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A UNIQUE EXPOSURE OF CAMBRIAN MEGARIPPLES IN THE HAMPTON FORMATION, UNICOI COUNTY, TENNESSEE

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ABSTRACT—A spectacular 26-crest set of megaripples is described from sandstones and associated finer-grained rocks from the Hampton Formation (Lower Cambrian), Unicoi County, Tennessee. These megaripples are exposed on a single bedding plane that is exceptionally and unusually well preserved in three dimensions, thereby allowing for bed form measurement and analysis usually only possible for modern sedimentary deposits. The megaripples occur on the upper bedding plane of a 35-cm thick, medium to coarse-grained quartz arenite. This bed is both underlain and overlain by fine quartz sandstone, interbedded with micaceous siltstone beds, some of which preserve a well-developed *Cruziana* ichnofacies association. The wavelengths of the exposed megaripples range from 66–120 cm, and amplitudes range from 5.3–15.3 cm. Crests lines are straight to mildly sinuous and have well-rounded profiles. Measurement of face angles revealed average dips of 17.0 ± 1.7° and 19.1 ± 1.4° for NE and SW directed faces, respectively, indicating the megaripples are symmetrical. The structurally corrected mean azimuth for the paleo-current direction is 15.5°. The symmetrical profile and chemically mature nature of the megaripple sand requires a well-agitated setting, suggesting the influence of combined wave and tidal action. The presence of fine sandstone and laminated siltstone preserving a *Cruziana* ichnofacies association require periods of more quiescent conditions. This suggests the megaripple sandstone/fine grained sandstone/siltstone interbed sequence formed in a fluctuating shallow-marine environment characterized by fluctuating energy conditions in which deposition alternated between just below and within wave base.

Fossil megaripples were accidentally discovered during expansion of a factory car park as workers used a backhoe to remove rock from a northwest dipping sequence of alternating coarse sandstones and siltstones within the Hampton Formation (Lower Cambrian). A combination of the backhoe digging method, bedding dip, and competence differences between the siltstone and sandstone units caused the rocks to part along bedding planes. This resulted in exposure of a remarkable 26-crest set of megaripples, in three dimensions, on a coarse-grained sandstone bedding-plane surface. Fortunately, the factory manager left the ripple marks undisturbed and graciously permitted researchers and students from East Tennessee State University to study them. The polygonal-shaped exposure has a maximum length of 26 m, a height of 12 m, and covers an area of ca. 200 m^2. Although flow-related sedimentary structures are common in the sedimentary rocks of northeastern Tennessee, it is most unusual to see them exposed on this scale and preserved so well in three dimensions, thus allowing their measurement and description in great detail. This paper describes this unique megaripple sequence and explores possible modes of origin of these sedimentary structures in the shallow waters of the Cambrian Sauk Sea.

LOCATION AND GEOLOGIC SETTING

The megaripples described in this report are exposed on the southeast wall of the Driecor Inc. employee car park located on Old Highway Road, Erwin, Tennessee (latitude: 36°5′23″N, longitude 82°28′45″W)(Fig. 1). The wall exposes beds of the Hampton Formation (Lower Cambrian), the middle unit of the Chilhowee Group (Rodgers, 1953; King and Ferguson, 1960; Hardeman, 1966). The exposure occurs within a fault-bounded, but relatively complete sequence of the Chilhowee Group that is one of a series of three imbricate thrust sheets that repeat the Unicoi-Hampton-Erwin formation sequence in the area. These thrust sheets all exhibit motions from the southeast to the northwest, directions of motion that are the norm for northeastern Tennessee (Fig. 2).

The Chilhowee Group, first described by Safford (1856), is named for exposures on Chilhowee Mountain and is subdivided into three formations in ascending stratigraphic order: the Unicoi, Hampton and Erwin in northeastern Tennessee (Keith, 1903). It preserves a rift-to-drift transition that developed on the Cambrian Laurentian-Iapetus margin (Schwab, 1972; Mack, 1980; Cudzil and Driese, 1987). The Unicoi Formation contains basalt flows in its basal units but largely consists of immature conglomerate, arkose and subarkosic arenite (Rodgers, 1953). Cudzil and Driese (1987) interpreted the Unicoi Formation as having been deposited in a braided river channel sequence. The source of these sediments was an extensive granitic basement complex located to the west (Whisonant, 1974). The Hampton Formation contains dark silty and sandy shale, argillaceous shale, feldspathic sandstone and impure quartzite arenites (Rodgers, 1953) interpreted to have been deposited in shallow-marine conditions by Cudzil and Driese (1987). The Erwin Formation is divided into four members, which comprise alternating units of clean quartz sandstone and finer-grained lithologies (Rodgers, 1953). The quartz sandstone is interpreted to

FIG. 1. Hampton Formation megarippled sequence exposed at Driecor car-park, Old Erwin Highway, Erwin, Tennessee. (Jacob Staff lying perpendicular to megaripples is 1.5 m long.)

represent reworked fluvial sediments deposited in a near-shore transgressive environment (Cudzil and Driese, 1987).

FIELD AND LABORATORY METHODS

The exposed rock face that contains the fossil megaripples was measured with a meter tape and a 1.5 m Jacobs Staff. Wavelengths of the ripples were calculated using a single distance measured perpendicular to the ripple crests and averaged between 26 crests. Individual crest-to-crest measurements were made between adjacent ripples to determine the variability of wavelength across the entire section. Ripple amplitudes were measured at the deepest point between two crests. Bedding and megaripple orientation data were measured using a Brunton transit compass. Stoss and lee ripple face dip-angles were measured with a protractor mounted on a 1.5 m Jacobs Staff placed between, and perpendicular to each crest pair. Sediment samples for grain size analysis were collected as 2.5 cm diameter cores and hand samples. Mineral identification and sediment grain sizes were measured on thin sections prepared from core samples and on cut faces of hand samples. Rock thin sections were examined with a Nikon petrographic microscope mounted with a micrometer-calibrated reticle eye-piece.

OUTCROP DESCRIPTION

The Hampton Formation megaripples (HFM) are exposed on the upper surface bedding plane of a 35 cm thick coarse-grained sandstone. The bedding plane has strike and dip values of 45° and 58° NW, respectively. The exposed sedimentary waveforms have well-rounded crests and troughs which maintain a fairly uniform height along their length. The crests are straight to mildly sinuous, and bifurcation of individual crests is minimal. The long, relatively straight crests and uniform height qualify these features as having 2D ripple geometry (Costello and Southard, 1981).

Individual crest-to-crest distances range from 66 to 120 cm, qualifying these features as megaripples (Swift et. al., 1979, 1983). Waveform amplitudes vary from 5.3 to 15.3 cm and average 11.2 cm. The exposed megaripple surface is dominated by medium- to coarse-grained quartz sandstone. Freshly broken surfaces exhibit interstitial matrix that ranges from fine-grained, clean quartz sandstone and siltstone, hematitic claystone and cements. The exposed surface exhibits a characteristic red-orange color, presumably due to weathering of iron oxides. The HFM bedding-plane surface also displays a complex series of joint and fracture patterns, most of which trend either parallel or perpendicular to the trend of the megaripple crests. Although the megaripples are well preserved at this time, it appears the exposed sandstone beds are weathering rapidly and this outcrop will not survive for an extended period of time.

At the southwest end of the outcrop the HFM bed is overlain by approximately two meters of laminated fine-grained sandstone and siltstone. This area is prone to collapse, producing many newly fallen blocks with fresh faces. The sandstone ranges from quartz arenite to micaceous arenite in composition. The finely laminated siltstone is also micaceous. Many blocks preserve mottled textures that are clearly attributable to bioturbation. These are dominated by subhorizontal to horizontal feeding traces that are most likely attributable to the *Cruziana* ichnofacies (Walker, 1984).

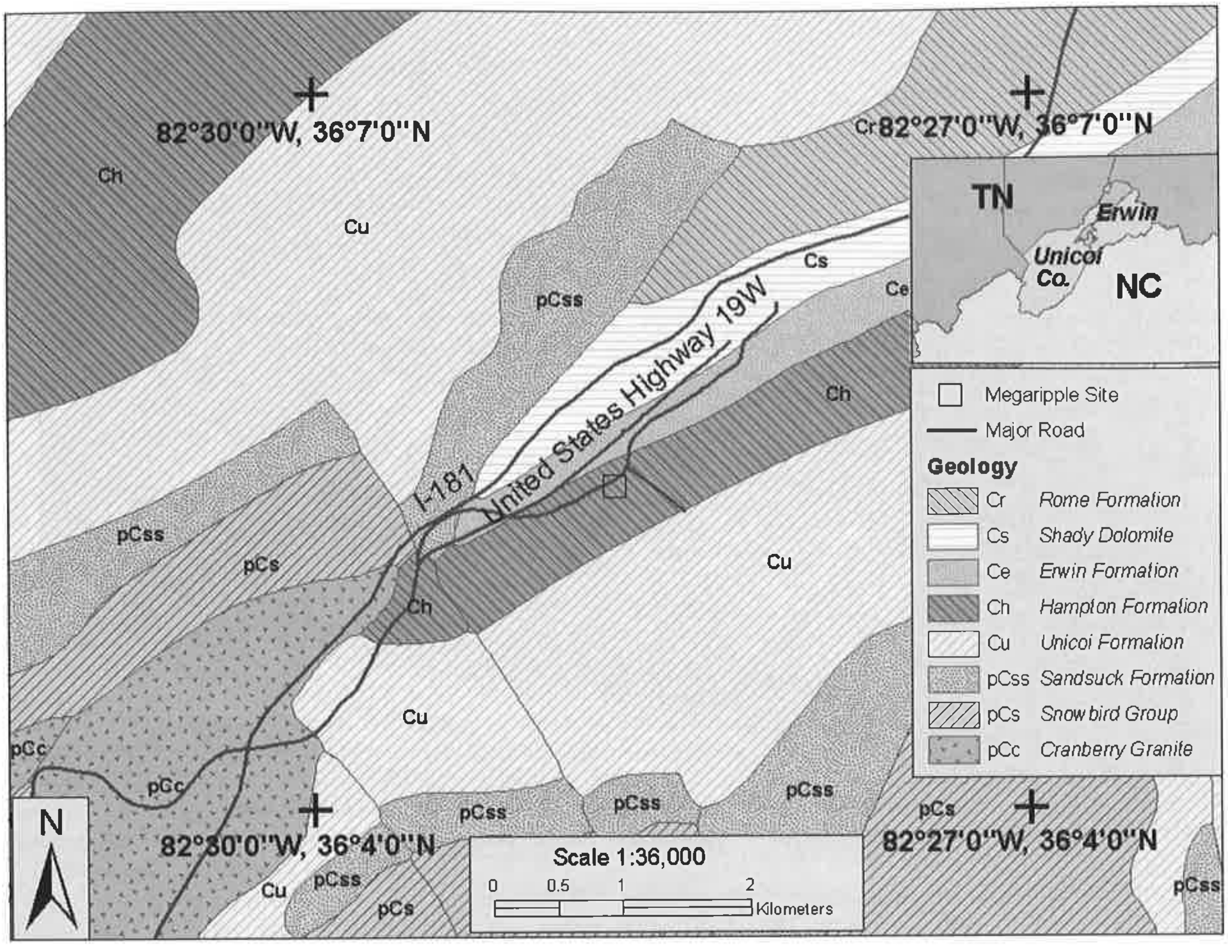


FIG. 2. Location and geologic map of the Hampton Formation megaripples, Unicoi County, Tennessee (after Hardemann, 1966). GPS Co-ordinates: 36°5′23″N, 82 °28′45″W.

The exposed meagripples are underlain by an approximately 10 m thick series of additional interbedded siltstone and sandstone that can be observed approximately 50 m northwest of the exposed HFM face, on a rock face cut perpendicular to bedding. This outcrop occurs behind the main manufacturing plant building, but was only examined at a distance because it has been undercut down-dip and almost constantly produces a rain of falling debris. This exposure preserves several additional coarse-grained sandstone beds, ranging up to 90 cm thick, which are interbedded with finer sandstone and siltstone. Some of the coarse-grained sandstone units appear to preserve additional megarippled surfaces. These coarse-grained sandstone beds alternate with laminar to massive fine sands and silts and compare favorably with the "classic" Hampton Formation sections described by Rodgers (1953) and Cudzil and Driese (1987) that occur along the Doe River and on Highway 19E at Hampton, Tennessee.

PETROGRAPHY

Rock thin sections were prepared from core samples drilled on both megaripple crests and troughs across the exposed rock face. Petrographic analysis reveals the HFM sandstone is a quartz arenite dominated by moderately-sorted, medium- to coarse-grained (0.4–2.0 mm diameter) quartz sandstone with grains that range from sub-rounded to sub-angular in shape. Occasional granules exceeding 3 mm in diameter occur, as do rare polycrystalline quartz grains. These grains commonly exhibit undulose extinction and grain margins are ragged. Grains range from sharing sutured surfaces to being encircled by cement. Feldspar and lithics are absent. Interstitial material is dominated by hematite cements but also includes minor amounts of quartz cement. The dominance of quartz, lack of other minerals, grain shape, and sorting are all consistent with sediment derived from a crystalline basement that has undergone a significant degree of reworking. Ragged grain boundaries and undulose extinction reflect a history of diagenetic alteration and micro-deformation, presumably related to the occurrence of the HFM within one of five thrust sequences that occupy the Erwin area (Hardemann, 1966).

The HFM quartz arenite bed is both underlain and overlain by laminar, thinly-bedded sandstone and siltstone, which occur in beds from 0.5 cm to 6 cm thick. These beds are micaceous, but are dominated by relatively clean, fine- to very fine-grained quartz sandstone and siltstone. Minor amounts of claystone and hematite cements also are present. Some beds have been subjected to significant amounts of bioturbation, which gives some siltstones a mottled appearance. Horizontal grazing traces are marked by a distinct increase in grain size within each trace, and are highlighted by orange-colored diagenetic products, presumably iron oxides and/or oxyhydr-

TABLE 1. Megaripple wavelength and amplitude data. Wave versus current generated ripple discrimination criteria. Ripple Index (RI) < 4 (wave generated) and RI > 15 (current generated). Ripple Symmetry Index (RSI) < 2.5 (wave generated) and RSI > 3.0 (current generated). Parallelism Index (PI) < 2.0 (wave generated) and PI > 4.0 (current generated).

Crest Pair	Wavelength (cm)	Amplitude (cm)	Ripple Index	Ripple Symmetry Index
1-2	92	9.4	9.8	1.3
2-3	115	13.9	8.3	1.0
3-4	113	14.5	7.8	1.0
4-5	114	15	7.6	0.9
5-6	100	14.3	7.0	0.9
6-7	93	10.6	8.8	1.1
7-8	100	14.7	6.8	1.2
8-9	120	12	10.0	0.6
9-10	66	7.1	9.3	1.3
10-11	87	9	9.7	1.0
11-12	86	13.5	6.4	1.1
12-13	97	15.3	6.3	1.0
13-14	99	10.2	9.7	0.9
14-15	92	12.6	7.3	1.2
15-16	112	10.9	10.3	0.8
16-17	94	12.2	7.7	0.9
17-18	88	10.5	8.4	1.0
18-19	89	9.5	9.4	0.9
19-20	81	5.3	15.3	1.1
20-21	86	12.4	6.9	1.2
21-22	100	12.5	8.0	0.9
22-23	92	9.7	9.5	0.8
23-24	70	5.3	13.2	1.0
24-25	70	9	7.8	1.0
Mean	94.0	11.2	8.8	1.0
Standard deviation	14.3	2.9	2.1	0.2
Standard Error	2.9	0.6	0.4	0.0
95% confidence limits	6.0	1.2	0.9	0.1
Skewness	−0.08	−0.52	1.63	−0.48
Parallelism Index	0.6			

oxides, which mark the boundaries of the traces. These traces are clearly representative of the *Cruziana* ichnofacies (Pettijohn et. al., 1973; Walker, 1984).

EVALUATION OF MEGARIPPLE DATA AND DISCUSSION

Individual ripple wavelengths range from 66 to 120 cm with a mean wavelength of 94 cm. Ripple amplitudes range from 5.3 to 15.3 cm with a mean of 11.2 cm (Table 1). The frequency of wavelength, amplitude, and face slope-angles of the measured megaripples all display distributions that are slightly skewed from standard normal distribution curves, but skewness is within one standard error (Fig. 3, Tables 1 and 2). A significantly positive correlation exists between wavelength and amplitude (Fig. 4). Slope angles for NE-facing megaripple faces range from 7–24° and average 17.0 ± 1.7°. Slope angles for SW-facing megaripple faces range from 13–26° and average 19.2 ± 1.4° (Table 2). A *t*-test of the face angles shows that no significant difference exists between the mean dip angles of the NW and SE facing megaripple faces (Table 3). The *t*-test result indicates these megaripples are symmetrical.

The lack of a hummocky cross-stratification on the exposed bedding plane precludes interpretation of this unit as a storm deposit (Swift et. al., 1983). The 2D geometry of these megaripples requires consideration of the influence of both oscillatory flow (wave action) and unidirectional flow, (tidal, storm wave or bottom generated currents) on their formation (Ashley, et. al., 1990). Modern 2D geometry megaripples have been observed on the Atlantic Continental Shelf and interpreted as both wave and tidal megaripples (Swift et. al., 1983). It also has been recognized that oscillatory and unidirectional influences can occur simultaneously in shallow marine conditions as a combined-flow and produce megaripples (Grant and Madsen, 1979). Symmetry of these combined-flow megaripples varies considerably. Where opposing flow vectors are strongly assymetrical the megaripple profile also is strongly assymetrical and has a characteristic steep slip face of 30–35° (Ashley et. al., 1990). More nearly symmetrical reversing tidal currents create close to symmetrical bedforms that have more gentle slopes, typically up to 10° but occasionally up to 20° (Ashley et. al., 1990). The characteristic HFM profile and slope angles clearly fall within the range of megaripples generated by a nearly symmetrical

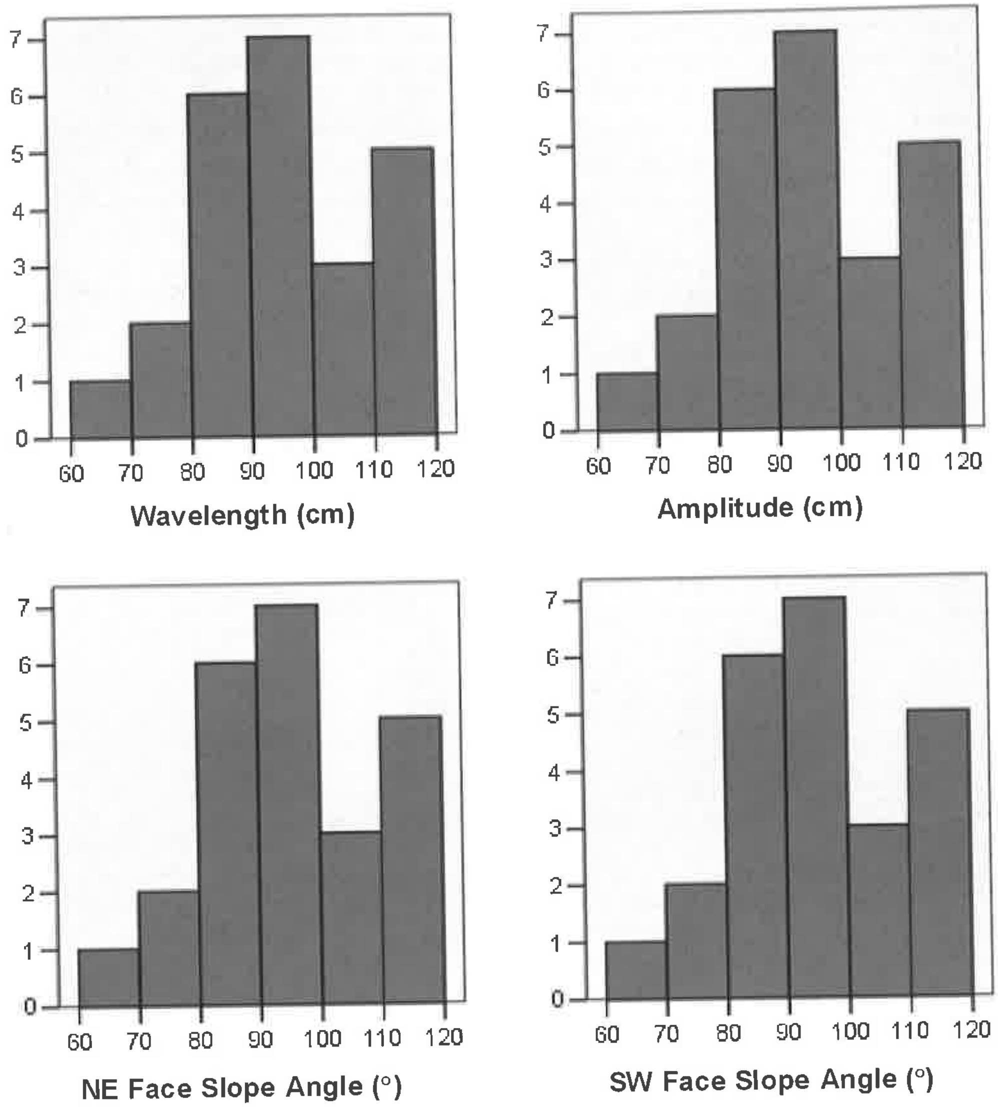


FIG. 3. Frequency distribution of megaripple wavelength, amplitude and face slope angles.

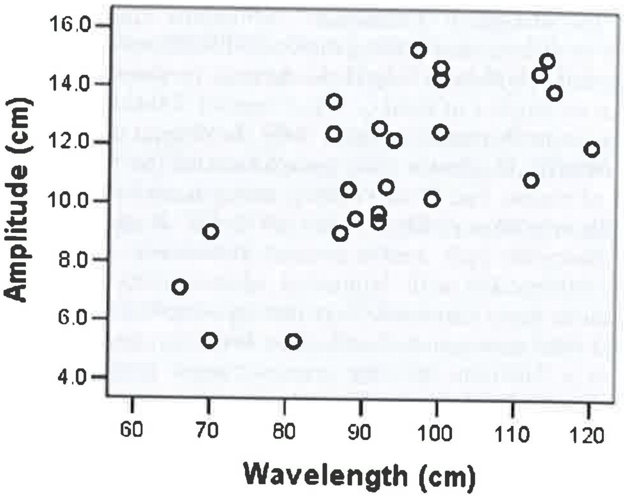
reversing combined-flow influence. The 2D geometry combined-flow megaripples also have been modeled in flume experiments (Arnott and Southard, 1990; Boguchwal and Southard, 1990; Southard and Boguchwal, 1990). It was found that 2D geometry ripples could be created with relatively low oscillatory and unidirectional velocity flows and, when a unidirectional component is applied, beds quickly develop a downstream asymmetry (Arnott and Southard, 1990). As previously stated, the average HFM face slope angles of 17.0 ± 1.7° (NE face) and 19.2 ± 1.4° (SW face) are statistically identical at the 95% confidence level. However, Fig. 3 clearly indicates a small skewness for asymmetry. It is clear that wave oscillation was an important controlling influence on the formation of the HFM but a combined-flow mechanism is also possible.

Collinson and Thompson (1982) provide a variety of measurable criteria for differentiating current from wave ripples. Ripple index (RI), ripple symmetry index (RSI), and parallelism index (PI) are calculated for the HFM (Table 1). According to Collinson and Thompson (1982), RI = wavelength/amplitude, RSI = wavelength of the stoss side/wavelength of the lee side, and PI = (maximum wavelength – minimum wavelength)/average wavelength. The HFM RI ranges from 6–15, with an average RI of 8.8. Collinson and Thompson (1982) defined a distinct wave RI as a value < 4 and a distinct current RI as having a value > 15. The HFM RI of 8.8 falls in the intervening range and therefore the RI value for the HFM is indeterminate. Wave generated ripples are defined as having a RSI < 2.5 and current generated ripples have an RSI > 3.0. As can be seen from Table 1, the RSIs of these same ripples are well below 2.5, with an average RSI = 1.0. The HFM have a RSI that clearly falls in the wave-generated domain. Wave generated ripples are defined as having a PI < 2.0 and current generated ripples have a PI $>$ 4.0. The HFM clearly have a PI (0.6) that falls within the wave-generated domain. These data, together with the distinctly straight and continuous crest lines, support formation dominated by wave action.

After tilt correction, the mean current flow direction for the HFM is 15.5° ($n = 22$). Whisonant (1970) reported a current flow direction of S 73° E. (107°) from a single locality in the Hampton Formation, northeastern Tennessee, and

TABLE 2. Megaripple face slope angle data.

Crest	NE Face Angle (°)	SW Face Angle (°)
1	19	15
2	16	14
3	21	19
4	16	24
5	19	19.5
6	13	16
7	22	16
8	18	15
9	16	20
10	13	23
11	22	19
12	22	19
13	10	25
14	19	19
15	18	26
16	10	19
17	16	19
18	19	16
19	19	20
20	24	25
21	13	21
22	13	13
23	18	20.5
24	19	15
25	7	20
26	20.5	20.5
Mean	17.0	19.2
Standard deviation	4.2	3.5
Standard Error	0.8	0.7
95% confidence limits	1.7	1.4
Skewness	−0.63	0.21



		Wavelength (cm)	Amplitude (cm)
Wavelength (cm)	Pearson Correlation	1	.695(**)
	Sig. (2-tailed)		.000
	n	24	24
Amplitude (cm)	Pearson Correlation	.695(**)	1
	Sig. (2-tailed)	.000	
	n	24	24

** Correlation is significant at the 0.01 level (2-tailed).

FIG. 4. Correlation analysis between megaripple wavelength and amplitude.

interpreted this to indicate that Chilhowee currents moved primarily down the regional paleoslope to the southeast. Cudzil and Driese (1987), reported unimodal directions for the Hampton Formation with a mean of 75° ($n = 125$) but widely dispersed directions between 0°–180°. They conclude that

TABLE 3. A *t*-test statistical analysis indicating that no significant difference exists between the mean dip angles of the NW and SE facing megaripple faces.

One-Sample Statistics

	n	Mean (°) Face Angle	Std. Deviation	Std. Error Mean
NE Face	26	17.02	4.220	0.828
SW Face	26	19.17	3.516	0.689

One-Sample Test

	Test Value = 0					
					95% Confidence Interval of the Difference (°)	
	t	*df*	Sig. (2-tailed)	Mean Difference(°)	Lower	Upper
NE Face	20.564	25	0.000	17.019	15.31	18.72
SW Face	27.809	25	0.000	19.173	17.75	20.59

within the Hampton Formation "sandstone facies", it is difficult to differentiate among deposition in response to wave activity, tidal currents or long shore currents because conclusive evidence in support of tidal or wave regimes is lacking.

These observations, together with the overall appearance of the outcrop, suggest a close comparison to the "sandstone facies" of Cudzil and Driese (1987), which occurs throughout the Chilhowee Group. The "sandstone facies" is characterized by medium- to very coarse-grained subarkosic to arkosic arenite interbedded with laminated siltstone and sandstone with sedimentary structures that indicate deposition in tidal and sub-tidal areas and shoals. The bed that preserves the HFM is a medium- to very coarse-grained quartz arenite interbedded with laminated siltstone and sandstone. The rounded and symmetrical nature of these megaripples and the chemically mature nature of the sandstone is consistent with deposition in a shallow-marine wave-dominated environment. The megarippled bed lacks the arkosic to sub-arkosic nature reported to be common in the "sandstone facies" by Cudzil and Driese (1987). The lack of feldspar is likely due to efficient re-working of these deposits by wave action.

The close association of laminated fine sandstone and siltstone, some preserving *Cruziana* ichnofacies, interbedded with the megaripples requires fluctuations of current strength that may be related to deposition at slack tide, after tidally- or storm-enhanced currents waned or in sub-wave base conditions. The association of megarippled sandstone beds and interbedded laminated and bioturbated fine-grained sediments indicates this sequence was deposited in a near-shore environment. The sequence was influenced by both wave activity, minor unidirectional (tidal?) current activity, and/or combined flow conditions and water depth may have ranged from intertidal to sub-wave base.

CONCLUSIONS

This study has described a unique sequence of megaripple sedimentary structures that occur within the Hampton Formation (Lower Cambrian) near the town of Erwin, Tennessee. The megaripples are preserved in extraordinary three-dimensional detail. They are exposed on the upper bedding plane of a medium- to coarse-grained quartz arenite, and are interbedded with fine sandstone and laminated siltstone, some of which preserve *Cruziana* ichnofacies traces. Additional coarse-grained sandstone sheets that display channel forms, and perhaps additional megaripples, are preserved in the same section but were not accessible for this study. Measurement and analysis of individual crest lee and stoss slopes indicate the megaripples are symmetrical. This finding, together with the mineralogical maturity of the megarippled sandstone, analysis of plan-view crest patterns, and calculation of Ripple Symmetry and Parallelism Indices all support their formation in shallow-marine conditions in which wave action and combined flow were important factors. The presence of laminated siltstone, and associated *Cruziana* ichnofacies, interbedded with the megaripples, argues for deposition in shallow-marine conditions that fluctuated from wave base to just below wave base. This sequence contains an exceptional suite of features that clearly add support to previous interpretations that the Hampton Formation was deposited in shallow-marine conditions as part of the Chilhowee Group rift-to-drift depositional sequence.

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