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SEDIMENTOLOGY AND PALAEOENVIRONMENT OF THE PLIOCENE BOWDEN FORMATION, SOUTHEAST JAMAICA

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The Pliocene Bowden Formation of southeast Jamaica, estimated to be at least 150 m in thickness, is composed of three lithofacies herein termed the conglomerate/sandstone, marlstone, and micritic limestone lithofacies. Six measured sections, encompassing approximately 70 m of strata, indicate that these lithofacies represent 11%, 87% and 2%, respectively, of the formation. The conglomerate/sandstone lithofacies is interpreted as a product of sediment gravity flows, more specifically turbidites, and constitutes an integral component of the Bowden shell bed that occurs near the base of the sequence. The marlstone lithofacies is interpreted as a product of pelagic and hemipelagic deposition from low density turbidity currents, or possibly even bottom water nepheloid layers, and the micritic limestone lithofacies as selectively cemented carbonate-rich nodules and horizons within the marlstone lithofacies. Marlstones are characterised by abundant ichnofaunas which collectively are indicative of more or less stable ecological systems in hydrodynamically low-energy, deep-water environments. Together with sedimentological data, this suggests the Bowden Formation to have been deposited in a deep-water environment, below storm wave base, that possibly deepened upwards. We speculate that the most likely palaeoenvironment was not too dissimilar to the present-day Yallahs Basin of southern coastal Jamaica.

Key words — Bowden Formation, Pliocene, sedimentology, palaeoenvironment.

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INTRODUCTION

Despite the focus of much historical and present-day palaeontological research on the sequence, the Pliocene Bowden Formation of southeastern coastal Jamaica was only formally named by Robinson in 1969. He defined the formation as comprising essentially horizontally bedded or gently southward-dipping (2-10°) conglomeratic layers and associated foraminiferal marls (Woodring's 1925 and 1928 'Bowden shell bed'), overlain by predominantly silty and sandy marls interlayered with uncommon, thinly bedded sandstones and micritic sandy limestones. The formally designated stratotype (Robinson, 1969a) is exposed in cliffs on the eastern side of Port Morant Harbour between approximately 200 m north of Pera Point downsection to the Bowden Wharf (Fig. 1; Pl. 1). However, the stratotype does not include the underlying Bowden shell bed, as exposed in the village of Bowden, that should still be regarded as an integral part of the formation albeit as an informal descriptor, as its mappability cannot be demonstrated.

The Bowden shell bed, unlike the remainder of the sequence, has attracted many palaeontological studies (see later, and papers in Wright & Robinson, 1993), probably a reflection of it being the most fossiliferous sequence in Jamaica, having yielded over 600 species of molluscs, plus algae, vertebrates and numerous other invertebrates (Donovan *et al.*, 1995). As discussed in more detail later, there has been considerable debate and controversy with respect to the depositional environment of the Bowden Formation because most previous interpretations have been made based on palaeoautecological studies of selected groups within the fauna preserved in the Bowden shell bed with little or no consideration of the remainder of the sequence nor of sedimentological observations made on the shell bed itself.

The purpose of this contribution is, therefore, to provide sedimentological observations made by us on both the Bowden shell bed and the remainder of the sequence, and to utilise these observations with respect to the interpretation of the overall depositional scenario of the Bowden Formation. Our observations and interpretations are supplemented with reference to the ichnology of the Bowden Formation and consideration of taphonomic aspects of the Bowden shell bed.

GEOLOGICAL SETTING

The Bowden Formation comprises the uppermost stratigraphic unit of the Lower Coastal Group and, as noted, is Pliocene in age (Robinson, 1969b; Berggren, 1993; Aubry, 1993). In its type area of the Bowden district, natural exposures of the formation are poor and discontinuous, so that a complete and detailed stratigraphy of the entire sequence cannot be determined.

Nevertheless, based on map interpolation, Pickerill *et al.* (1996) estimated a minimum thickness of 150 m. The basal part of the formation is unexposed and is considered to grade somewhat arbitrarily into lithologically similar marlstones of the Buff Bay Formation.

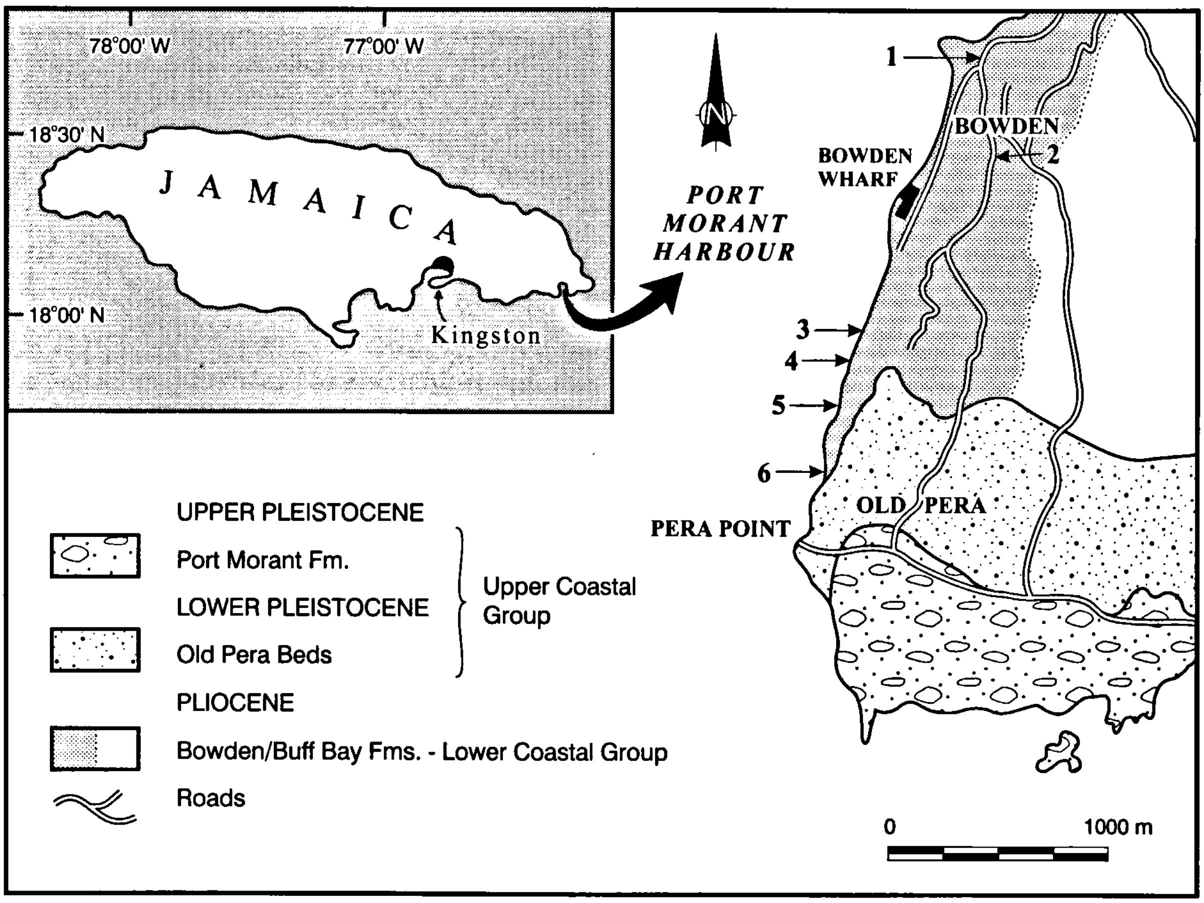

Fig. 1. Simplified geological map of the eastern side of Port Morant Harbour, southeast coastal Jamaica, indicating location of Sections 1-6 as documented herein (see Figs 2-5).

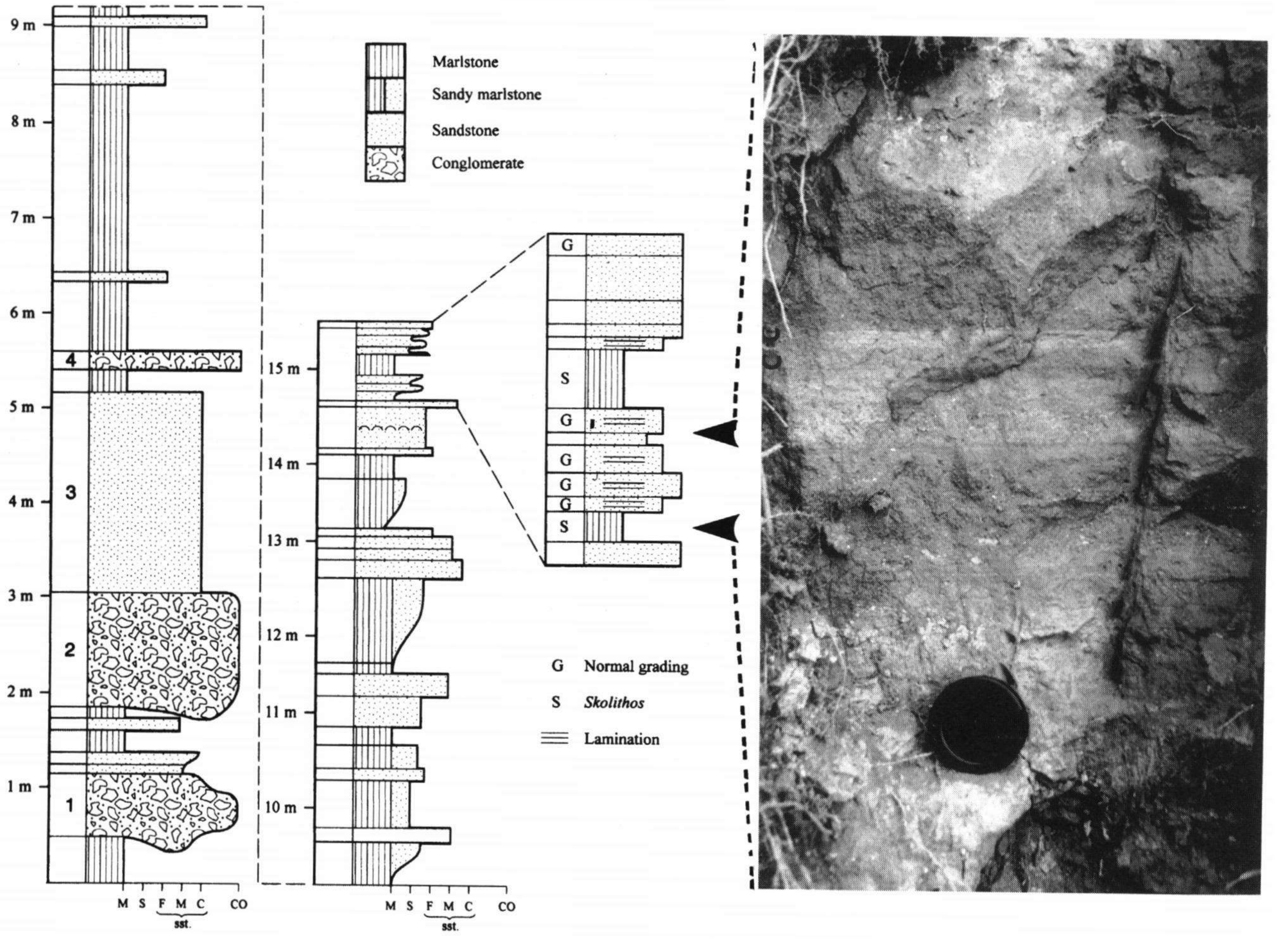

Fig. 2. Stratigraphic log of the Bowden Formation at Section 1, that includes the Bowden shell bed herein defined as those strata from the base of unit 1 to the top of unit 4 (see also Fig. 3). M = Marlstone; S = Siltstone; F, M, C are fine-, medium - and coarse-grained Sandstone (= sst.); and Co = Conglomerate. Amalgamated, fine- to medium-grained turbiditic sandstones illustrating Bouma Ta-b sequences are shown on the right.

The top of the sequence, as exposed at the stratotype in the cliffs approximately 200 m north of Pera Point, is defined by the nonconformably overlying, early Pleistocene Old Pera Beds of the Upper Coastal Group (Fig. 1). These latter strata comprise an essentially shallow-water neritic succession (Robinson, 1969a) of limestones and siliciclastic strata dominated by storm-generated, medium- to coarse-grained sandstones interbedded with fine- to medium-grained sandstones that are typically highly bioturbated (Pickerill *et al.*, 1993).

METHODOLOGY

In addition to its discontinuous exposure, detailed observations on strata of the Bowden Formation are hampered by dense vegetation cover, the subtropical weathering of the generally poorly lithified marlstones that results in most strata being veneered by fine-grained regolith, and by individual sections being extremely prone to slippage resulting in coverage by slide deposits. In order to demonstrate the overall character and variation in the sequence we therefore chose six sections to examine in detail (Fig. 1). Section 1, located on the east side of the road immediately north of the junction of the road to Old Pera and the Bowden Wharf (Fig. 1), was selected because it exposes, and is the type location of, the Bowden shell bed. Trenches were dug in order to provide as complete a stratigraphic section as possible at this location, and to facilitate a definition for the Bowden shell bed, which has never been previously discussed. Section 2 is located approximately 250 m to the south of Section 1, on the east side of the road leading to Old Pera immediately to the south of the hairpin bend that provides an alternative route to Old Pera (Fig. 1). Sections 3-6 are located at various sites within the stratotype of the Bowden Formation (Pl. 1) and can be accessed by wading the waters of Port Morant Harbour (Fig. 1). These sections were chosen either where the strata exhibited lithological variation and/or visible internal detail, or where the strata were sufficiently exposed to enable a vertical section to be constructed.

Collectively these sections encompass a vertical thickness of approximately 70 m of strata. Sections 1 and 6 are, respectively, the lowermost and uppermost in the sequence. However, we are unable to correlate with any accuracy the stratigraphic position of Section 2 with respect to Sections 3-5 (themselves located in ascending stratigraphic order) though we do suspect, based on map interpolation, it is located above Section 4.

Representative samples from individual sections were collected for slabbing, thin section and geochemical analysis. These samples are housed in the Department of Geology, University of New Brunswick. Detailed stratigraphic logs of Sections 1-6 are exhibited in Figures 2-5. Articulated bivalve molluscs discussed herein are deposited in the Geology Museum, University of the West Indies, Mona.

SOME NOTES ON TERMINOLOGY

The Bowden shell bed — As previously noted, much palaeontological research has been conducted on the essentially conglomeratic layers comprising the Bowden shell bed (for example, Palmer, 1945; Rácz, 1971; Robinson, 1969a; Goodfriend, 1993; Katz & Miller, 1993; Donovan & Paul, 1996), though the nature of this stratigraphic unit has never been previously clarified.

Although we prefer to retain the descriptor as stratigraphically informal, herein we define it as those strata occurring between the base of the lowermost to the top of the uppermost conglomeratic layer(s) in Section 1 as located herein (respectively, units 1 and 4 of Figs 2, 3). This definition is consistent with previous general usage (Robinson, pers. comm.) and indicates that the 'shell bed', actually comprises four distinct, highly fossiliferous conglomerate to coarse-grained sandstone layers (units 1-4 of Figs 2, 3), interbedded with reduced proportions of thinner bedded, medium- to coarse-grained sandstones and marlstones. The Bowden shell bed is, therefore, approximately 5 m thick.

Marlstone — The American Geological Institute (AGI) 'Glossary of Geology' (Bates & Jackson, 1980) defines a 'marl' as an '... old term loosely applied to a variety of materials ...' and the descriptor has commonly historically been adopted for convenience rather than a specific lithotype (Stow, 1985). Marls typically comprise '... loose earthy deposits consisting chiefly of an intimate mixture of clay and calcium carbonate ...' (Bates & Jackson, 1980, p. 403). Strata in the Bowden Formation have consistently been referred to as marls by all previous authors, but strictly, because they all exhibit some degree of lithification, they are more worthy of being termed marlstones. Compositionally the strata are ubiquitously calcareous, but petrographic and geochemical analysis suggest that the carbonate content is consistently lower than the accepted definition (Lydka, 1978) of a marlstone at >30% by total weight (Tab. 1).

	1	2	3	4	5	6	7	8	9	10
SiO_2	48.57	49.31	48.61	46.68	46.46	48.75	48.98	49.55	50.59	22.64
TiO_2	0.78	0.81	0.76	0.74	0.77	0.81	0.79	0.83	0.83	0.30
Al_2O_3	13.38	13.86	13.36	12.41	12.70	14.08	13.42	14.08	13.43	6.21
MgO	4.20	4.70	4.42	3.59	4.13	4.47	4.10	4.44	4.00	2.99
CaO	9.13	8.03	9.07	9.11	10.42	8.37	8.85	7.96	8.66	33.06
MnO	0.09	0.09	0.09	0.08	0.09	0.13	0.09	0.11	0.09	0.26
Fe_2O_3	6.79	7.18	6.80	6.29	6.51	7.30	6.76	7.34	6.51	3.11
Na_2O	3.20	3.06	3.35	3.00	3.14	2.94	2.80	3.31	3.38	1.18
K_2O	1.54	1.90	1.66	1.13	1.25	1.55	1.58	1.63	1.61	0.68
P_2O_5	0.14	0.15	0.12	0.13	0.13	0.13	0.15	0.13	0.13	0.12
CO_2	5.08	3.85	4.60	5.42	5.88	3.99	4.64	3.95	4.91	25.36
H_2O	7.10	7.08	7.14	11.41	8.52	7.47	7.84	6.68	5.86	4.10
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
$CaCO_3$	11.55	8.76	10.46	12.33	13.37	9.07	10.55	8.98	11.17	57.68

Table 1. Normalised major element analysis for nine randomly selected marlstones (1-9) and one micritic limestone (10) from the Bowden Formation of southeast Jamaica. Note that following the method of Galle & Runnels (1960), $C0_2$ was calculated by the difference from heating to 550°C and 1,000°C and H_20 by heating at 550°C for twenty-five minutes. All other elements were determined by XRF on ignited samples for 1.5 hours and corrected for lost volatiles on ignition.

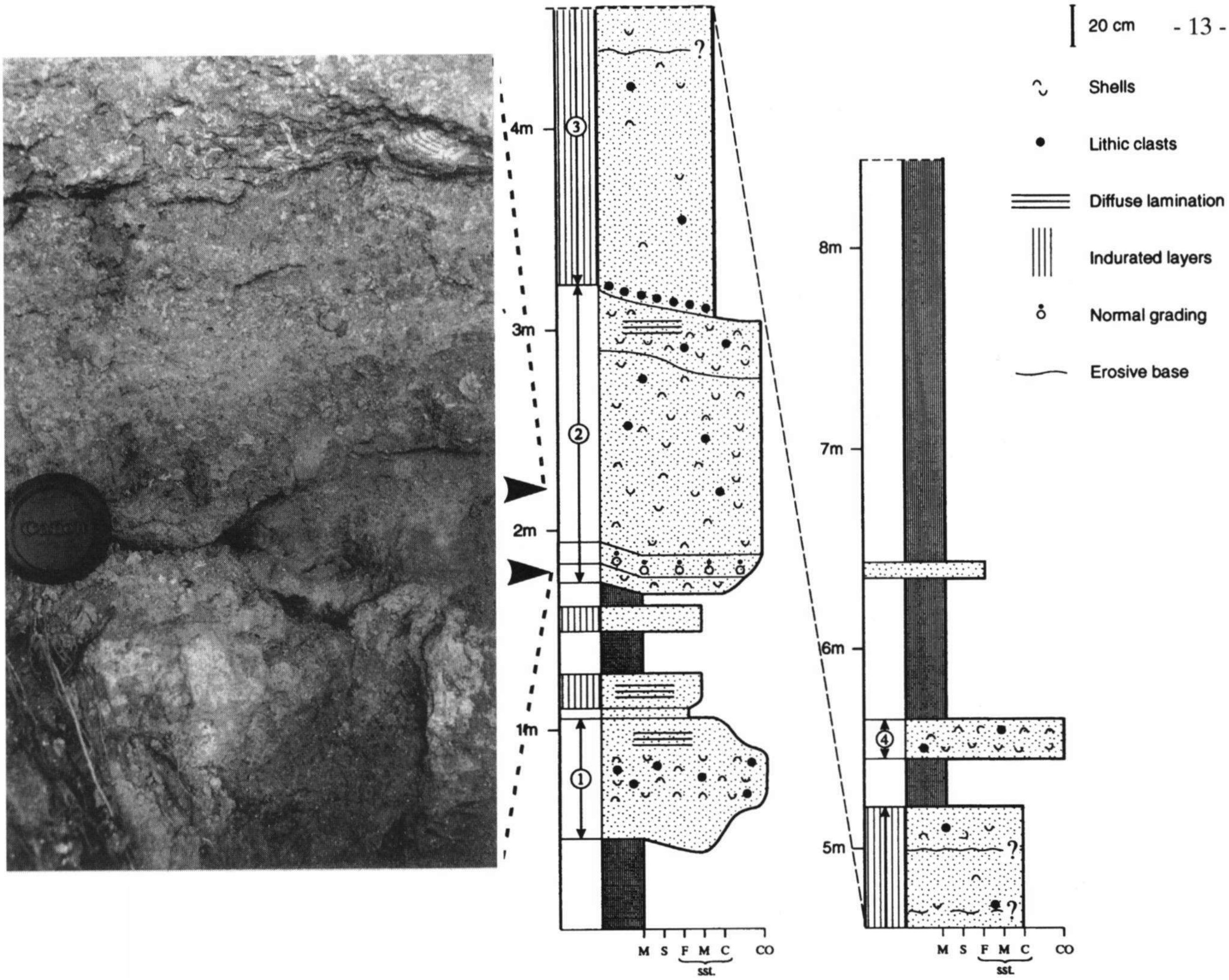

Fig. 3. Stratigraphic log of the Bowden Formation at Section 1 illustrating details of the Bowden shell bed (units 1-4 inclusive). Amalgamated, erosively based conglomerate layers from unit 2 are illustrated on the left. M, S, F, M, C, Co as in Figure 2.

Additionally, grain size can vary from clay to silt to even fine-grained sand and the detrital clastic component from essentially non-existant to being the primary constituent. Thus, marlstones of the Bowden Formation are, lithologically and compositionally, extremely heterogeneous. Herein, we therefore follow the AGI definition whereby a marlstone is considered to be a general term referring to a mixed carbonate to fine-grained clastic rock with no specific limits on the relative proportions of one or the other components. Where other material is an integral component we use the appropriate qualifier (for example, sandy).

SEDIMENTARY LITHOFACIES

For convenience we describe and interpret lithofacies of the Bowden Formation with respect to its three component and contrasting lithologies. These are, in decreasing order of abundance, marlstone, conglomerate/sandstone and micritic limestone lithofacies. Most sedimentological information can be gleaned from the conglomerate/sandstone lithofacies and, therefore, this category is discussed first.

Conglomerate/Sandstone Lithofacies

Description — Conglomerate layers constitute only approximately 4% of the vertically measured sections, collectively of about 70 m in thickness, and are essentially, though not exclusively, associated with the Bowden shell bed (units 1, 2, 4 of Figs 2, 3). On the scale of the present-day outcrop, these units are laterally continuous over several metres and previous suggestions on their lenticularity (for example, Robinson, 1969a) are regarded as speculative. Clasts in the conglomerate layers comprise variably-sized shells, mainly molluscs, and sporadically distributed, well-rounded lithic pebbles and cobbles ranging up to 12 cm in diameter. The latter are of variable composition, and include siltstone, rhyolite, basalt and andesite; smaller pebbles also include quartz and chert (Palmer, 1945). Sorting is extremely poor. Shells are typically highly leached, and may be complete, broken, articulated or disarticulated and exhibit considerable size variation for individual species. Disarticulated valves of bivalve molluscs are preserved in all orientations from bedding parallel (both concave up and concave down) to perpendicular to bedding. Some of the larger, disarticulated valves are complete, but shattered by a pattern of cross-cutting fractures.

Articulated shells may be 'empty', that is, not infilled by sediment. Carbonized wood fragments are also common. The conglomerate matrix comprises medium- to coarse-grained calcareous sandstone that is composed of bioclastic and siliciclastic grains of similar composition to the clast component. The internal texture of single conglomerate layers is heterogeneous with matrix- and clast-supported fabrics being variably developed both vertically and laterally.

Megascopically, units 1, 2 and 4 of the Bowden shell bed appear massive and generally disorganised with no obvious internal structures.

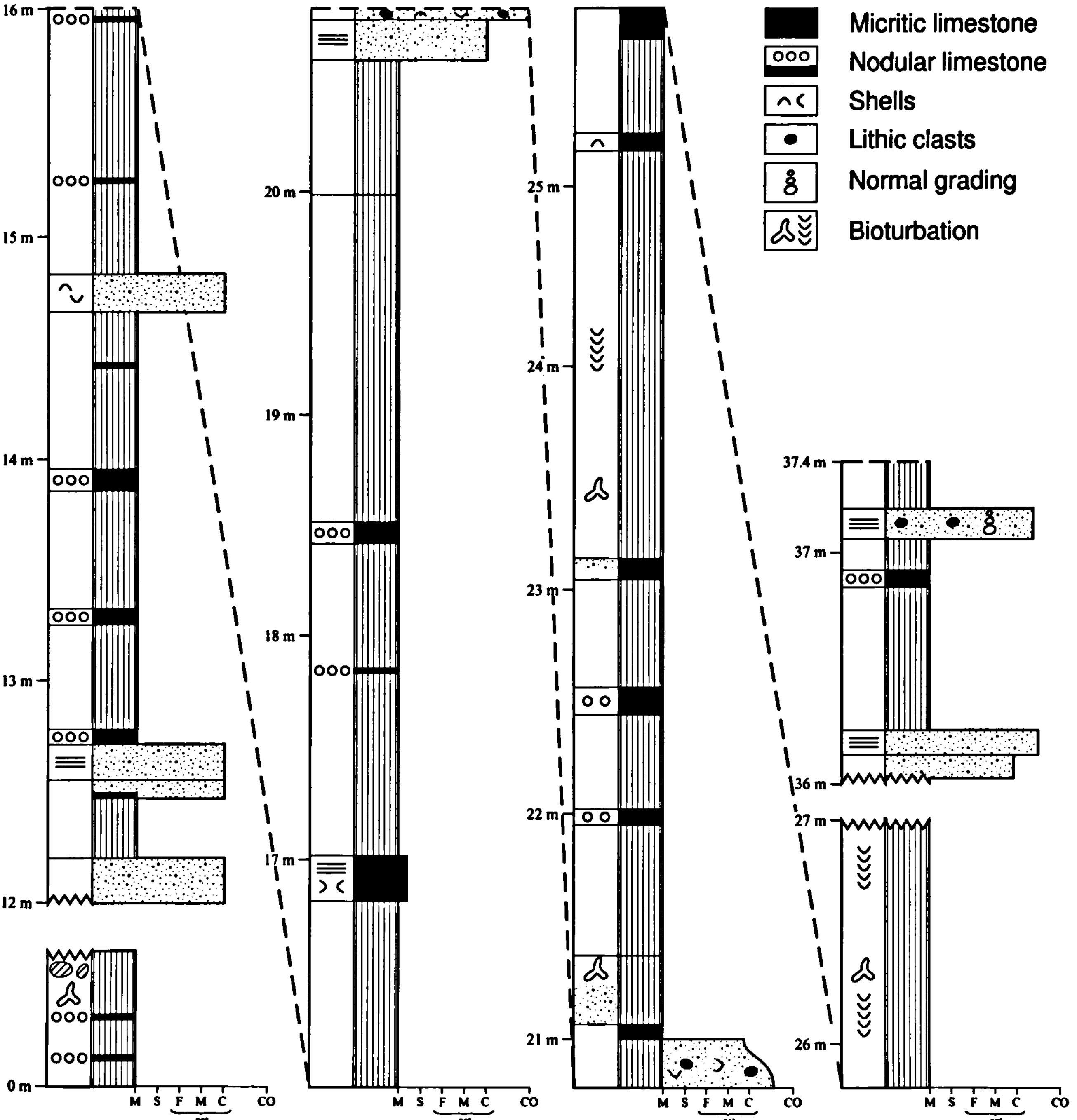

Fig. 4. Stratigraphic log of the Bowden Formation at Section 2. Note that the boulders (cross-hatched near the base of the column to the extreme left) near the base of the section actually occur 78 cm below the lowermost coarse-grained sandstone layer. M, S, F, M, C, Co as in Figure 2; other symbols as in Figure 3.

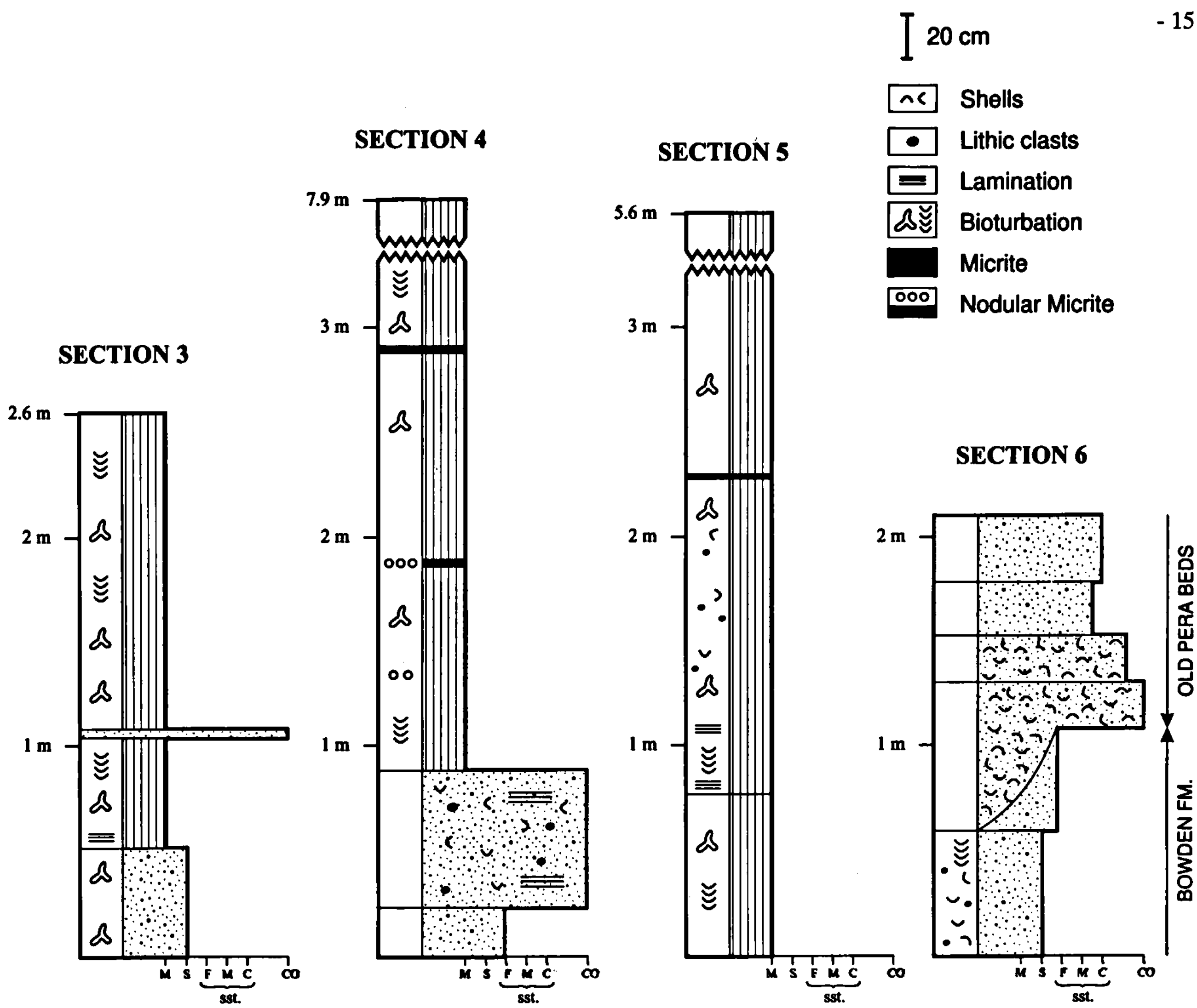

Fig. 5. Stratigraphic logs of the Bowden Formation at Sections 3-6 at the stratotype (for locations see Fig. 1; Pl. 1). M, S, F, M, C, Co as in Figure 2; other symbols as in Figure 3.

This is particularly true of unit 4. However, close inspection of the 147 cm thick unit 2 reveals that it is comprised of four amalgamated units, each with an erosive base (Fig. 3). At least one of these units is normally graded and a second exhibits diffuse horizontal to low angle stratification/lamination in its upper horizons (Fig. 3). Diffuse lamination is also developed in the uppermost part of unit 1. Within our six measured sections the only other occurrence of a conglomeratic unit is that from Section 4 (Fig. 5). This unit, 65 cm in thickness, comprises alternating layers (1-2 cm thick) of bioclastic- and clastic-rich material that both contain outsized (up to 5 cm diameter) volcanic pebbles, and large disarticulated molluscan and scleractinian fossils. The basal portions of this particular unit preserve the trace fossil *Thalassinoides*; otherwise, all conglomerate units are devoid of bioturbation.

Sandstone layers are typically calcareous, tan-coloured and constitute approximately 7% of the measured sections. Individual layers are laterally continuous on outcrop scale and vary in thickness from 2.5 to a maximum 180 cm. However, this latter layer, unit 3 of the Bowden shell bed (Figs 2, 3), may comprise amalgamated sandstone layers, particularly in its uppermost horizons, though this cannot be convincingly demonstrated. Otherwise, most sandstone layers are between 5 and 20 cm thick. Sandstones are particularly prominent in Sections 1 and 2, but less so in Sections 3-6 (Figs 2-5); in Section 1 they are commonly amalgamated (Fig. 2). Most layers exhibit sharp, planar lower and upper surfaces; however, several exhibit erosional and irregular lower surfaces. Most are medium- to coarse-grained, and possess disarticulated and/or broken shell material, plant debris and lithic clasts similar in composition to those observed in conglomeratic units. This is particularly true for unit 3 of the Bowden shell bed that, in addition, possesses sporadically distributed, large, articulated or disarticulated shells. All sandstones lack bioturbation.

Internally, several sandstone units appear massive (Pl. 2, Fig. 3), but we regard this to be a function of weathering. More commonly, and in decreasing order of abundance, they exhibit: (i) normally graded layers; (ii) normally graded passing vertically into parallel-horizontally-laminated layers (Fig. 2; Pl. 2, Fig. 1); (iii) pervasively horizontally-laminated layers; and (iv) rare, normally graded, passing vertically into horizontally-laminated, and in turn into cross-laminated, layers.

Interpretation — Most conglomerate and calcareous siliciclastic/bioclastic sandstone layers exhibit evidence of deposition from sediment gravity flows. The presence of tractional features in several units and erosional bases in several others suggests deposition from high density, decelerating turbidity currents. In the sandstone layers this is indicated by normally graded horizons passing vertically into parallel- and/or parallel- overlain by cross-laminated horizons within individual depositional units. In terms of the classic Bouma (1962) sequence of internal structures within single turbidites, such layers can be interpreted respectively as Ta-b and Ta-c sequences. Given such an interpretation, normally graded sandstones or horizontally-laminated sandstones can best be equated with partial Bouma Ta and Tb sequences. Several conglomeratic layers, particularly those of unit 2 of the Bowden shell bed, also indicate evidence of rapid deposition from erosive turbidity currents.

The massive sandstone and conglomerate layers form a much lower proportion of the lithofacies and are more difficult to interpret sedimentologically. Several apparently massive sandstones reveal diffuse horizontal laminations when vertically sectioned and polished; therefore, as previously noted, we suspect their massive nature is a function of weathering and they, too, are best interpreted as Bouma Tb turbidites. Massive and disorganised conglomerates similar to those in the Bowden Formation, particularly the Bowden shell bed, are commonly developed in association with turbiditic sequences (Walker, 1975) and in the absence of experimental work their depositional mechanisms should best still be regarded as speculative (Walker, 1992). However, the intimate association of these massive conglomerates with other turbiditic units does suggest that these, too, are a product of deposition by sediment gravity flows.

Conglomerates and sandstones in Section 1, where they are most common, are commonly amalgamated, lacking intervening pelitic material, and the internal sequences exhibited by them would, in a classical sense, suggest a 'proximal' depositional environment (see Pickering *et al.*, 1989; Middleton, 1993, for reviews). However, no layers exhibit evidence of reworking by either fairweather or storm wave activity, suggesting that they were deposited in relatively deep water below storm wave base.

The preservation of disarticulated bivalves in multiple orientations provides convincing supporting evidence of sedimentation by some sort of mass flow event, analogous to that shown by, for example, horizontal to upright crinoid pluricolumnals in the Silurian Thornton Reef, Illinois (Donovan *et al.*, 1997). Articulated ark shells that are not infilled with sediment are also indicative of rapid burial. Of the three 'empty shells' collected from units 1 and 2, two are the ark *Barbatia prephina* Woodring, the third a large *Trigonicardia*, perhaps closest to extant *T. media* (Linné). Arks are epifaunal bivalves that attach by a byssus and prefer to inhabit depressions in firm substrates (Kauffman, 1969, p. N150). It is at least conceivable that shells of *B. prephina* were attached to lithic clasts or shell debris in shallower water, and were transported downslope by the turbidity current and buried alive. Not being adapted for burrowing, the buried shells were probably held tightly shut as the mollusc awaited an amelioration of environmental conditions that never came.

Marlstone Lithofacies

Description — Marlstones comprise the dominant lithology of the Bowden Formation, constituting approximately 87% of the overall thickness of the six measured sections. The marlstones are typically tan or light beige in colour, soft and friable, and poorly, but variably, cemented. They form horizons of variable thickness, are ubiquitously calcareous, although the carbonate content is variable as is the grain size, which is commonly clay, but can range to silt to even fine-grained sand. For this reason, particularly silty or sandy marlstones have been identified as such in the stratigraphic logs illustrated in Figs 2-5. Most marlstones contain irregularly dispersed bioclastic debris, coarse-grained sand grains, and granules and small pebbles of quartz, chert and, particularly, siltstone and volcanic material. Of particular interest is the occurrence in Section 2 at 78 cm below the top of the lowermost 12 m thick marlstone (Fig. 4) of two large siltstone clasts, the larger of which is 54 cm on the long axis, completely enveloped by typical marlstones (Pl. 3, Fig. 5).

Internally the marlstones preserve little in the way of primary fabrics. They do preserve horizontal- and parallel-laminations, particularly where they are obviously more cemented, and very thin non-graded layers (<2-3 mm thick), but such occurrences are uncommon (Pl. 3, Fig. 2). In vertical polished slabs diffuse horizontal laminations can also uncommonly be seen, but are by no means an integral component of the overall preserved fabric. We have also observed a single omission surface, two poorly preserved examples of current ripple cross-lamination and rare examples of small-scale erosional scours (Pl. 3, Fig. 3). Internal fabrics are essentially secondary, a result of production by intense bioturbation mainly by presumed crustaceans and annelids (see below). Where weathering permits, such bioturbation can be easily discerned megascopically and has imparted an extremely irregular mottled texture to the marlstones that consequently exhibit a heterogeneous admixture of irregularly distributed material of variable grain size and composition. Vertically polished slabs of apparently homogeneous marlstones also exhibit complex bioturbation fabrics. Ichnofabric indices (*sensu* Droser & Bottjer, 1986) are typically 4 or 5, so that discrete ichnotaxa are uncommonly preserved.

Interpretation — The general absence of primary fabrics precludes unequivocal interpretation of the marlstone lithofacies. Although the rare presence of laminae implies the existence of tractional bottom currents, the nature of these remains enigmatic. Incorporation within the marlstones of variable, but generally large, proportions of terrigenous and bioclastic material together with sporadically distributed shells perhaps suggests deposition primarily from low density turbidity currents or possibly even bottom water nepheloid layers. The source of terrigenous sediment could have been shelf material re-suspended by waves, aeolian input or river discharge (Dimberline *et al.*, 1990). The presence of non-graded laminae and thin layers (mainly siltstone and fine-grained calcareous sandstone) possibly suggests reworking of the material by normal bottom current activity that perhaps could also have been responsible for the production of the small scours. The marlstones also contain much fine-grained carbonate material and abundant pelagic fossils, particularly foraminifera. Thus, like earlier suggestions (for example, Steineck, 1974), we interpret the marlstone lithofacies to have formed as a result of pelagic and hemipelagic deposition. The absence of any evidence of wave activity suggests deposition in relatively deep water below storm wave base. Extensive bioturbation suggests generally slow rates of deposition, but also indicates that bottom conditions were aerobic.

The aforementioned boulders within the marlstones are also of interest with respect to the depositional environment. The origin of similar isolated clasts has recently been discussed by Bennett *et al.* (1996), who recognised four main processes of transport and formation: biological rafting, ice rafting, projectiles, and floatation and gravitational processes. Given their size and composition, and the latitudinal position during emplacement, the former three can easily be dismissed. Instead, we consider gravitational processes to have been responsible for their emplacement and interpret the isolated boulders to have been deposited in one of two ways. First, they possibly represent remnants of a relatively dilute debris flow whose strength was insufficient to raft clasts along, with the result that the boulders sank to the base of the flow and settled on the sea floor while the main body of the flow moved on downslope (compare with Pickering, 1984; Wignall & Pickering, 1993, Pickerill *et al.*, 1995). Second, and perhaps more appealing, they could be interpreted as outrunner boulders that became detached from the terminus of a mass flow deposited upslope and continued to roll or slide downslope before final deposition. Similar outrunner blocks have been documented by Prior *et al.* (1982) from a recent submarine landslide off the coast of British Columbia. In either case, a relatively deep water environment and the presence of a slope must be inferred. We prefer the latter interpretation because the boulders occur in part of a thick marlstone sequence (Pl. 3, Fig. 5) that is devoid of evidence of coarse-grained sediment gravity flow deposits.

Micritic Limestone Lithofacies

Description — Micritic limestones constitute approximately only 2% of the overall thickness of the six measured sections and occur mainly, though not exclusively, in Section 2 (Fig. 4). There, as elsewhere in the sequence, they assume two contrasting modes of occurrence. They may form laterally continuous layers up to 15 cm in thickness, typically 5-10 cm, or, alternately, nodular horizons paralleling stratification, individual nodules being more or less of the same vertical scale in thickness (Pl. 2, Figs 2, 4; Pl. 3, Figs 1, 4). Continuous layers typically occur as discrete units within the marlstones; more rarely, they occur as couplets forming the basal limestone divisions and are erosionally overlain by thin layers of the conglomerate/sandstone lithofacies within the marlstones (Pl. 2, Fig. 2). Nodular horizons consist of discrete or locally laterally-amalgamated, hard marlstones with a micrite cement. Individual nodules are elongated parallel to bedding and have a thickness range of 2-10 cm. They have little internal structure except, in some cases, where a central concentration of large macrofossils (usually bivalves) is present. These shell concentrations are parallel to bedding. Locally, some nodules have amalgamated to produce semi-continuous bands with variations in vertical thickness reflecting the originally discrete nodules.

Interpretation — Because of their sharp boundaries, the continuous layers are interpreted as selectively cemented, primary depositional sedimentary units. These units were presumably associated with higher primary carbonate contents which acted as a source for the cement. The nodules are interpreted to be of diagenetic origin, since they occur as cements around a primary shell concentration, at least in those layers where such a primary concentration is recognised. Early development of the micrites is indicated by the amalgamated couplets which have a basal micrite overlain erosively by a conglomerate/sandstone unit. This possibly suggests that erosion proceeded down to the level at which the marlstone had been cemented and, therefore, that the cementation preceded the erosive event. Alternatively, the conglomerate/sandstone layers could possibly have provided a suitable conduit for carbonate-bearing fluids. This lithofacies, although distinctive in the field, is therefore interpreted as a diagenetic modification of the marlstone lithofacies and possibly reflects initially higher carbonate contents.

ICHNOLOGY

As previously noted, the marlstone lithofacies is extensively bioturbated, typically exhibiting ichnofabric indices of 4 or 5. The resultant fabrics are, as a consequence, extremely variable and discrete ichnotaxa are those superimposed on earlier formed, diffuse and irregularly developed bioturbation structures (Pl. 4). The detailed systematics of these discrete ichnotaxa have recently been documented by Pickerill *et al.* (1996), who figured and described: *Beaconites coronus* (Frey, Pemberton & Fagerstrom, 1984), *Chondrites* isp., *Circulichnis*? *montanus* Vyalov, 1971, *Ophiomorpha*? isp., *Palaeophycus tubularis* Hall, 1847, *Palaeophycus*? *heberti* (de Saporta, 1872), *Palaeophycus*? isp., *Phycosiphon incertum* von Fischer-Ooster, 1858, *Planolites* isp., *Skolithos* isp., *Taenidium cameronensis*? (Brady, 1947), *Teichichnus rectus* Seilacher, 1955, *Teredolites longissimus* Kelly & Bromley, 1984, and *Thalassinoides*? isp. Most of these ichnotaxa reflect likely production by either crustaceans (for example, *Ophiomorpha*?, *Thalassinoides*?) or, more typically, annelids (for example, *Palaeophycus* ispp., *Phycosiphon incertum*, *Planolites*, *Chondrites*) produced as a result of deposit-feeding activities. Perhaps more importantly, collectively they are indicative of more or less stable (equilibrium or K-selected) ecological systems in hydrodynamically low-energy environments (see Pickerill *et al.*, 1996 for discussion). Comparable assemblages are typical of relatively deep-water settings, both modern (see Shaoping & Werner, 1994, and references therein) and ancient (see Bromley, 1996, and references therein). Given our sedimentological conclusions, there is no reason to doubt a similar palaeoenvironmental scenario for the Bowden Formation.

DISCUSSION AND CONCLUSIONS

Historically, there has been considerable debate and controversy with respect to the depositional environment of the Bowden Formation (Tab. 2). Most previous studies have based environmental interpretations on the palaeoautecology of its contained faunas, particularly those in the Bowden shell bed, with little or no consideration of sedimentological or ichnological details. Vaughan (1919), assessing its coral faunas, concluded that water depth was less than 10 m and Woodring (1928), utilising its rich molluscan fauna, concluded that neritic conditions up to about 50 m prevailed. