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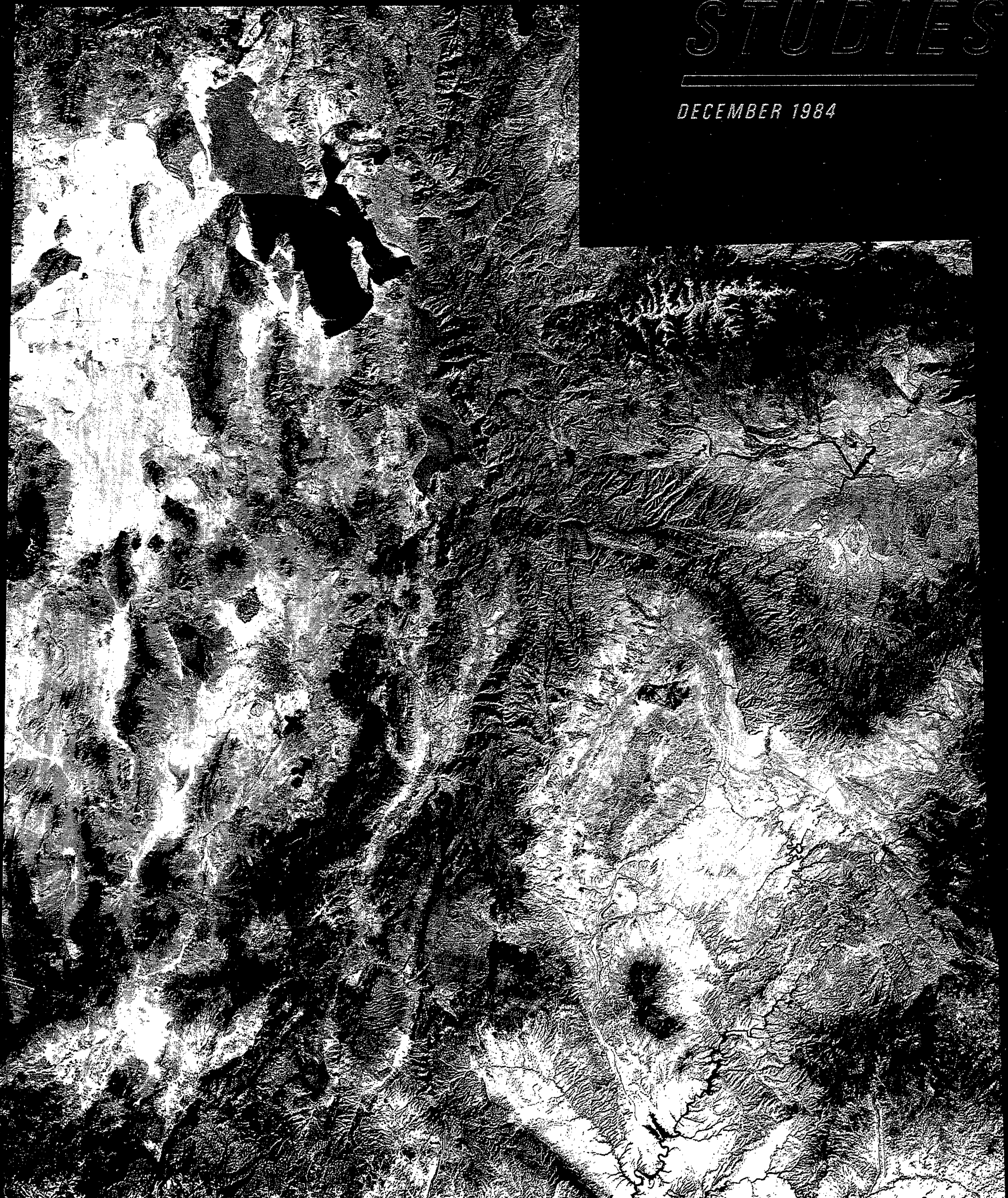

VOLUME 31, PART 1

BRIGHAM YOUNG UNIVERSITY GEOLOGY STUDIES

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THE GLORY OF GOD IS INTELLIGENCE

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Depositional Environments and Paleoecology of Two Quarry Sites in the Middle Cambrian Marjum and Wheeler Formations, House Range, Utah*

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ABSTRACT

Depositional environments and paleoecology of two quarry sites were studied in the upper Wheeler Shale at Swasey Spring and in the lower Marjum Formation at Sponge Gully. The Wheeler Shale at Swasey Spring represents a deep basinal facies of the House Embayment that extended westward from the House Range. Sedimentation was dominated by rapid influx of detritus in turbidity currents coming off the carbonate platform to the east and flowing into the deep basin. This environment is characterized by thin-bedded dark shale and limestone, graded beds, lack of any type of gravity slides, moderately well oriented fossils, and tool marks.

A transitional slope to basin environment is seen in the lower Marjum Formation at Sponge Gully. As the carbonate bank migrated westward during the Middle Cambrian, turbidity current deposition reflected the transition from basin to slope. Dark shale and limestone (thicker and coarser than that at Swasey Spring), graded beds, soft-sediment folds and slides, well-oriented fossils, and tool and sole marks demonstrate the slope-to-basin transitional environment.

The organisms at both quarries appear to have been transported in by turbidity currents and rapidly buried to allow their excellent preservation. A minor benthic community existed at times and is recorded by trace fossils, but they appear to have been only temporary communities established because of influx of oxygen in turbidity currents. These communities quickly diminished when the oxygen was depleted.

INTRODUCTION

Two quarry sites, which produced excellently preserved Middle Cambrian fossils, were excavated in the House Range, Utah (fig. 1). One is in the upper Wheeler Shale near Swasey Spring (fig. 2), and the second is in the lower Marjum Formation at Sponge Gully (fig. 3). The Middle Cambrian Wheeler and Marjum Formations within the quarries represent a moderately deep turbidite facies. The quarries expose mostly repetitive, coarse-to-fine, thin-bedded (0.3 to 5 mm), dark gray calcareous shales, with minor amounts of coarse-to-fine, thin-bedded (1 to 10 mm), black limestone.

Wheeler and Marjum beds are included within the *Bolaspidella* trilobite zone (Robison 1964a, p. 999; 1976, p. 96). During that part of Middle Cambrian time a deep-water embayment extended eastward into the carbonate

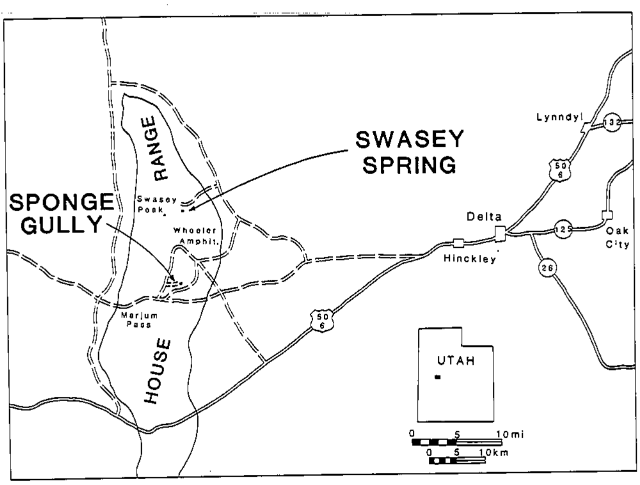

FIGURE 1.—*Index map showing location of quarries.*

*A thesis submitted to the Department of Geology, Brigham Young University, in partial fulfillment of the requirements for the degree of Master of Science, May 1983.

FIGURE 2.—*View looking south at the Wheeler Shale in the Swasey Spring quarry.*

FIGURE 3.—*View looking north at the Marjum Formation in the Sponge Gully quarry.*

shelf, through the present day House Range (Brady and Koepnick 1976; fig. 4). A detailed study of the depositional environments and paleoecology of the turbidite facies in the quarries will be the scope of this paper.

LOCATION

SWASEY SPRING SITE

The Swasey Spring quarry is located on the northeastern slope of the House Range (fig. 1), approximately 0.65 km (0.4 mi) south of the BLM watering trough, in the SE ¼, SW ¼, NE ¼ of section 24 (unsurveyed), T. 16 S, R. 13 W, on the Swasey Peak 7½-minute Quadrangle. The locality is 0.65 km (0.4 mi) south and 0.56 km (0.35 mi) west of the northeast corner of section 24. The quarry is on the brow of a small spur, with light-colored rock debris on both sides, which makes it easily seen from the road.

SPONGE GULLY SITE

The Sponge Gully quarry is approximately 5 km (3.1 mi) northeast of Marjum Pass (fig. 1) in the NE ¼, NE ¼, SE ¼ of section 4, T. 18 S, R. 13 W (unsurveyed), along the east flank of the House Range, on the Marjum Pass 7½-minute Quadrangle. The locality is 1 km (0.62 mi) south and 0.28 km (0.17 mi) west of the northeast corner of section 4. Gently tilted lower Marjum beds are exposed beneath a pediment thinly veneered with gravel.

METHODS OF STUDY

Detailed stratigraphic sections were measured with a meter stick in each quarry and markers were established every 25 cm, or less, so that the stratigraphic position of each recovered fossil could be recorded. During quarrying, bedding planes were exposed, allowing detailed observation over large bedding surfaces. Occurrence, association, and orientation of fossils, together with lithologic composition and sedimentary structures were noted for each exposed surface and tied into the 17 m of studied section.

Numerous samples were taken for use in polished blocks, acetate peels, X-ray radiography, and thin-section study. These samples helped in analysis of lithology and microscopic sedimentary structures not seen in the field.

PREVIOUS WORK

The Wheeler Shale and Marjum Formation were originally described by Walcott (1908, p. 10). The type local-

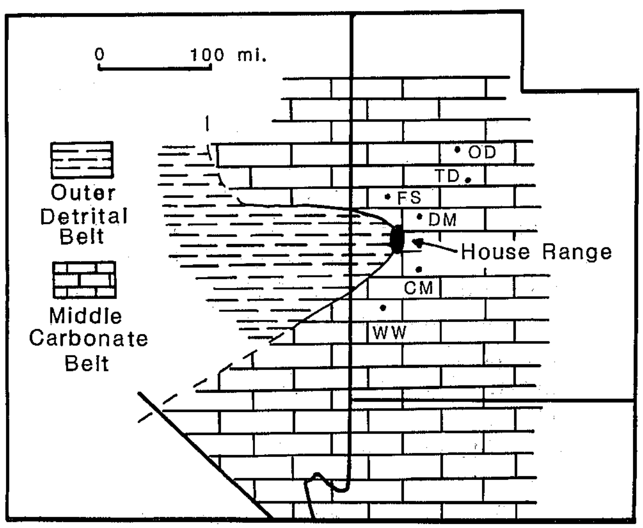

FIGURE 4.—*Middle Cambrian (*Bolaspidella *zone) lithofacies map showing House Embayment. CM = Cricket Mountains, DM = Drum Mountains, FS = Fish Springs, OD = Ophir District, TD = Tintic District, WW = Wah Wah Mountains (after Robison 1964).*

ity for the Wheeler Shale is the center of Wheeler Amphitheater, 2.9 km southeast of Antelope Spring, and the type locality for the Marjum Formation is the cliffs on the south side of Marjum Pass in the central part of the range (fig. 1). These areas have been mapped by Hintze (1982).

For many years amateur and professional collectors have worked the trilobite beds of the House Range. As a result of this collecting, numerous trilobites (Robison 1964b, 1982; Rowell and others 1982), sponges (Rigby 1966, 1969, 1978, 1983), medusoids (Morris and Robison 1982), large bivalved arthropods (Robison and Richards 1981), and other invertebrates have been recovered and described. Robison (in press) has described a new species of *Aysheaia* from the Wheeler Shale of the House Range. Gunther and Gunther (1982) illustrated the flora and fauna of Middle Cambrian rocks in the area, with an emphasis on trilobites.

Compared to the extensive systematic paleontological work done on faunas of the area, very little has been done on interpretation of the deposition and paleoenvironments of the Wheeler and Marjum Formations. Brady and Koepnick (1979) showed the rapid facies change of the Marjum Formation from the adjacent carbonate platform on the northeast, east and southeast, to a deep embayment on the west in the House Range area (fig. 4). Palmer (1960) defined three distinct lithofacies belts in the area during Cambrian time including, (1) an inner detrital belt, (2) a middle carbonate belt, and (3) an outer detrital belt. A detailed study of segments of the slope-to-basin environment in the outer detrital belt will be the scope of this paper.

The Middle Cambrian carbonate-dominated shelf, now exposed in segments across the Basin and Range, came about because of a combination of factors. The most important was the formation of a broad continental terrace composed mostly of terrigenous sediments during late Precambrian and Early Cambrian time (Stewart 1972). Carbonate deposition began in Early Cambrian, but regionally the major period of carbonate sedimentation occurred after the deposition of the Chisholm Shale (fig. 5) and continued for much of the remainder of the Cambrian. Expansion of the carbonate belt was related to reduction in available terrigenous debris due to burial of nearby source areas by the overall transgressive Sauk Sequence (Wheeler 1960, p. 50–51).

Kepper (1976, p. 75) concluded that the shelf was in the low latitudes on the basis of paleomagnetic data (Irving 1964, p. 126). That latitude would be conducive to carbonate sedimentation.

Cambrian rocks in the Basin and Range Province show a general east to west pattern of shelf-slope-basin transition. Wheeler (1960, p. 49–51) discussed a general sedimentologic model for Cambrian rocks that consisted of a belt of coarse detritus along the margin of the craton, followed seaward by *carbonates* and, distally, by a belt of detrital fine sediments bypassed across the intermediate zone. Palmer (1960) used the terms *inner detrital belt, middle carbonate belt,* and *outer detrital belt* to describe his model of Cambrian deposition. Robison (1964a, p. 996–97) noted that these facies occur in sinuous, laterally interfingering belts that were approximately parallel to the ancient cratonic shoreline. Rocks of the inner and outer detrital belts are characterized by a high content of argillaceous and arenaceous material, whereas rocks of the middle belt are relatively clean carbonates.

All three environments played important roles in deposition at both quarry sites. Organisms living on the carbonate shelf, along with sediment produced there and terrigenous muds bypassed across the shelf from the inner detrital belt, were deposited in the slope-to-basin environment by turbidity currents.

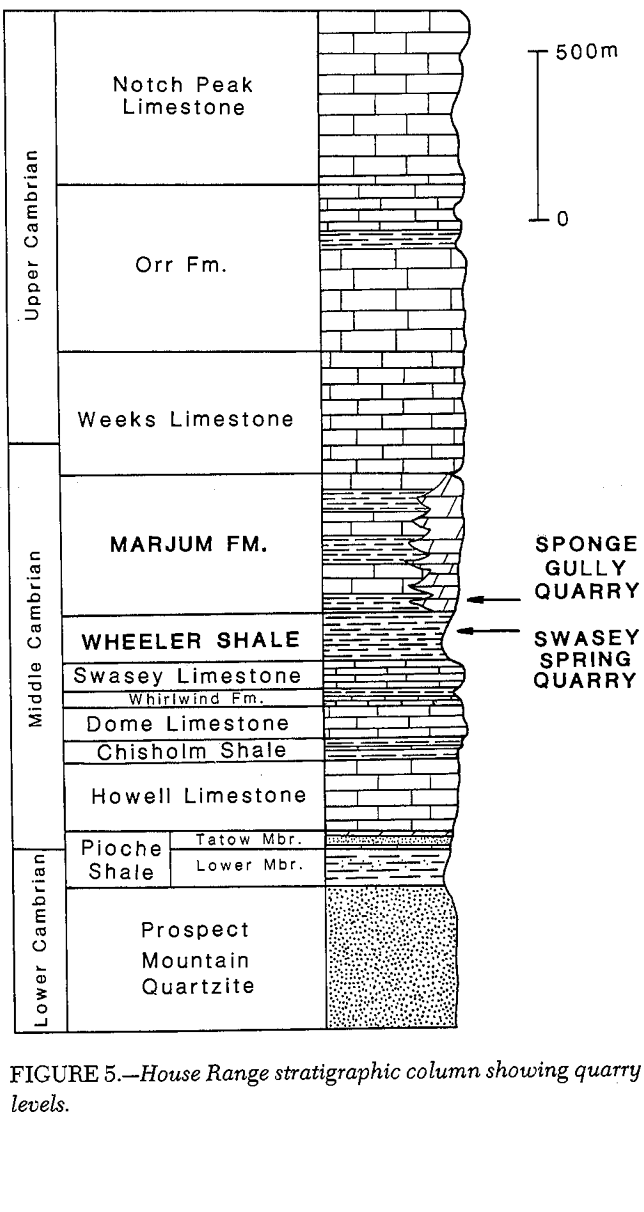

FIGURE 5.—*House Range stratigraphic column showing quarry levels.*

The basin that existed during late Wheeler and early Marjum time is known as the House Embayment (fig. 4). Brady and Koepnick (1979) described it as a deep-water embayment that extended eastward onto the carbonate shelf and in the area of the present-day House Range. The House Embayment was the depocenter for debris carried off the shelf that surrounded the embayment on three sides. Such a paleogeography produced the rapid changes in facies from basin to slope to shelf seen when units are traced eastward.

STRATIGRAPHY

Cambrian rocks exposed in the House Range include the Prospect Mountain Quartzite (Lower Cambrian) and the overlying approximately 2,600 m (8,930 ft) of limestone, dolomite, and shale that extend up to the Notch Peak Limestone (Upper Cambrian), as summarized by Hintze and Robison (1975). The Middle Cambrian Wheeler Shale and Marjum Formation are bounded below by the Swasey Limestone and above by the Weeks Limestone (fig. 5).

SWASEY LIMESTONE

The Swasey Limestone is composed of dark gray, fine-grained limestone that occurs in beds 2.5 cm to 60 cm thick. Regional lithofacies relationships indicate conformable contacts between the Swasey Limestone and Wheeler Shale (Robison 1964a, p. 1000).

WHEELER SHALE

Robison (1964a, p. 1000–1) noted that the Wheeler Shale, at its type locality in Wheeler Amphitheater (fig. 1), consists of a heterogeneous succession of highly calcareous shale, shaly limestone, mudstone, and thin flaggy limestone. More homogeneous highly calcareous shale and shaly limestone sections occur northward in the northern House Range, in the Fish Springs Range, and in the Drum Mountains (fig. 4). Terrigenous silt and clay content decreases toward the northeast, where carbonate rocks become increasingly dominant until the section is only carbonates in stratigraphically equivalent units in the Tintic and Ophir districts (fig. 4).

A much more abrupt transition was documented by Robison (1964a, p. 1001) of equivalent beds traced southeastward from the House Range. In that direction the closest Middle Cambrian outcrops occur in the Cricket Mountains and the Wah Wah Mountains (fig. 4). There stratigraphically equivalent rocks are relatively pure, often massive carbonates.

Near the Swasey Spring quarry the Wheeler Shale is approximately 142 m (466 ft) thick, and the top of the quarry site is 70 m (230 ft) below the base of the Wheeler-Marjum contact. That contact is conformable, as described by Robison (1964, p. 1001), and is marked by the upward change from shale to limestone.

MARJUM FORMATION

The Marjum Formation, at its type locality in Marjum Pass, consists of approximately 60% thin-bedded, fine-grained, silty limestone and 38% shale and mudstone. A few beds of intraformational flat-pebble conglomerate, algal biostromes, and other miscellaneous rock types make up less than 2% (Robison 1964a, p. 1001–3).

Robison (1964a, p. 1001–3) traced the unit throughout the House Range and documented the general lithologic transition. The formation changes from interbedded shale and limestone in the south at Marjum Pass, to thin-bedded limestone with smooth silty bedding at Wheeler Amphitheater, to thin-bedded limestone with silty mottles and irregular bedding surfaces in the Swasey Peak area, and finally to massive pure limestone at the north end of House Range (fig. 1).

The Sponge Gully quarry is located near Marjum Pass, where the Marjum Formation is approximately 410 m (1,345 ft) thick. The quarry is in the outer detrital belt as described by Robison (1964a, p. 995–1000). The quarry section is dominated by thin-bedded shale, with minor amounts of thin-bedded limestone. The base of the Sponge Gully quarry is 41 m (135 ft) above the Wheeler-Marjum contact.

WEEKS LIMESTONE

Robison (1964a, p. 1003) described the lower Weeks Limestone in the Marjum Pass area as consisting of beds of medium to dark gray, fine-grained, laminated limestone, 8 cm to 30 cm thick, that alternate with beds of medium gray silty limestone 3 mm to 6 mm thick. The unit is similar lithologically to parts of the underlying Marjum Formation, but Weeks outcrops tend to form slopes.

A study of Upper Cambrian stratigraphy (Bentley 1958, p. 12–13) and paleontology (Robison 1960, p. 6–7; 1964a, p. 1007) in western Utah indicated that the Middle–Upper Cambrian boundary is in the lower part of the Weeks Limestone. A later study (1975) by Hintze and Robison places the boundary in a similar position.

SPONGE GULLY QUARRY

The Sponge Gully quarry is considered to be the principle site of the study, for the most effort was expended and the greatest variety of sedimentary structure and fossils were observed in the Marjum beds. Consequently, it is discussed first even though these rocks are younger than those studied at the Swasey Spring quarry.

LITHOLOGY

Rocks at this location are dominantly thin-bedded (0.3–5 mm), dark gray, calcareous shale with a minor amount of thin-bedded (4–16 mm) black limestone (fig. 6). Both the shale and the limestone show distinct and very repetitive, fining-upward, graded bedding.

The shale is composed of approximately 60% clay, 30% fine-grained calcium carbonate, 8% silt-size quartz, and 2% trilobites, algae, sponge spicules, and other fossil debris (fig. 7).

The limestone is a packstone with lime mud that has altered to microspar between the grains. The limestone unit caps the Sponge Gully quarry and is 14 cm thick, with the clay and lime mud content decreasing upward in the upper 9 cm of that bed to become increasingly calcareous. Clasts within the unit are peloids, coated grains, intraclasts (clay and limestone), and fossil fragments consisting of trilobite spines, algal debris, echinoderm fragments, and sponge spicules (fig. 8).

GRADED BEDDING

The most striking feature of the Marjum Formation at Sponge Gully is its laterally and vertically consistent thin laminations. Such laminations may be reflected as color banding (red, purple, orange, or black) caused by concentration of organic debris and iron in the coarser units. Close examination of the bedding reveals that each fine unit has a corresponding coarse unit below it. Repetitive graded bedding occurs throughout the shale and limestone and is indicative of turbidity current deposition.

