.86 | -0.14 | 1.00 |
| 2.90 | 1.61 | 0.62 | -0.03 | 1.05 |
| 1.37 | 1.75 | 0.71 | -0.02 | 1.04 |
| 0.76 | 1.87 | 0.79 | 0.11 | 0.91 |
| 0.00 | 1.88 | 0.75 | -0.02 | 0.89 |
| | Lone Mountain Sec.28,29, T.17 S., R.13 W. | | | |
| 5.03 | 2.37 | 0.62 | -0.07 | 1.26 |
| 4.72 | 1.70 | 0.81 | -0.07 | 0.99 |
| 4.42 | 1.80 | 0.71 | -0.04 | 1.05 |
| 3.35 | 1.57 | 0.72 | -0.09 | 1.06 |
| 1.37 | 0.48 | 0.93 | 0.10 | 1.12 |
| 0.15 | 1.71 | 1.01 | 0.10 | 1.06 |
| | Florida Mountains | | | |
| 15.24 | 1.68 | 0.98 | -0.06 | 0.79 |
| 12.50 | 1.42 | 0.98 | -0.01 | 0.99 |
| 10.67 | 1.07 | 1.09 | -0.03 | 0.97 |
| 6.10 | 1.50 | 0.96 | 0.02 | 1.02 |
| 3.66 | 1.68 | 1.03 | -0.11 | 0.90 |
| 2.29 | 1.97 | 0.79 | -0.23 | 1.15 |
| 1.52 | 2.03 | 1.17 | -0.21 | 0.99 |
| 0.61 | 2.45 | 0.84 | -0.39 | 1.32 |
| | Big Hatchet Mountains Sec.29, T.30 S., R.15 W. | | | |
| 4.57 | 2.25 | 0.73 | -0.33 | 0.81 |
| 3.05 | 2.01 | 0.87 | -0.05 | 0.85 |
| 1.83 | 2.31 | 0.76 | -0.35 | 0.82 |
| 1.22 | 2.32 | 0.89 | -0.38 | 0.75 |
| 0.30 | 2.24 | 0.74 | -0.14 | 0.74 |
| 0.00 | 2.27 | 0.74 | -0.03 | 0.76 |
| | Caballo Mountains Sec.10, T.16 S., R.4 W. | | | |
| 7.62 | 0.92 | 1.34 | -0.01 | 0.87 |
| 6.40 | 1.08 | 1.19 | -0.04 | 0.90 |
| 5.79 | 1.20 | 1.31 | -0.18 | 0.76 |
| | Sacramento Mountains Sec.6, T.17 S., R.10 E. | | | |
| 1.98 | 2.24 | 1.25 | -0.30 | 0.63 |
| 1.07 | 0.80 | 1.30 | 0.14 | 0.67 |

A generalization can be made about variations in mean grain size across the field area. Typically, the Cable Canyon Sandstone tends to be coarser-grained where the unit is thick (more than 9 m), that is, along the central axis of the depositional lobe, and finer-grained where the unit is thin (less than 3 m), that is, around the edges of the lobe. In contrast to the regional differences in mean grain size, there does not appear to be much lateral variation in sorting, skewness or kurtosis across the study area.

In addition to regional variations, mean grain size also varies from the base to the top of the formation. At five of the nine measured sections, the Cable Canyon coarsens-upward from the base to the middle and then fines-upward toward the top (Table 2; Bruno, 1987). Two of the measured sections show no clear vertical trend, and two others are inconclusive because of too few data points. These trends substantiate less quantitative field estimates of variations in mean grain size. There does not appear to be much vertical variation in sorting, skewness or kurtosis.

## SEDIMENTARY STRUCTURES AND PATTERN OF DEPOSITION

Throughout most of the study area, the Cable Canyon Sandstone has been extensively bioturbated, and thus, primary sedimentary structures formed by traction transport processes have rarely been preserved. However, at Lone Mountain a well developed sequence of primary sedimentary structures has been preserved because bioturbation was minimal. Although the Lone Mountain exposure is unique in this respect, the textural and compositional similarities of the Cable Canyon Sandstone at this location, when compared to other exposures throughout the study area, suggests that a similar set of processes were active throughout the region. It is unclear why primary sedimentary structures were preferentially preserved at Lone Mountain. However, they do provide a firm basis for interpreting the depositional environment of the Cable Canyon Sandstone.

At the Lone Mountain exposure, the Cable Canyon Sandstone can be subdivided into four zones, A through D, from bottom to top, on the basis of primary sedimentary structures and bedding characteristics (Fig. 4).

Sitting directly above stromatolitic horizons on the El Paso Group, the lowermost part (zone A) of the Cable Canyon consists of a 0.6- to 1.0-m-thick interval that contains quartz-sand-filled burrows, and lenses and thin beds of quartzarenite, in a matrix of essentially siliciclastic-free dolomicrite (Fig. 5A). Fragments of crinoids, brachiopods, gastropods and bryozoans were noted in this zone. In other parts of the field area this same interval consists of either alternating thin interbeds of dolomicrite and quartzarenite (e.g., at Mescal Canyon in the Big Hatchet Mountains), or of extensively bioturbated quartz-sand-rich dolomicrite with no discernible bedding. The variability in this interval

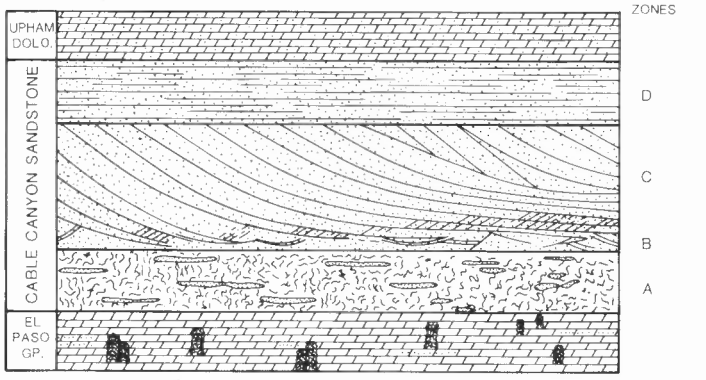



FIGURE 4. Schematic diagram of the Cable Canyon Sandstone at Lone Mountain. Zones based on sedimentary structures. See text for explanation.

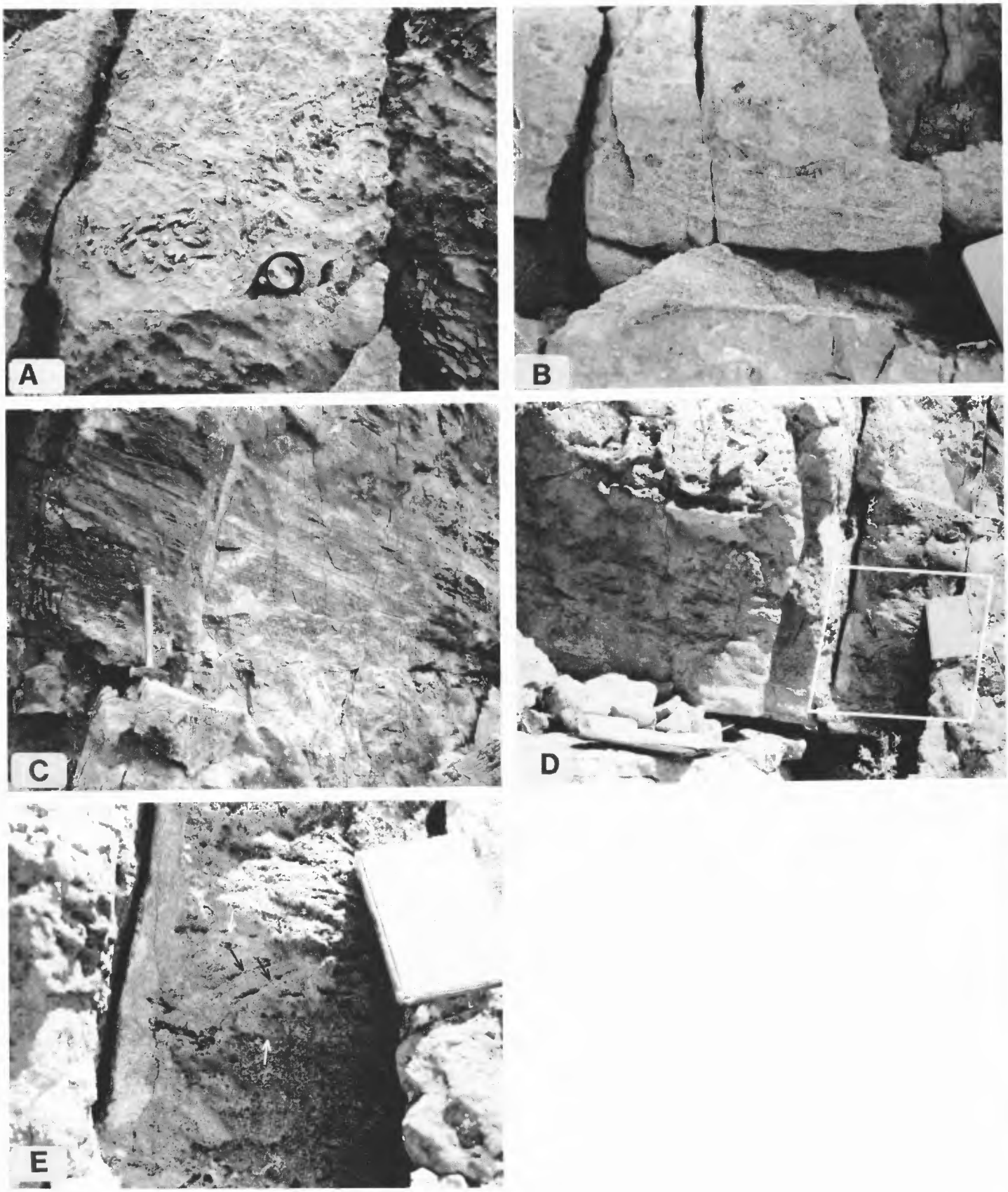



FIGURE 5. A, Zone A: quartz sand-filled burrows in a matrix of dolomicrite. Hand lens is approximately 2.5 cm; B, Zone B: trough cross-stratification. Field notebook is 18 cm long; C, Zone C: large-scale foresets. Sledge hammer is 40 cm long; D, Small-scale tabular foresets (black arrow); E, Close-up view of box shown in D; small-scale tabular foresets (black arrows) between bounding surfaces of large-scale foresets (white arrows). Field notebook for scale.

simply reflects different degrees of bioturbation in strata that accumulated as alternating carbonate and siliciclastic interbeds.

Zone B, which is in sharp contact with zone A, is 0.5 to 1.0 m thick, and consists of poorly preserved, medium-scale, trough cross-stratified, dolomitic quartzarenite (Fig. 5B). Zone B is less micritic than the underlying zone A and more micritic than the overlying zones C and D. The siliciclastic constituents of zone B are slightly coarser-grained than those in the other three zones. In addition, field observations indicate that the siliciclastic constituents within zone B define a subtle, fining-upward sequence. The orientations of the trough axes show a spread of 90° (Fig. 6a), but, in general, have a northeasterly trend. The regional significance of these and other paleocurrent directions measured at the Lone Mountain exposure should not be over-emphasized, as they represent a small number of data points from only one location.

Large-scale, simple, lenticular foresets are the dominant primary sedimentary structure in zone C (Fig. 5C). The foresets are 1.0 to 1.8 m in height, up to 12 m in length and asymptotically approach, and in places truncate, the underlying zone of trough cross-stratification (zone B). Dip angles on the foresets range from 16° to 19° near the tops of the foresets to less than 2° along their tangential bases. Figure 6b illustrates the spectrum of dip directions measured on the foresets, which, in general, are to the southeast. Individual foresets are medium to thinly bedded, show thicknesses of 8.0 to 20.0 cm near the top of the zone and thin to between 3.0 and 8.0 cm where the beds approach the lower bounding surface.

Within some of the large-scale foresets there is a subordinate class of small-scale, tabular foresets (Figs. 5D, E). These smaller foresets: (1) are 5 to 10 cm in height, (2) dip at 15° to 20° in a northwesterly direction (Fig. 6c) and (3) only occur on the lower one-third of the large-scale lenticular foresets. In contrast, the internal structure of the upper two-thirds of the large-scale foresets is massive, showing subtle fining-upward sequences.

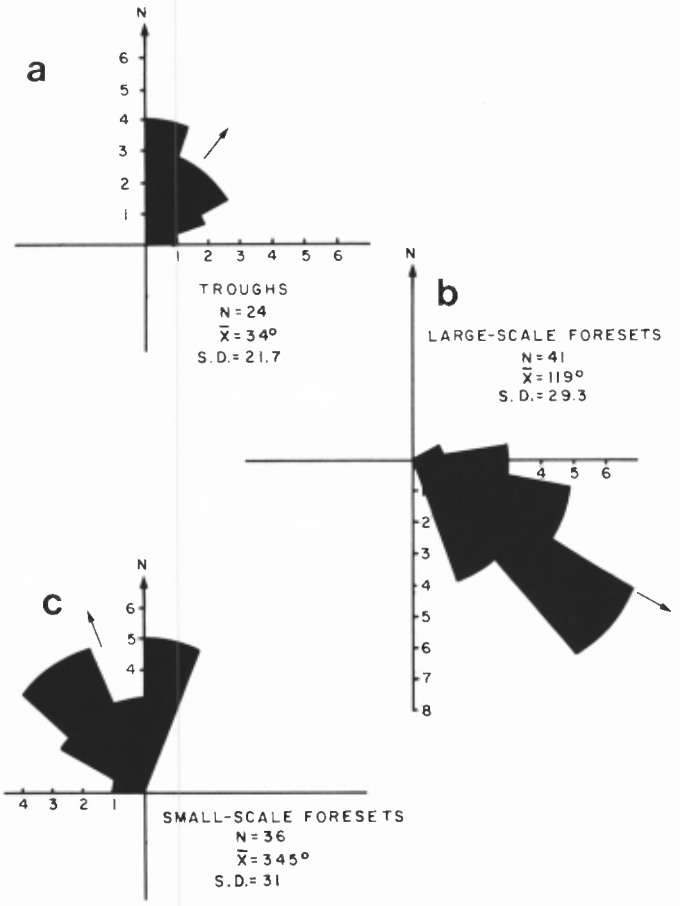



FIGURE 6. Paleocurrent measurements from Lone Mountain.

Zone D consists of 0.3 to 0.5 m of poorly preserved, 2- to 10-cm-thick, planar(?), horizontal beds which truncate the tops of the underlying large-scale lenticular foresets of zone C. These planar beds are difficult to trace laterally due to bioturbation and patchy silicification.

At Lone Mountain, the contact between the Cable Canyon Sandstone and the Upham Dolomite, although still clearly gradational, is sharper than at other places in the field area. This probably reflects lower levels of bioturbation at this exposure. The contact parallels the planar(?), horizontal beds of zone D.

## DEPOSITIONAL ENVIRONMENT OF THE CABLE CANYON SANDSTONE

Several fundamental deductions can be made about the depositional environment of the Cable Canyon Sandstone: (1) Faunal constituents and extensive bioturbation clearly demonstrate that the Cable Canyon Sandstone was deposited in a subtidal, open-marine environment; (2) The pattern of primary sedimentary structures observed at Lone Mountain and the presence of coarse-grained quartz sand record periods of high energy, while large quantities of depositional micrite suggest periods of low-energy conditions; (3) A transgression accompanied the introduction of siliciclastic material. At Lone Mountain, this transgression is recorded by the change from intertidal, stromatolite-dominated, dolomicrite strata (the upper El Paso Group), to subtidal, mixed carbonate-siliciclastic deposits that contain an assortment of open-marine fossils and have undergone a moderate to high degree of bioturbation (Bruno, 1987); alternatively, the change may reflect the inundation of exposed El Paso Group carbonate strata (i.e., a transgression over a disconformable, subaerially exposed surface), as has been suggested by Kelley and Silver (1952), Flower (1953) and Kottlowski et al. (1956). In either case, a transgression must have accompanied the initial introduction of siliciclastic material.

Prior to final deposition, the siliciclastic component of the Cable Canyon Sandstone may have experienced a residence period in high-energy coastal environments (i.e., eolian and beach environments). This is indicated by the abundance of rounded quartz grains, overall compositional maturity and general lack of rock fragments. Eschner and Kocurek (1986) found that slumping, liquefaction and mass flowage commonly occur when coastal dunes and ergs are inundated; furthermore, these processes were found to be significant mechanisms for both dune destruction during transgression and for transport of sand to the shelf.

With the three deductions enumerated above as constraints, the strata that comprise the Cable Canyon Sandstone are interpreted to have been deposited as a sandwave complex on a current-swept siliciclastic shelf. Sandwave complexes have been described from both Holocene and ancient deposits. These complexes develop where strong tide, storm and/or wave-driven currents sweep sand grains into large-scale subaqueous dunes (Banks, 1973).

Modern sandwave complexes have been described from many locations, in both open-marine settings such as: (1) the North Sea (Stride, 1963), (2) the Irish Sea (Harvey, 1966), (3) Georges Bank (Jordan, 1962) and numerous other places on the North American Atlantic shelf (Swift et al., 1979), (4) off the coast of the southeastern tip of Africa (Flemming, 1978) and (5) in the Taiwan Straits (Boggs, 1974), and in estuarine settings (Jago, 1980). These sandwave complexes are most common on broad, shallow shelves, generally occurring in water depths between five and 60 m, in areas dominated by strong tidal currents (Dingle, 1965; Belderson and Stride, 1969; Twichell, 1983). Nio (1976) concluded that marine transgressions, in association with strong tidal currents, were important to the development of sandwave complexes. Observations made during this study support Nio's (1976) conclusion, because the depositional sequence for the Cable Canyon Sandstone is interpreted to record the seaward redistribution of siliciclastic coastal deposits, mainly by asymmetrical tidal currents, in response to a transgression.

In most cases, modern sandwaves have been identified from shallow seismic (sparker) profiles and side scan sonar. Although modern subaqueous sandwaves have been thoroughly documented by remote sen-

sing techniques and occasionally photographed (Field et al., 1981), the internal structure of these modern bedforms has not been adequately examined due to the limitations of contemporary coring techniques. In addition, some authors (e.g., Walker, 1984) have noted that the surfaces of modern sandwaves show evidence of extensive bioturbation, suggesting that, like the Cable Canyon Sandstone, primary sedimentary structures may not be well preserved.

Although most attempts to examine directly the internal structure of modern sandwaves have been unsuccessful, some workers have developed models based on fluid-dynamic considerations (Allen, 1980a, b). In addition, detailed work on ancient sandwave complexes in which primary sedimentary structures have been preserved (Swett et al., 1971; Narayan, 1971; Nio, 1976; Level, 1980; Blakey, 1984), combined with the theoretical models, provide a framework for identifying paleo-sandwave complexes. Comparing these theoretical and practical models with the depositional pattern observed at Lone Mountain provides much of the basis for interpreting the depositional environment of the Cable Canyon Sandstone.

The depositional sequence observed at Lone Mountain is interpreted to record the "life-history" of this paleo-sandwave complex. Nio (1976) recognized similar stages in the Cretaceous Lower Greensand Formation which he interpreted as a sandwave complex. The Lone Mountain exposure can be subdivided into five phases, each reflecting a stage in the "life" of the sandwave complex. These are: prenatal, birth, life, death and burial.

### Prenatal

The lowermost meter of the Lone Mountain exposure (zone A), the zone that contains quartz-sand-filled burrows and discrete lenses/beds of quartzarenite surrounded by siliciclastic-free dolomicrite, was deposited during the "prenatal" or initial phase of the sandwave complex (Fig. 7A). In the early part of this stage, subtidal carbonate accumulation predominated, as indicated by both the presence of an open-marine fauna and the rather high level of bioturbation; siliciclastic material was slowly introduced into this offshore setting. The compositionally and texturally mature siliciclastic material was probably derived from quartzose sedimentary and metamorphic rocks, and/or high-energy coastal accumulations such as beaches and eolian deposits. The siliciclastic material was transported offshore by tidal and/or storm processes. Across most of the depositional site sedimentation rates were slow enough to allow most of the terrigenous sand to be burrowed. However, based on examination of the less bioturbated areas, where quartz sand occurs only in burrows and discrete beds, there is some indication that the siliciclastic material was deposited in an episodic fashion. The lowermost parts of some other ancient sandwave complexes also consist of bioturbated, interbedded fine- and coarse-grained strata (e.g., the Roda sandwave complex, Tertiary of northern Spain and the Lower Greensand sandwave complex on the Isle of Wight off the southern coast of England; Nio, 1976).

### Birth

The 0.5 m of trough cross-stratified quartz sandstone records the "birth" of the sandwave complex and the shift from predominantly carbonate accumulation to predominantly siliciclastic accumulation (Fig. 7B). The trough cross-stratification developed from migrating, medium-scale (probably less than 1.0 m in height), sinuous-crested, subaqueous dunes of quartz sand.

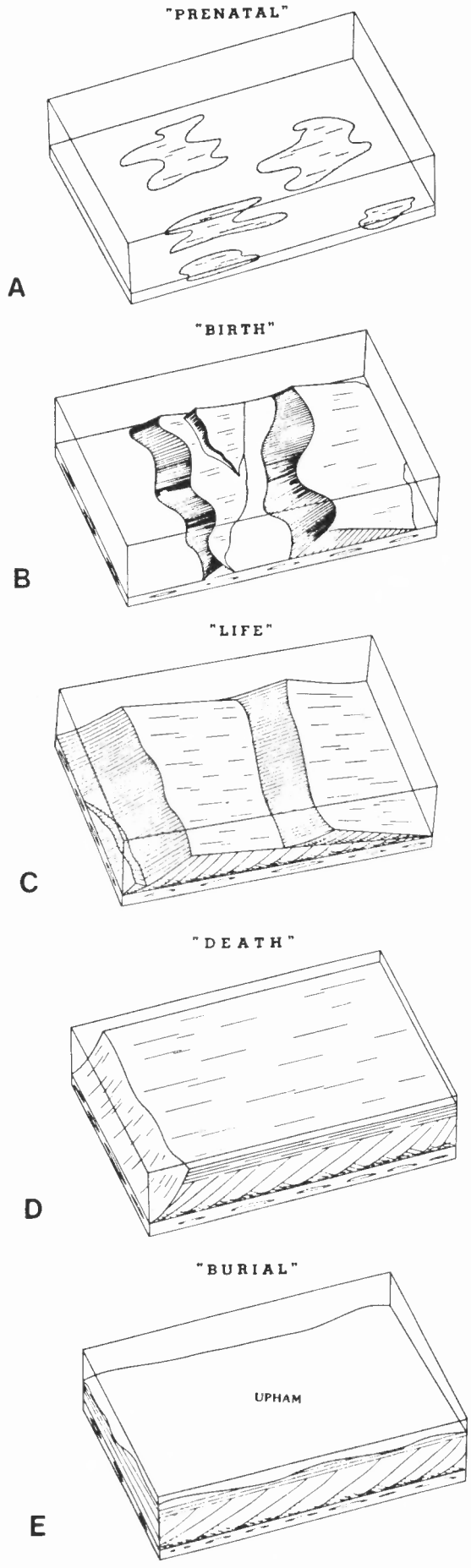



FIGURE 7. Interpreted stages in the "life" of the sandwave complex. A, Prenatal: during the initial phase of the complex, terrigenous sand is slowly, perhaps episodically, introduced into a subtidal, carbonate mud-dominated environment; B, Birth: the birth of the sandwave complex records the change from predominantly carbonate to predominantly siliciclastic deposition. Medium-scale, sinuous-crested dunes migrate across the sea floor; C, Life: this is the climax of the sandwave complex. Large-scale, relatively straight-crested, subaqueous dunes of quartz sand dominate the shelf; D, Death: during the death phase of the complex the dunes begin to wash out and are truncated; E, Burial: as siliciclastic deposition slows, subtidal carbonate sedimentation (i.e., the Upham Dolomite) dominates the shelf.

### Life

Large-scale lenticular foresets record the maximum development of the siliciclastic sandwave complex (Fig. 7C). These large-scale foresets developed from migrating 1- to 2-m-high, relatively straight-crested, subaqueous dunes of quartz sand. While these bedforms indicate that this area was dominated by high-energy conditions, the carbonate matrix denotes at least brief periods when lower energy conditions prevailed.

The small-scale, back-flow cross-stratification that is present on the lower third of the slip faces of these large-scale dunes (Fig. 5D, E) may have developed in response to asymmetrical tidal currents, with the subordinate tidal current resulting in a small amount of sediment being moved in the opposite direction of the dominant tidal current, and/or separated flow, that is, down and back-curling currents that develop whenever rapidly moving fluids pass over an obstruction (the sandwaves in this case) (Allen, 1980a).

Some estimates can be made about the hydrodynamic conditions under which the strata that comprise the "life" phase were deposited. The internal structures of sandwaves reflect the hydrodynamic regime under which they accumulated, taking into account both the velocity and the directional symmetry of the currents (Dingle, 1965; Allen, 1980b). Allen (1980a) developed six theoretical classes of sandwaves based on variations in internal structure. Based on Allen's (1980a) work, the pattern of structures observed in the "life" stage suggests relatively strong (shear velocities greater than 100 cm/sec), persistent, highly asymmetrical (i.e., almost unidirectional) currents. Velocities on this order of magnitude have been recorded over modern sandwave complexes. For example, currents between 50 cm/sec and 120 cm/sec were found over sandwaves on Georges Bank (Twichell, 1983).

Allen (1970) suggested that a relationship exists between the height of sandwaves and the water depths under which they accumulate. The proposed relationship holds that sandwave height (H), and water depth (d), are related by the equation:

$$H = 0.086d^{1.19}$$

This relationship may indicate that the sandwaves that form the Lone Mountain exposure were deposited in waters between 5 and 15 m deep.

Alternatively, Bokuniewicz et al. (1977) found that sandwave height was independent of water depth in most cases in the Long Island Sound area of New York, and that the equation offered by Allen (1970) gives only the maximum sandwave height for a given water depth. Thus, the sandwaves in question could have been deposited in deeper water.

### Death

The poorly preserved, thin, horizontal beds of quartz sandstone that truncate the tops of the large-scale foresets mark the "death" or washout phase of the sandwave complex (Fig. 7D). This may reflect either a depletion of the source of siliciclastic material, or the development of new hydrodynamic conditions which were either incapable of delivering siliciclastic material to the shelf or unable to maintain the sandwave bedform. Bokuniewicz et al. (1977) suggested that sandwave development is controlled primarily by the availability of suitable sediment, rather than suitable flow. Alternatively, it also seems reasonable that continued or renewed transgression may have resulted in isolation of the sediment source and/or deeper water conditions with lower energy bottom currents. Pryor and Amaral (1971) described a similar depositional sequence from the St. Peter Sandstone of southern Wisconsin. They attributed a zone above truncated foresets to reworking by wave and current action or bioturbation.

### Burial

The change from predominantly siliciclastic sand deposition back to predominantly carbonate mud accumulation, and consequently the burial of the sandwave complex, is recorded in the gradational contact between the Cable Canyon Sandstone and the Upham Dolomite (Fig. 7E). The lower part of the Upham Dolomite is interpreted to record open-marine, shelf-carbonate accumulation (Bruno, 1987).

Another line of evidence that supports the sandwave interpretation is the local thickness variations, up to 2 m over a lateral distance of hectometers. These variations may reflect the ridge and swale topography of the sandwaves, and are on scale with height-to-length ratios of 1:200 to 1:1000 that have been reported for some modern sandwaves (Caston, 1965; McCave, 1971; McCave and Langhorne, 1982; Twichell, 1983).

It is difficult to compare the grain-size variations observed during this study to modern sandwaves, because both fining-upward sequences (Harvey, 1966; Twichell, 1983) and coarsening-upward sequences (Terwindt, 1971; Langhorne, 1973) have been recognized. However, integrating vertical grain size variations with compositional variations (i.e., quartz sand-to-micrite ratios) gives further insight into the development of the sandwave complex. In the early stages of the sandwave complex, small amounts of generally finer-grained siliciclastic sediment were deposited. As sedimentation continued (moving into the "Birth" and "Life" phases), higher energy conditions evolved, resulting in the deposition of larger amounts of generally coarser-grained siliciclastic sediment. Finally, as the complex "died" and began to be buried, energy conditions waned, and both the size and amount of siliciclastic sand being deposited were reduced.

## CONCLUSIONS

Primary sedimentary structures, combined with textural and compositional data, indicate that the Cable Canyon Sandstone was deposited as a sandwave complex. The "life cycle" of this complex can be deduced from the depositional pattern observed at Lone Mountain. A transgression accompanied the introduction of siliciclastic sand into what had been a shallow subtidal, carbonate-mud-dominated environment. Subsequently, large subaqueous dunes of quartz sand developed. These dunes eventually entered a washout phase, and the area was again dominated by subtidal, carbonate-mud accumulation (the Upham Dolomite). By analogy with modern sandwave complexes and theoretical models, the sandstone was deposited in waters at least 5 to 15 m deep, under strong, persistent, highly asymmetrical (almost unidirectional) currents.

Vertical variations in grain size and bulk composition reflect changes in energy conditions at the site of deposition. Paleocurrent data from Lone Mountain suggest sediment transport was largely to the southeast during the climax of the complex. Because the Cable Canyon Sandstone is gradationally overlain by the Upham Dolomite, the lobate shape of the sandbody, as well as the observed thickness variations, must be related to depositional process and are not due to post-Cable Canyon erosion.

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