Two types of graded beds have been observed. The first, termed coarse tail grading (Middleton 1967), shows grading only in the coarsest percentiles of the size distribution at the base and is found mostly in the shale. In experimental flows, Middleton (1967) showed that this type of grading was produced by a high-concentration flow where grading was probably due, in part, to decay of initial turbulence, decreasing competency of the tail of the turbidity current, and concentration of coarse grains in the head of the current. This type of grading is most common in the Marjum Formation shale and concentrated relatively larger clasts (fossils and organic debris) in the basal unit. Such grading shows as an abrupt shift from the graded, coarse bottom unit to the ungraded, capping, finer unit, with no intermediate size material (fig. 7).

The second type of grading, termed distribution grading (Middleton 1967), shows size distribution shifts to finer sizes progressively from bottom to top of the bed and is seen in both shale and limestone. This type of grading is characteristic of graded beds deposited layer upon layer by relatively dilute turbidity currents, as shown by experiments (Middleton 1967). This type of grading is rare in the shale at Sponge Gully. Distribution grading is much coarser than coarse tail grading, and its thickness generally ranges between 1 and 3 mm. It reflects an occasional higher-energy turbidity current that flowed into the basin and was able to carry a wider range of clast sizes (fig. 9).

The limestone at Sponge Gully is 14 cm thick. The lower 5 cm are dominated by calcareous mud and clay, with peloids increasing in number upward. The upper 9 cm show very distinct distribution grading of peloids, intraclasts (clay and limestone), coated grains, and fossil debris as the unit becomes increasingly more calcareous (fig. 10).

SOFT-SEDIMENT FOLDS

Soft-sediment flow folds occur in the Marjum Formation at Sponge Gully (figs. 11, 12). Three units show this disrupted bedding; they are at levels 1.52 m, 2.84 m, and 4.75 m (fig. 6). Folds involve several coarse to fine couplets, and the disrupted beds are 10 to 20 cm thick (fig. 11). The slump structures are bounded above and below by undisturbed horizontal beds, indicating that these folds were nearly penecontemporaneous with deposition. Small blocks (8 cm × 8 cm × 2 cm) of semiconsolidated shale are associated with these folded beds and were transported from higher up on the slope when the slumping was initiated.

Slumping is a common feature in sediments deposited on shallow slopes with gradients generally less than 5° and decreasing rapidly basinward to slopes of 1° or less (Cook and others 1975, p. 481). Compaction of the sediment, caused by gravity, may result in gradual steepening of the gradient and slumping of the upper layers. A critical point is reached at which the load imposed by an unusually large influx of sediment, can cause rapid slumping (Conybeare and Crook 1968, p. 38–40). In this environment slumping could easily have been started by a turbidity current. Marjum sediment was probably in a quasi solid state because it shows some small faults and gave rise to slide-slump bedding (fig. 11) like that noted by Eliott (1965).

The upper slump unit at Sponge Gully is preserved well enough so that it could be sampled and cut to expose numerous folds. The maximum dip and direction of slumping were calculated to determine the trend of the basin at Sponge Gully, assuming that slumps traveled downslope, generally perpendicular to the depositional strike. Soft-sediment flow folds indicate that the floor of the House Embayment during deposition of the beds at Sponge Gully sloped gently south 25° west (fig. 12).

LOW-ANGLE TRUNCATIONS

Low-angle truncations of bedding are found occasionally in the Sponge Gully quarry. Well-bedded units are truncated by overlying units, giving the appearance of small angular unconformities (fig. 13). These structures were produced by slumping of evenly thin-bedded strata without much deformation. They may be of great size, masses several hundred feet long (fig. 14) or very small and offset beds within only 5 mm of each other vertically. The small structures are impossible to see without preparing polished blocks cut at a low angle to the bedding to make an apparent expansion of the laminations (fig. 15). The slumped masses have slid over the stable part of an equivalent section and represent semiconsolidated masses which moved down the gentle slopes like those described elsewhere in similar fine basin facies (Wilson 1969).

The fault plane on which the upper beds moved is nearly parallel to the upper bedding, indicating that shearing began as a local weakness in the bedding. Movement followed the bedding plane downslope, cutting across the beds underneath the slump. No other signs of soft-sediment slumping, such as folded beds, are present in

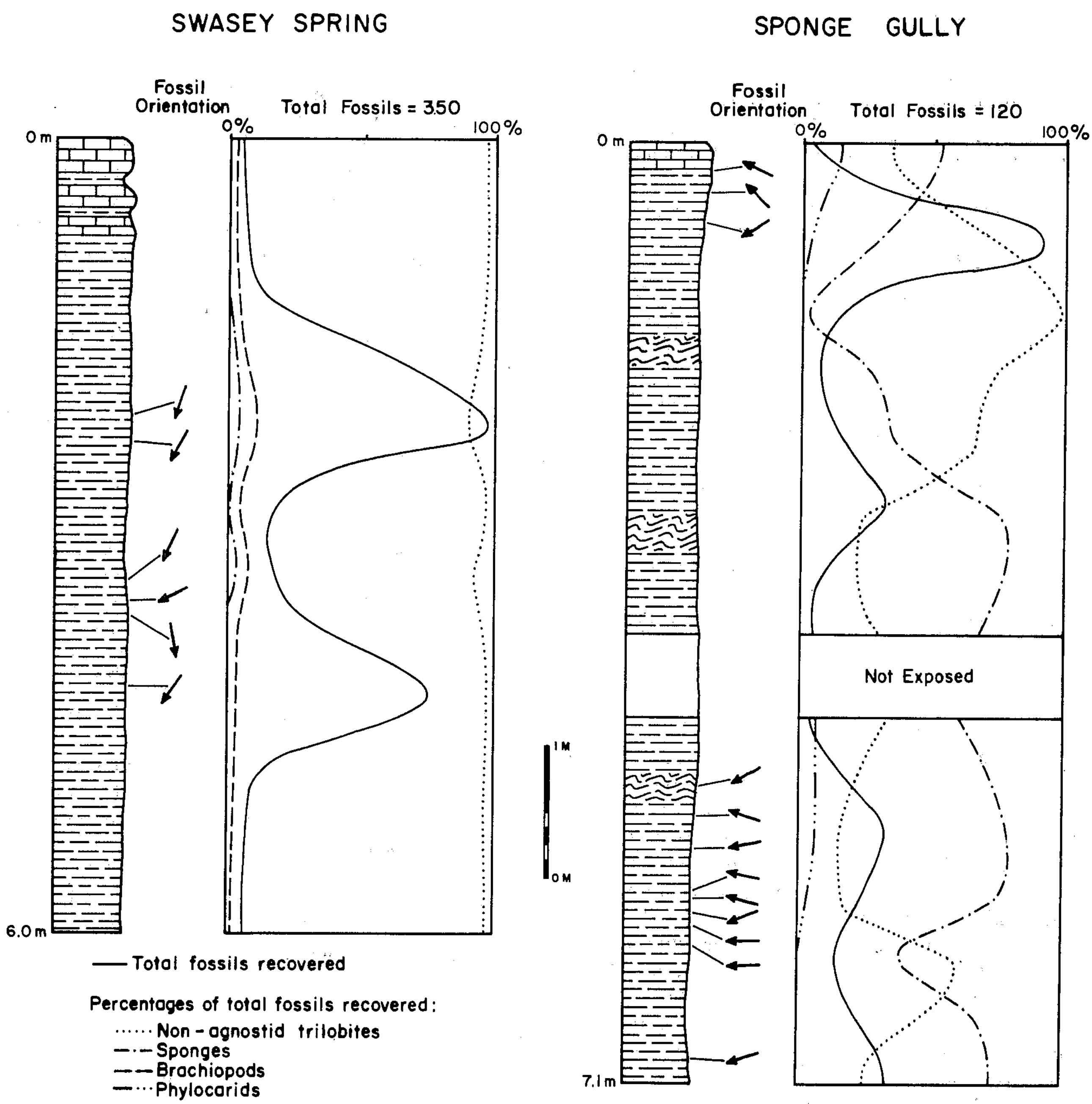

FIGURE 6.—*Stratigraphic section of quarries showing fossil orientation and fossil abundance.*

these slumped wedges. Wilson (1969) noted that similar movement in thin-bedded lime mudstones and calcisiltites rarely show intraformational folds.

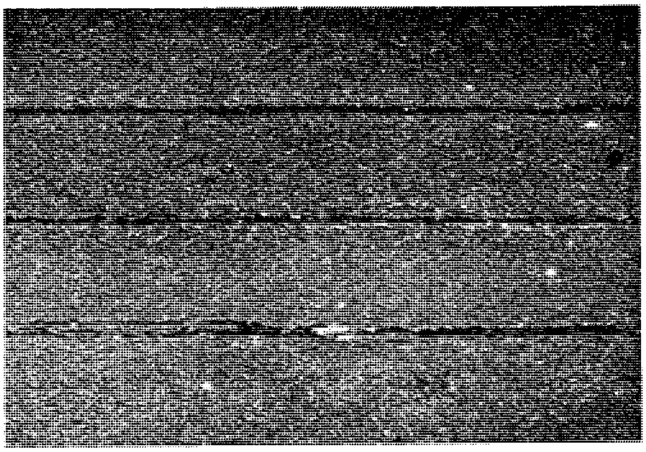

FIGURE 7.—*Photomicrograph of the shale in the Marjum Formation at level 5.21 m in the Sponge Gully quarry, shows coarse tail grading (X10).*

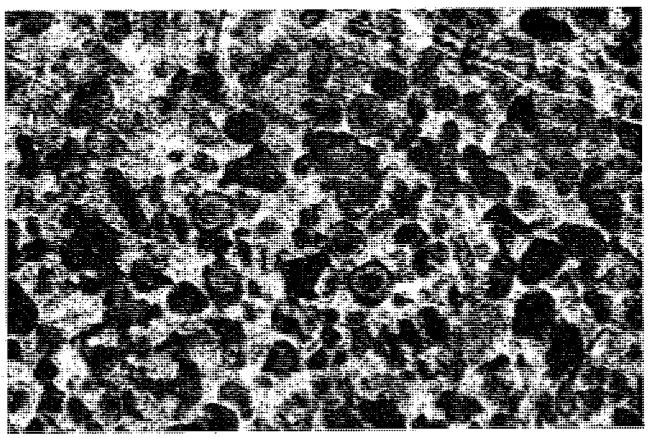

FIGURE 8.—*Photomicrograph of the limestone in the Marjum Formation at level 0.45 m at the Sponge Gully quarry (X15).*

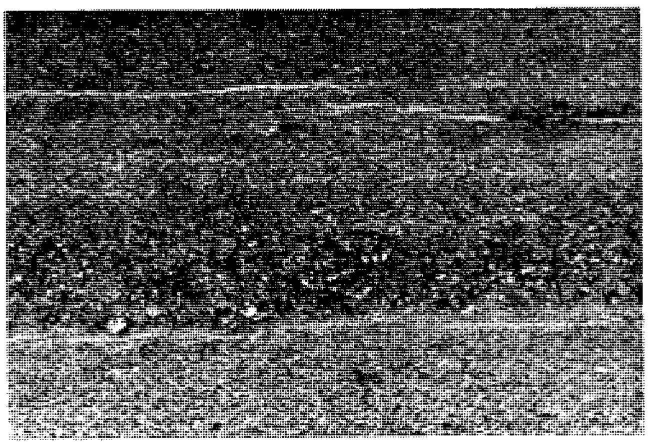

FIGURE 9.—*Distribution grading in the Wheeler Shale at level 5.22 m at the Swasey Spring Quarry (X20).*

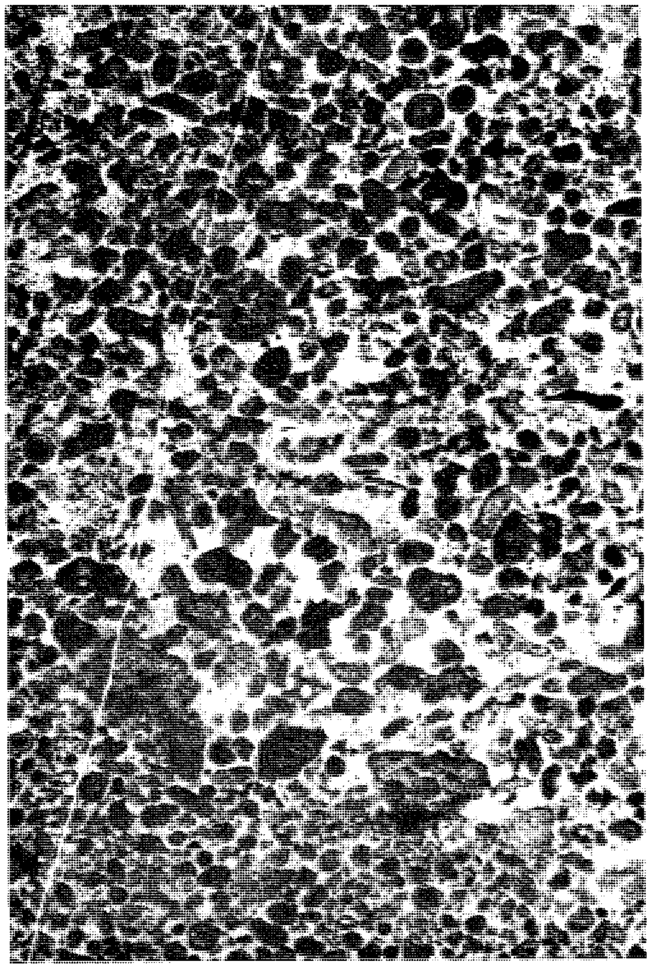

FIGURE 10.—*Photomicrograph of the graded limestone in the Marjum Formation at level 0.27 m in the Sponge Gully Quarry (X10).*

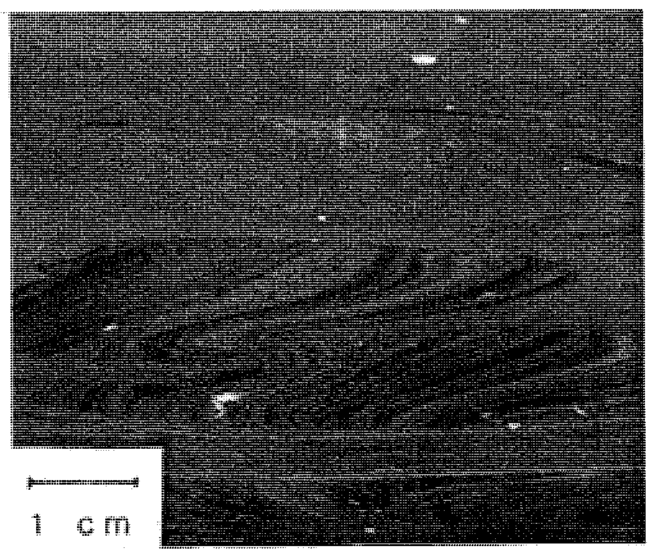

FIGURE 11.—*Soft-sediment fold in the Marjum Formation at level 4.75 m in the Sponge Gully quarry that shows a small fault.*

ORIENTED FOSSILS

Fossils acted as relatively coarse clasts and are concentrated in the coarse basal unit of each turbidite deposit. Agnostid trilobites and fragmented filamentous algae are the most common fossils. Robison (1972) suggested that agnostid trilobites were adapted to a pelagic mode of life. When they died, they fell to the ocean floor and were transported basinward by turbidity currents. Their pelagic habit accounts for their widespread distribution in the rocks of both quarries. Filamentous algae lived in shallower water to the east. Occasional storms could have broken the algae into long, thin stringers and transported these fragments into the basin in turbidity currents. Lightweight algal remains were oriented by the transporting current much better than the associated agnostids (fig. 16).

Orientations of fossils at Sponge Gully are pronounced. Alignment varies from bed to bed, and ranges from NE–SW to SE–NW, with a developing trend in an east-west direction. Each bedding plane has its own distinct orientation but is not consistent with other beds (fig. 17). This pattern suggests that turbidity currents had variable sources originating on the bank slopes from the northeast to the southeast. Such directions fit the shape of the House Embayment (Robison 1964a; fig. 4) during Middle Cambrian time (fig. 18). The Sponge Gully quarry site was nearer the carbonate bank edge than the Swasey Spring quarry site for that margin prograded westward during Cambrian time (fig. 19). Therefore, the turbidity currents depositing sediment at Sponge Gully are relatively stronger and have produced the distinct orientation of organisms seen at this quarry.

FIGURE 13.—*Low-angle truncations due to gravity sliding along bedding planes at level 0.63 m in the Sponge Gully quarry.*

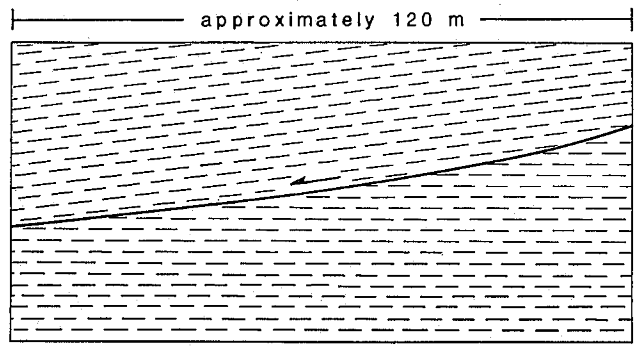

FIGURE 14.—*Large-scale gravity slide (after Wilson 1969).*

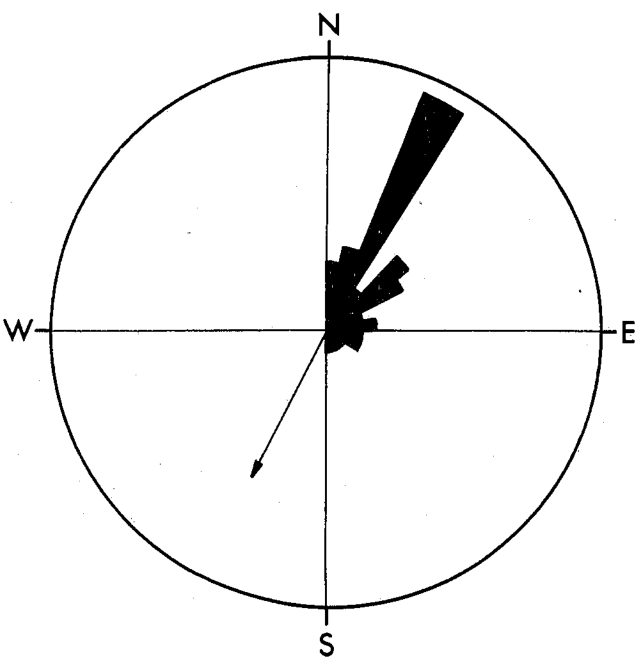

FIGURE 12.—*Orientation of direction perpendicular to soft-sediment fold axes at level 4.75 m to 4.93 m at Sponge Gully. Shows the trend of the basin during deposition of the Marjum Formation at Sponge Gully to the southwest.*

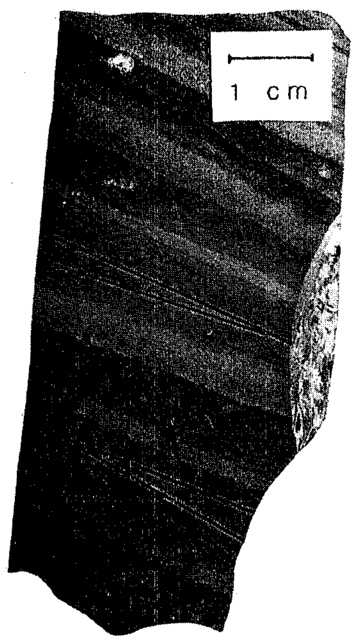

FIGURE 15.—*Small-scale gravity slide. Rock is cut at a low angle across lamina to expand bedding. From top to bottom 11 mm of rock are represented; from level 5.62 m in the Sponge Gully quarry.*

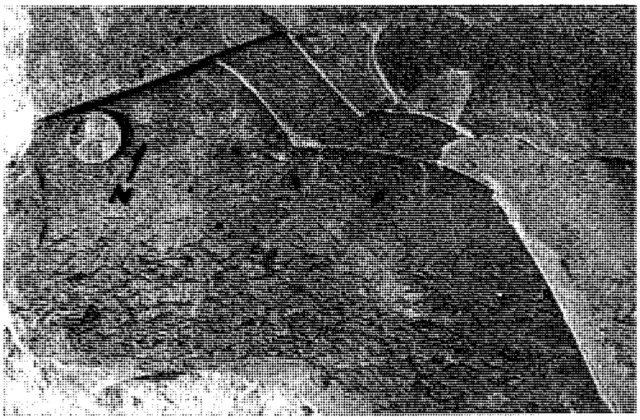

FIGURE 16.—*Fragmented* Yuknessia *algae deposited in the coarse basal unit of a turbidite; note orientation due to current flow at level 2.27 m in the Sponge Gully quarry.*

FRAGMENTED ORGANIC DEBRIS

Fragmented fossils are common in the basal unit of each turbidite, indicating the turbulent nature of their transport and deposition. However, the current was not strong enough to completely destroy all organisms. Some delicate fossils are well preserved in the quarries. Common fossil fragments include trilobites, sponges, algae, and unknown identifiable bits that have been termed specks.

Specks occur in the coarse basal unit of each turbidite throughout the section at both quarries. They are dark, are rounded to subrounded, range from 3 mm to 6 mm in diameter in the rocks at Sponge Gully, and are very well sorted (fig. 20). Thin sections, acetate peels, and radiographs of the specks failed to show any internal structure, and their origin is in question. Some may be poorly preserved fragments of the alga *Morania* as described by Walcott (1922, p. 225–34, pl. 43, 44). Others may be immature specimens of the sponge *Diagoniella cyathiformis* (Rigby 1983, p. 257–59) or *D. hindei* Walcott. Some possibly may be bits of an organic film that formed on the upper slope but was broken up and transported downslope by turbidity currents.

No matter what their origin, the specks were transported. Their sorting is striking and suggests that similar size specks were concentrated together when the waning current could no longer carry them.

TOOL MARKS, SOLE MARKS, AND MICROSCOPIC SCOURING

Tool marks and sole marks were occasionally found in the basal unit of some turbidites in the Marjum Formation at Sponge Gully. Such tool marks are long (15–20 cm), thin lineations that appear as scratches on the bedding plane of the rocks and have the same orientation as the sole marks (fig. 21). These lineations were probably produced by debris in the turbidity current being alternately dragged along the bottom and carried in suspension.

Sole marks are teardrop shaped and small (1–3 cm), and their depressions are filled with orange brown silt and very fine grained sand (fig. 22). They give a unidirectional movement of individual turbidity currents at specific levels. The direction of current flow varies from nearly due south to toward the northwest. In the few beds with sole marks seen at Sponge Gully the orientation in each individual bed is very distinct, but direction between beds varies greatly, fitting well with the model that turbidity currents originated at different locations on the slope or carbonate platform and flowed into the House Embayment.

Variation in direction of turbidity currents' flow suggests that the location of the quarry was on a gentle slope but near the trough of the embayment. If the quarry site had been located nearer one side of the embayment, it would probably have shown only a single direction of movement.

Sole marks and tool marks indicate occasional higher-energy turbidity currents than deposited most beds in the quarry. These more vigorous currents were able to carry large enough clasts to create tool marks and to erode the base, forming sole marks which were later filled with coarser silt and very fine grained sand.

Microscopic scouring did occur at the base of the graded beds at Sponge Gully. However, it must be seen in thin section. In these shales such a carved surface has relief so minute that it is difficult to see.

DEPOSITIONAL MODEL

The physical setting for deposition of the Marjum Formation at the Sponge Gully quarry is a slope-to-basin transition in Palmer's (1960) outer detrital belt, with a shallow carbonate platform and the inner detrital belt farther eastward. The carbonate platform surrounded the deep-water House Embayment in a semicircular fashion. This created a nearby source that gave rise to turbidity currents, each with different trends of movement, depending on its origin on the surrounding semicircular platform to the east (fig. 18).

Sedimentation was controlled by the rapid influx of sediment in turbidity currents. Pelagic sedimentation must have occurred, but it was reworked by the frequent flow of turbidity currents into the basin and was not preserved in the rock record studied in the quarry. The primary component of the turbidites are detrital fines (clays and silt) that were bypassed across the carbonate platform, possibly as the results of storms. In addition, fine-grained calcium carbonate produced on the shallow car-

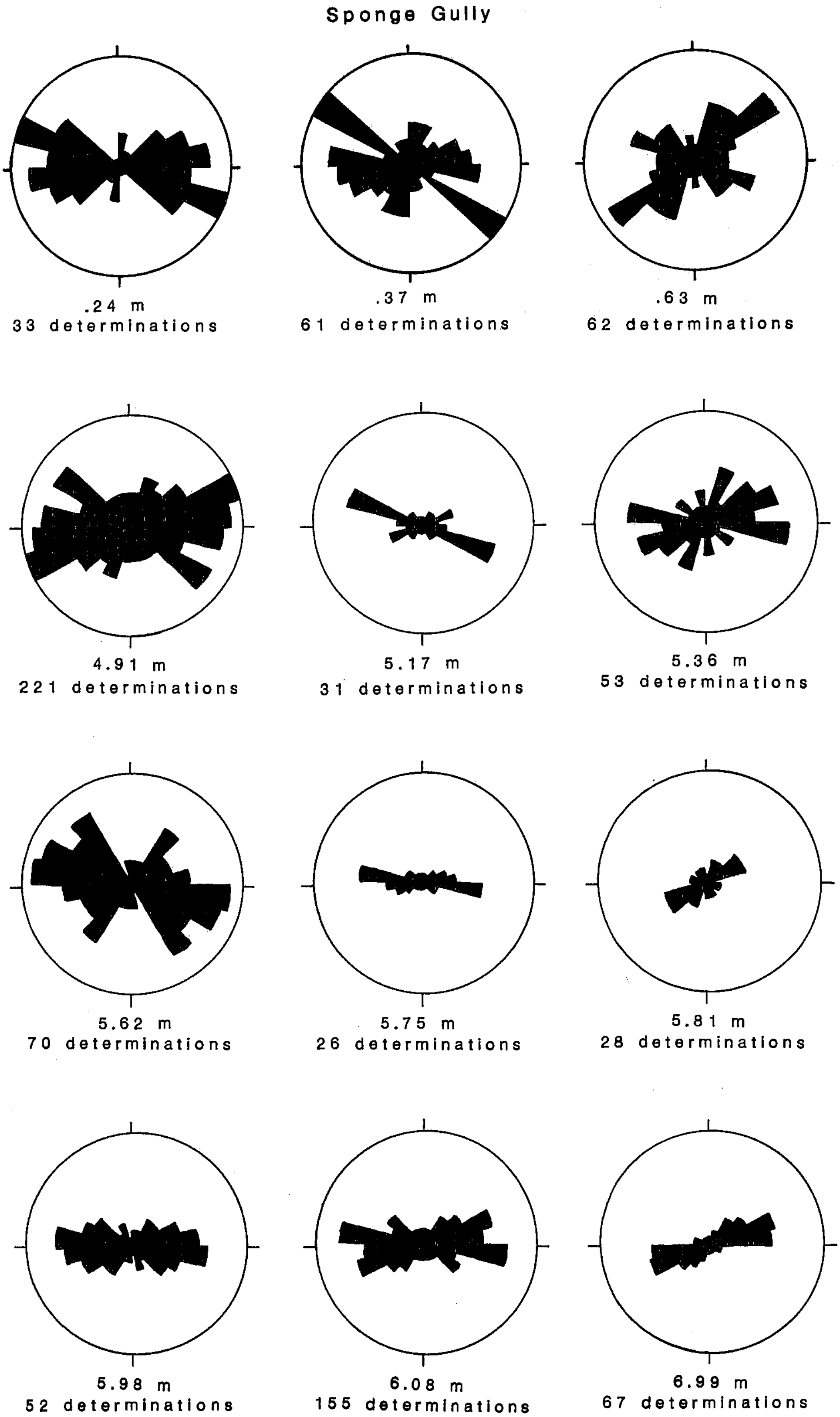

FIGURE 17.—*Orientation of organisms on single bedding planes at Sponge Gully gives the direction of turbidity current movement into the basin.*

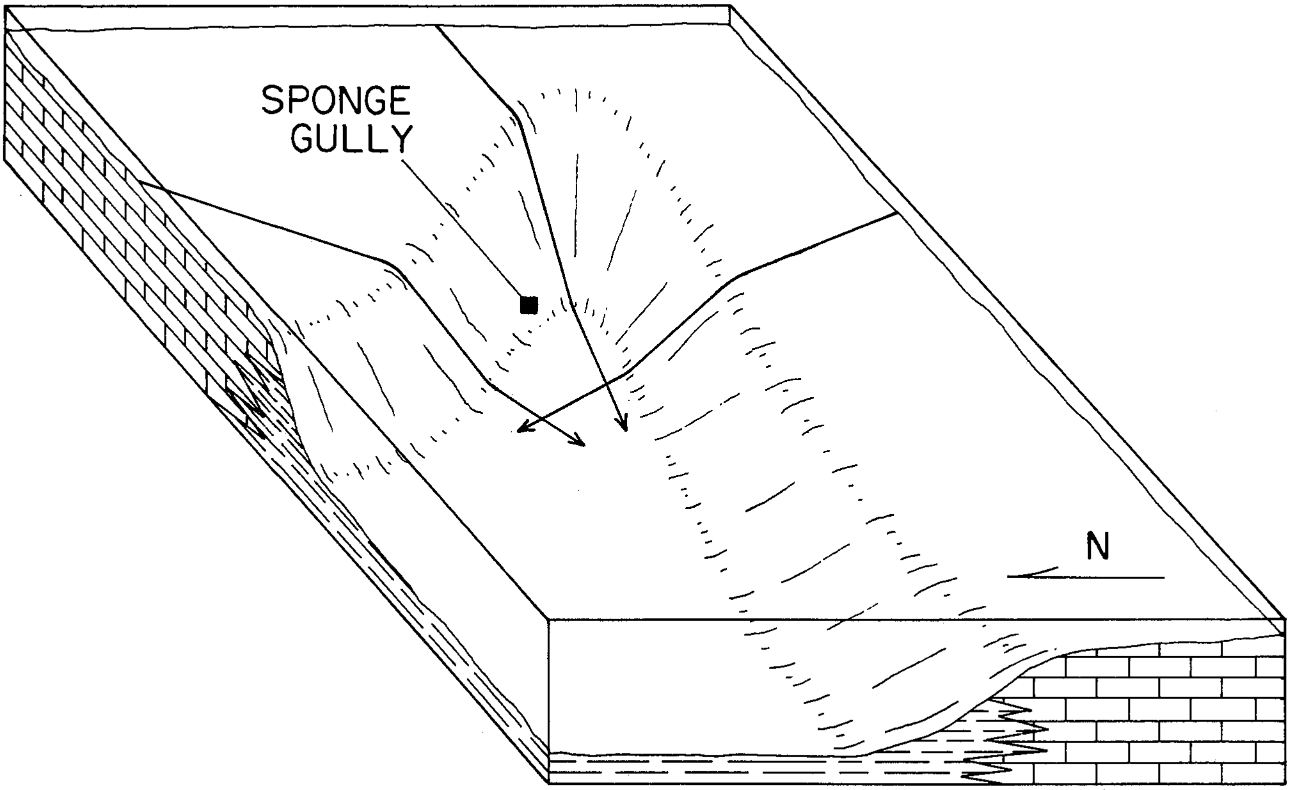

FIGURE 18.—*Diagrammatic model for deposition in the House Embayment for the rocks at Sponge Gully. Sediment and organisms were swept off the carbonate shelf and into the basin in turbidity currents. Not to scale.*

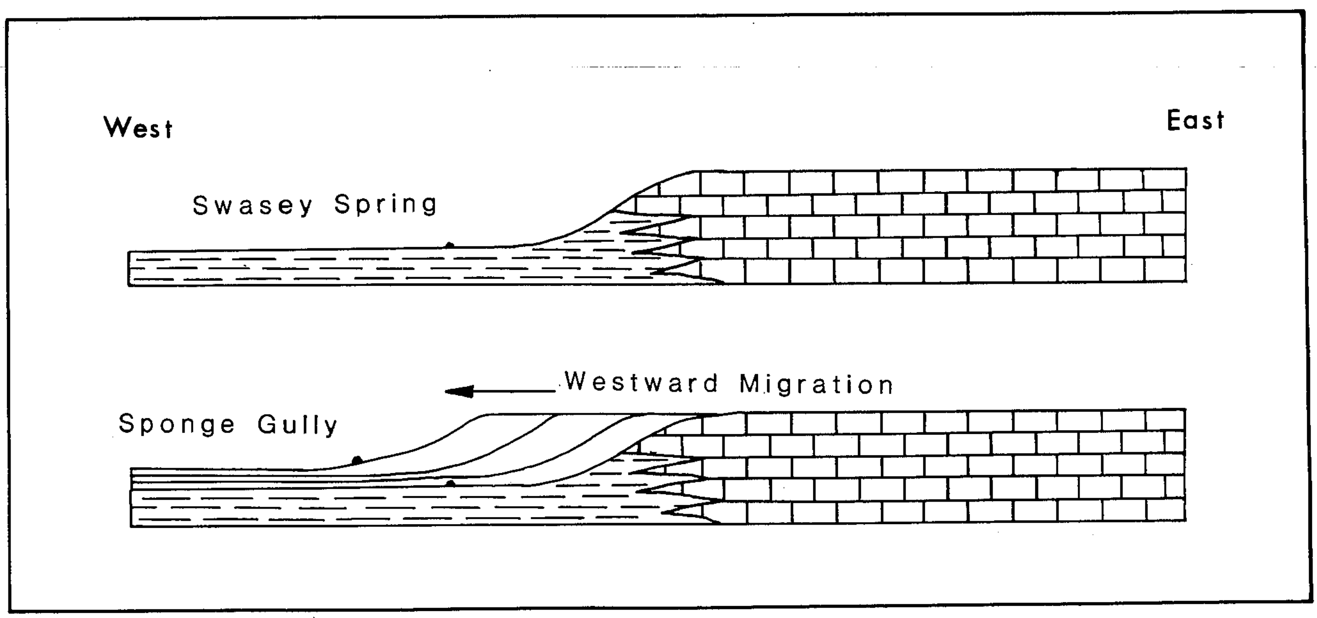

FIGURE 19.—*Westward migration of the carbonate platform and basin filling from deposition at Swasey Spring to that at Sponge Gully.*

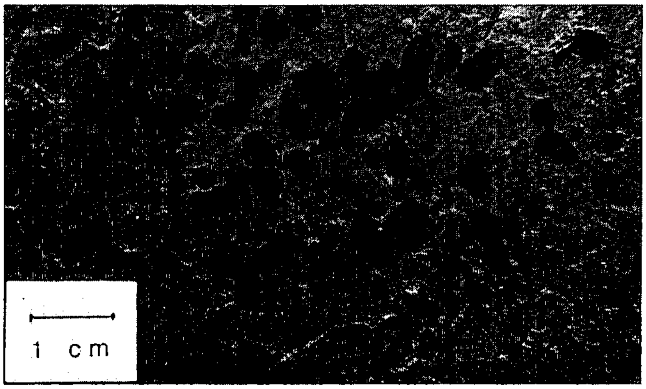

FIGURE 20.—*Relatively larger "specks" at Sponge Gully, level 4.92 m. Their origin is uncertain.*

bonate platform, along with organisms living there and on the upper slope were incorporated into the turbidity currents and transported basinward.

The 14-cm-thick, black limestone at the top of the Sponge Gully quarry shows excellent grading upward of peloids, coated grains, fossil fragments, and intraclasts (fig. 6). These grains are characteristic of the shallow-marine environment to the east. The distinct grading and fragmental nature of the fossils are strong evidence that the limestone was deposited in the same manner as the shale. Considering that the limestone is bounded above and below by thin-bedded, coarse-to-fine, dark basinal shale, it seems that the limestone recorded a brief change in conditions within the basin.

The slope into the basin has been estimated at between 2° and 3° (Brady and Koepnick 1978) because of the rapid transition eastward from basin to platform facies in the House Range. The slope extended well below wave base at the quarry locations, as judged by lack of any current structures other than tool and sole marks associated with turbidite sedimentation. Slumping like that seen at Sponge Gully (fig. 11) could have been initiated on such a shallow slope. Cook and others (1972, p. 481) noted that gravity features can form on slopes as gentle as 1°.

Rates at which turbidity currents flowed can only be estimated but were probably not great. Kuenen (1966) has shown that graded beds can be produced from a current carrying both silt and mud moving at velocities of around 15–30 cm/sec. At this rate the current would be able to carry smaller trilobites, delicate sponges, and algal fragments into the basin without a great amount of destruction to some of the organisms. Sponges, which most likely lived below wave base on the upper slope, are especially well preserved at Sponge Gully. They were dislodged from their growth position by turbidity currents and carried basinward as a leathery mass before physical and biological breakdown could occur. Large (5–10 cm long) trilobites, normally found in shallow-marine deposits, are uncharacteristic of a basinal facies and would seem too large to be carried by such low-velocity currents. However, as light buoyant masses they could be transported to basinal depths by these relatively weak turbidity currents.

Turbidity current deposition concentrated the organisms at the base of each turbidite because of their larger size in comparison with the surrounding sediment and then quickly covered them with finer sediment deposited by the waning currents. Almost instantaneous transportation and burial into the deep anaerobic environment prevented the normal decay of organisms and is responsible for their excellent preservation.

The carbonate platform that existed in the area of the House Range during deposition of the Marjum Formation

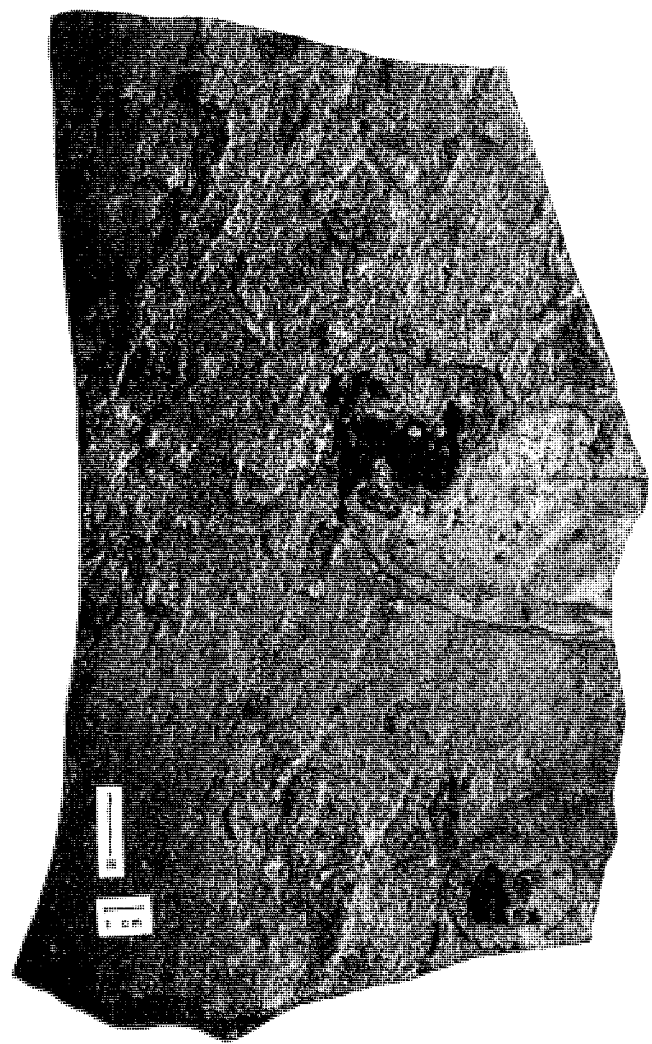

FIGURE 21.—*Tool marks in the Marjum Formation at Sponge Gully, level 4.22 m, showing orientation in the northeast–southwest direction.*

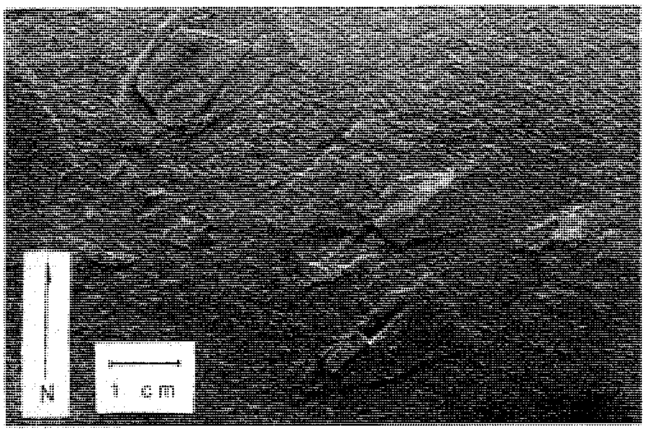

FIGURE 22.—*Sole marks in the Marjum Formation at Sponge Gully, level 5.89 m, indicating direction of movement to the southwest.*

at Sponge Gully had prograded westward from its position during deposition of the Wheeler Shale at Swasey Spring (fig. 19). Westward movement of the carbonate platform caused the basin to fill up as sediment input was greater than subsidence. The Marjum Formation at Sponge Gully reflects the basin filling and subsequent nearer-the-source deposition by thicker bedding, coarser-grained rocks, an abundance of larger specks, trilobites, and sponges, better-oriented fossils, presence of sole and tool marks, and slumping and folding that are indicative of the slope environment.

PALEOECOLOGY

The anaerobic basin, in which the dark shale and limestone of the lower Marjum Formation at Sponge Gully were deposited, was inhospitable for organisms to survive for any great period of time. From their orientation, it is apparent that nearly all organisms were transported in from the upper slope and carbonate platform. Agnostid trilobites, which are abundant throughout the section at both quarries, lived a pelagic life (Robison 1972). When they died, they sank to the ocean floor and were reworked and transported basinward in turbidity currents.

Sponges are abundant at three levels at the Sponge Gully quarry, with trilobites being secondary in abundance (fig. 6). The concentration of organisms at these levels is possibly due to a subaqueous channel that repeatedly swept currents by a sponge-rich environment on the upper slope. The currents picked up sponges and carried them to the basin and concentrated them in the "sponge beds." The channel ultimately changed course to an area not so rich in sponges and created the barren beds.

With the influx of sediment in turbidity currents, oxygen was brought into the basin for short periods (Piper 1972, p. 175). It allowed limited establishment of vagrant benthic organisms until the oxygen dissipated and the environment became inhospitable or until a new current flowed in and disrupted the short-lived community. Evidence of a living benthos is seen in the trace fossils at the Sponge Gully quarry, which are abundant near the top of the section but are rare near the base. They appear as trails and burrows (fig. 23) and have been identified as *Zoophycus* deepwater facies. Even though the trace fossils occur on many bedding planes near the top of the Sponge Gully quarry, they are extensive on only a few bedding planes, suggesting that the temporary community established was not very active and soon diminished. Trace fossils tend to be elongate in the direction of current flow where it can be established by filamentous algae. The organisms preferred grazing parallel to the algal strands rather than traveling perpendicular to them.

There are two ideas that explain how the living organisms arrived in the basin. In the first, organisms were transported in slow-moving turbidity currents and survived to live in the basin until the oxygen was depleted. In the second, organisms migrated basinward from the upper slope and platform when the oxygen level was increased with the influx of sediment.

PALEONTOLOGY

Fossil assemblages of the Marjum Formation at Sponge Gully are dominated by sponges. The quarry there has produced one of the most diverse Cambrian sponge faunas known in North America (Rigby 1983). Sponges which were recovered occur at three distinct levels (fig. 6) and include *Leptomitus metta* Rigby 1983, *Hamptonia bowerbanki* Walcott 1920, *Choia carteri* Walcott 1920, *Choia utahensis* Walcott 1920, *Diagoniella hindei* Walcott 1920, *Diagoniella* sp., *Valospongia gigantis* Rigby 1983, *Testiispongia venula* Rigby 1983, *Protospongia* (?) *elongata* Rigby 1983, and *Hintzespongia bilamina* Rigby

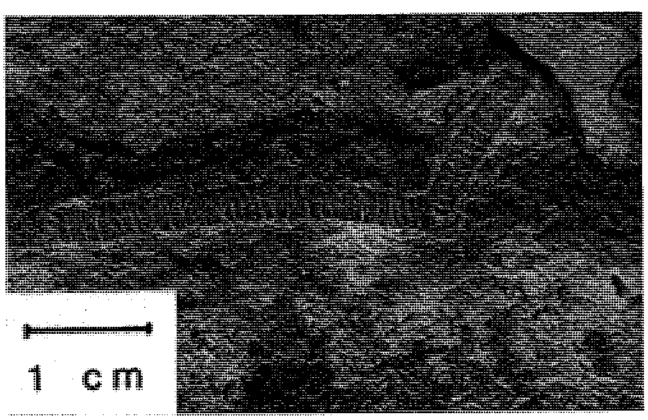

FIGURE 23.—*Trail in the Marjum Formation of the deepwater* Zoophycus *facies at the Sponge Gully quarry, level 0.75 m.*

and Gutschick 1976. In addition three or four new species were discovered and will be documented by Rigby.

Trilobites are also common at the Sponge Gully section. Agnostid trilobites are abundant and are distributed evenly throughout the section. Larger trilobites, indicative of a shallow-marine environment, are *Bolaspidella* sp. and *Modocia typicalis* Resser 1939. Additional arthropods recovered include an unidentified trilobitomorph and several phyllocarids.

Algae recovered are fragmented *Yuknessia* and the questionable specks that could possibly be *Morania*. Organisms with minor occurrences in the quarry section are a poorly preserved wormlike body, unidentified inarticulate brachiopods, and the pteropodlike fossil *Hyolithes*.

The diversity of the fauna in the Marjum Formation at Sponge Gully is higher than that at Swasey Spring (fig. 6), probably because of its closer proximity to the carbonate bank.

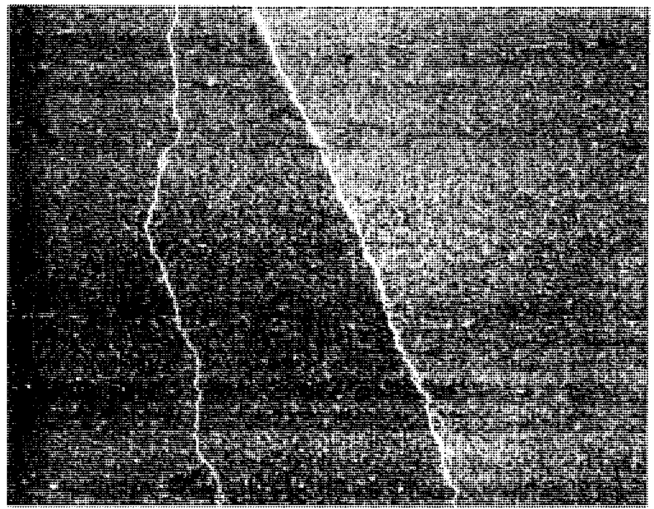

FIGURE 24.—*Photomicrograph of the shale in the Wheeler Shale at level 4.23 m at Swasey Spring (X10).*

SWASEY SPRING QUARRY

LITHOLOGY

Rocks at the Swasey Spring quarry are mostly thin-bedded (0.2–2 mm), dark gray calcareous shale. Three units of black, thin-bedded (0.2–2 mm) limestone occur at the top of the quarry section (fig. 6). The shale and limestone show a fining-upward pattern in each bed and are generally finer grained, with thinner laminations, than rocks at the Sponge Gully quarry. Graded bedding is not as easily seen in the Swasey Spring section because of the thinner laminations.

The calcareous shale at Swasey Spring, on the average, occurs in much thinner-bedded units which have ranges of 0.2 to 2 mm but are almost always less than 1 mm thick. The shale consists of 70% clay, 25% very fine calcium carbonate, 10% silt-size quartz, 3% sponge spicules, and 2% agnostid trilobites and other organic debris (fig. 24).

The three limestone units are all similar and contrast greatly with limestone at the Sponge Gully quarry. Limestone in the Swasey Spring quarry is much finer grained and thinner laminated with an abundance of clay and calcareous mud. Repetitive dark-light units are distinctive and show graded bedding. The dark units are relatively coarse, and the light ones are finer grained. The average thickness of each dark-light couplet is 0.8 mm. The limestone is composed of 60% fine-grained calcium carbonate, 18% silt-sized quartz, 10% clay, 10% sponge spicules, and 2% intraclasts (fig. 25).

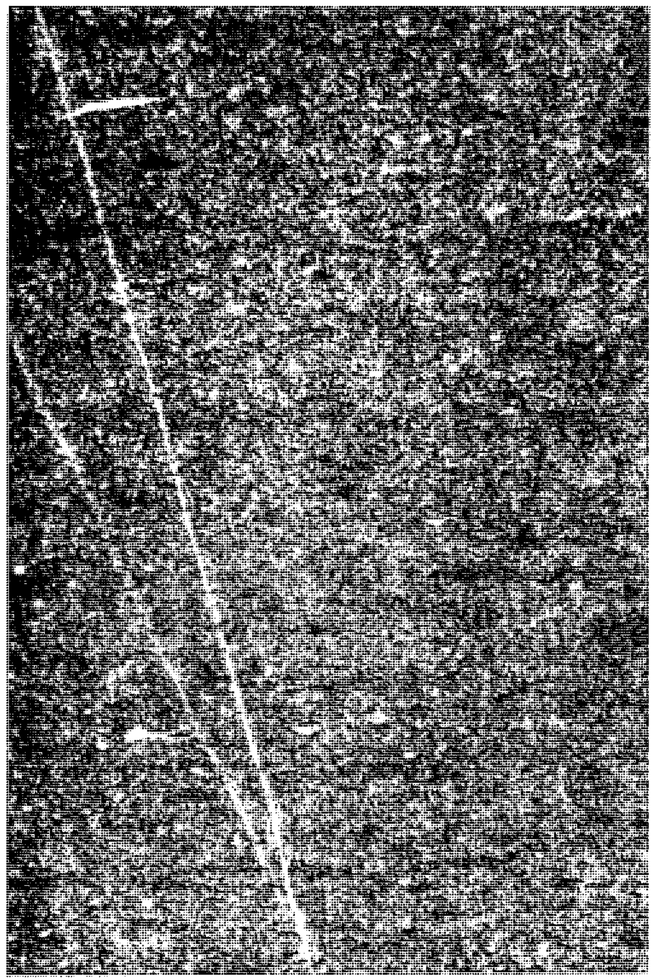

FIGURE 25.—*Photomicrograph of the limestone in the Wheeler Shale at level 0.31 m at Swasey Spring; note sponge spicule in the upper left (X10).*

GRADED BEDDING

Vertically and horizontally persistent thin laminations are seen throughout the Wheeler Shale at Swasey Spring.

The bedding is easily observed because of the color banding (red, orange, purple, or black) caused by concentration of iron and organic debris in the basal coarse unit. Bedding reveals couplets of coarse-fine laminae (0.2–2 mm), each being a single turbidite. Thinly laminated, fining-upward couplets occur throughout the section at Swasey Spring and are representative of turbidity current deposition.

Coarse tail grading (Middleton 1967) is the most common type of grading in the rocks, with distribution grading being very rare. Deposition at Swasey Spring was affected only by weak distal turbidity currents which created mostly coarse tail grading in the beds. Rare higher-energy turbidity currents flowed into the basin creating the very few beds with distribution grading.

The limestone at Swasey Spring quarry shows thin lamina (1 mm or less) and reflects graded bedding as alternating dark and light units. This is a result of concentration of coarser organic debris in the basal coarse unit and light colored fine grained sediment in the upper unit (fig. 25).

The Wheeler Shale at Swasey Spring is more thinly laminated than the rocks at Sponge Gully and reflects a more distal setting in the basin, and lower-energy realm turbidites.

SOFT-SEDIMENT FOLDS

Soft-sediment folds are not seen in the Wheeler Shale at Swasey Spring. Folds are indicative of a slope environment, and their absence in the quarry rocks suggests that the Wheeler Shale at the Swasey Spring quarry was deposited on a bottom so flat that penecontemporaneous slumping did not occur.

The stratigraphic separation of the two quarries is approximately 110 m. Because of this relatively small stratigraphic separation, it was assumed that during deposition of the Wheeler Shale at Swasey Spring the basin had a trend to the southwest (south 25° west) similar to that determined from folds at Sponge Gully (fig. 12).

LOW-ANGLE TRUNCATIONS

No low-angle truncations were seen in the Wheeler Shale at the Swasey Spring quarry. The lack of such features gives additional evidence of the flat-bottomed basinal setting with a depositional slope so minimal that no sliding between bedding surfaces occurred during sedimentation.

ORIENTED FOSSILS

Agnostid trilobites are concentrated in the basal coarse unit of the turbidites at Swasey Spring. Their abundance is due to their pelagic nature (Robison 1972) and subsequent reworking and basinward transport in turbidity currents. Transporting currents aligned agnostids and other small trilobites in the direction of current movement.

At Swasey Spring fossil orientation is not nearly so distinct as at Sponge Gully. Orientation varies from N–S to SE–NW, with the trend being set from north to south (fig. 26). Individual bedding planes reflect the variable trends of current movement that deposited each turbidite. Turbidity currents that deposited the Wheeler Shale at Swasey Spring originated on the slope banks and carbonate platform as did those at Sponge Gully. The multidirectional trend of currents fits the semicircular model of the House Embayment drawn by Robison (1964a) during Middle Cambrian time (fig. 8).

The Wheeler Shale at Swasey Spring apparently accumulated farther out in the basin and in deeper water than the rocks at Sponge Gully. The deeper bottom would have been affected only by relatively weak distal turbidity currents. Such weaker currents account for the less pronounced orientation of fossils in the Wheeler Shale at Swasey Spring.

FRAGMENTED ORGANIC DEBRIS

Fragmented organic debris in the Wheeler Shale is very rare, other than abundant specks similar to those found at Sponge Gully. Fossils found, other than pelagic agnostids, are mostly small (1–2 cm) whole trilobites (*Brachyaspidion microps* and *Jenkinsonia varga*). Turbidites deposited in the upper Wheeler Shale at Swasey Spring were too weak to break up the fossils because of the distal setting of Swasey Spring during deposition and the subsequent weaker current that could transport only smaller trilobites. Fragmented fossils probably occur farther eastward, where currents still had enough turbulence to break them up.

Specks are found abundantly throughout the section. They range from 1–3 mm in diameter (fig. 27) and are deposited in the same manner as those in the Marjum Formation at Sponge Gully. Their smaller size is diagnostic of the Wheeler Shale at this site. Because of their longer distance of transport, a rough trend would follow that downsection specks become smaller as the carbonate bank was farther eastward, and as it prograded west, rocks upsection show larger specks—for example, in the Marjum Formation at Sponge Gully.

TOOL MARKS, SOLE MARKS AND MICROSCOPIC SCOURING

Tool marks were seen in only one bed of the rocks examined at Swasey Spring. This bed was a coarse basal unit of a turbidite, and the tool marks appear as long (15–20 cm) thin laminations on the bedding plane (fig. 21). They have an orientation of northeast–southwest. Their rarity is due to the weak distal turbidity currents that characterized sedimentation at Swasey Spring. The currents lacked sufficient energy to carry, in traction, clasts large enough to create drag marks.

The distal setting of sedimentation at Swasey Spring can be used to explain the lack of sole marks in the Wheeler Shale at this site. The turbulent currents needed to scour the substrate and fill that scour with silt and very fine sand would not have been present this far into the basin. However, microscopic scoured surfaces are present and can be seen in thin sections.

DEPOSITIONAL MODEL

Deposition of the Wheeler Shale at Swasey Spring was in Palmer's (1960) outer detrital belt and represents a basinal facies. The setting and mode of deposition were the same as discussed for the Marjum Formation at Sponge Gully, the difference being that turbidites at Swasey Spring reflect a more distal nature of deposition due to the quarry's setting farther basinward during deposition. The carbonate bank was farther eastward during upper Wheeler Shale time and migrated westward to create rocks that show deposition nearer the source upsection throughout the Middle Cambrian in the House Range (fig. 19).

The minor amount of limestone at the top of the Wheeler Shale at Swasey Spring shows the effects of basin filling and migration of the carbonate bank westward. These thin limestone units are fine-grained, lime-rich mud (fig. 25) and most probably correlate laterally to coarser-grained limestone of the upper Wheeler Shale to the east

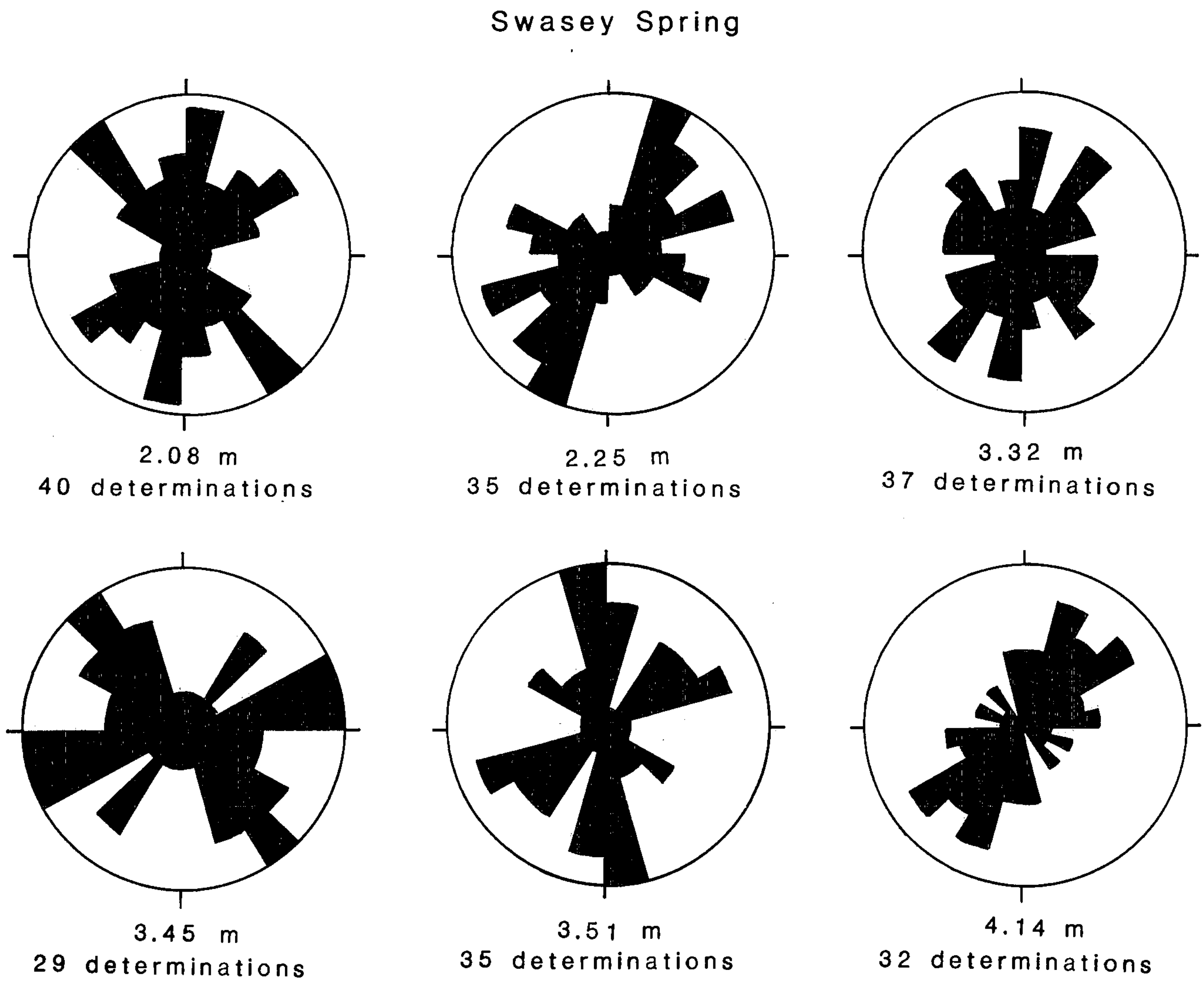

FIGURE 26.—*Orientation of organisms on single bedding planes at Swasey Spring shows the trend of movement of individual turbidity currents into the basin.*

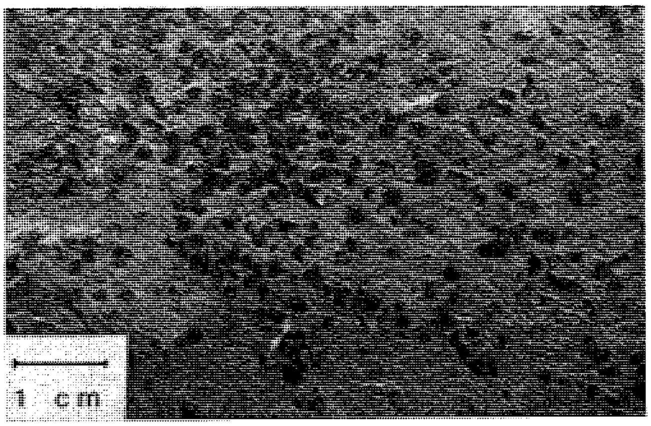

FIGURE 27.—*Relatively smaller "specks" at Swasey Spring are of uncertain origin.*

as they approach the carbonate platform, and most likely are similar to the limestone unit at Sponge Gully with graded peloids (fig. 9).

The estimate for the rate of turbidity current movement at Sponge Gully is 15–30 cm per second. The rate of current movement at Swasey Spring was somewhat less.

Because of the distal setting of the Swasey Spring quarry, the rocks lack many of the slope characteristics seen at Sponge Gully. The lack of penecontemporaneous folds and slides, fragmented fossils, sole marks, and limited fauna suggest an environment farther basinward from the slope. Additional evidence of a basinal setting is thinner bedding and finer-grained shale and limestone, less distinct orientation of organisms, and smaller specks and transported fossils when compared to the slope to basin transition environment at Sponge Gully.

PALEOECOLOGY

The dark calcareous shale and limestone of the Wheeler Shale at Swasey Spring was deposited in a deep anaerobic basin. The basin was not conducive to the survival of a living benthos for any great period of time. Deposition here was farther basinward than the slope-to-basin transition at Sponge Gully. All fossils recovered appear to have been transported into the basin by turbidity currents. The most common trilobites are agnostids, *Brachyaspidion microps*, and *Jenkinsonia varga*. The abundant agnostids found throughout the section lived a pelagic life (Robison 1972), fell to the basin floor, and were reworked by turbidity currents as they flowed basinward. The latter two trilobites are suggestive of the shallow-marine environment to the east and were transported out of their environment by turbidity currents moving off the platform and into the basin.

The greatest abundance of shallow-marine nonagnostid trilobites occurs in the section at two levels at Swasey Spring (fig. 6), suggesting that there was a controlling factor for their concentration on the platform to the east. Their localized abundance is possibly due to a process similar to that suggested for the "sponge beds" in the Marjum Formation at Sponge Gully. That is, subaqueous channels on the platform would repeatedly bring currents near a trilobite-rich community and transport them into the basin. The barren beds reflect a change in channel courses to an area that had a limited number of organisms.

Trace fossils are extremely rare in the rocks at Swasey Spring. The few seen are small burrows, 1 mm in diameter and 2 to 3 cm long, and are not extensive on the bedding planes on which they occur. Only very rarely was a benthos established within the basinal facies in which these rocks were deposited. The idea of transportation of organisms in turbidity currents, migration of organisms downslope, and diminishing amount of oxygen carried downslope by distal turbidity currents, as suggested for deposition at Sponge Gully, would also apply at Swasey Spring. However, with the basinal setting at Swasey Spring the distance for organisms to be transported or migrate would greatly hinder any establishment of a vagrant benthonic community. Only rarely was a living community established this far into the basin, as seen by the scarcity of trace fossils. The limited oxygen carried in by distal basinal turbidity currents would make the formation of a community very difficult, and, if formed, it would be very short lived.

PALEONTOLOGY

The Wheeler Shale at Swasey Spring quarry produced mostly trilobites (fig. 6). Swasey Spring rocks have a lower diversity when compared to Sponge Gully rocks, most likely because of the distance from the carbonate bank. Agnostid trilobites occur throughout the section because of their pelagic nature (Robison 1972). Trilobites of shallow-marine origin that were transported in are *Brachyaspidion microps* Robison, *Jenkinsonia varga* Robison, and *Elrathia*. Other arthropods found are an unidentified phyllocarid and pararthropod *Aysheaia* n. sp. (Robison in press).

Algae recovered are fragmented *Yuknessia* and specks whose origin might be *Morania*.

Other fossils are scarce when compared to trilobites. They include *Choia* sponges, unidentified inarticulate brachiopods, and *Peytoia* medusoids (Morris and Robison 1982).

CONCLUSION

The two quarry sites studied represent turbidite sedimentation in the deepwater House Embayment. Turbidity currents originated on a carbonate platform to the northeast, east, or southeast and carried fine silt, clay, and calcium carbonate into the basin that had a depositional slope to the southwest during deposition at the quarry sites. Organisms living on the platform and upper slope also were incorporated into the turbidity currents and carried basinward, where they were rapidly buried to allow their excellent preservation. Because of the semicircular nature of the House Embayment, trends of current movement varied greatly. A generalized trend of current movement from the northeast to the southwest is indicated by oriented organisms, sole marks, and tool marks.

The Wheeler Shale at Swasey Spring was located at some distance from the carbonate bank in a basinal setting. Edges of the carbonate bank and basin migrated westward during the Middle Cambrian. This basinal setting is represented in the rocks at Swasey Spring by thin bedding and fine-grained rocks, moderately well oriented fossils, no soft-sediment folds or slides, low faunal diversity, and rare tool marks. These features support a distal basinal setting with minimal depositional slope.

Deposition of the Marjum Formation at Sponge Gully was in a slope-to-basin transition, which came about after the carbonate bank had migrated westward and the basin began filling up. Consequently the rocks at Sponge Gully represent deposition nearer the source and on a slightly greater depositional slope. Evidence of this position is thicker bedding and coarser-grained rocks when compared to those at Swasey Spring, well-oriented fossils, soft-sediment folds and slides, higher faunal diversity, tool marks, and sole marks. These features suggest deposition of units at Sponge Gully accumulating in the slope-to-basin transitional zone, relatively near the carbonate bank.

The organisms recovered in both quarries were transported into the basin by turbidity currents or fell to the basin floor, as in the case of agnostid trilobites, and were reworked by turbidity currents moving basinward. The orientation of fossils and the shallow-marine origin of some trilobites and sponges support their transportation from the shallow-marine environment on the bank margin into the basin. However, the basin was not completely void of any living organisms. Trace fossils were found in both quarries, showing the existence of temporary communities established in the basin, allowed by oxygen brought intermittently into the basin. But the scarcity of these trace fossils indicates that the environmental conditions needed to survive in the basin were short lived. Trace fossils are rare at Swasey Spring and more abundant at Sponge Gully, especially near the top of the quarry. Such a pattern indicates vagrant benthonic communities were more commonly established nearer the carbonate bank in shallower water.

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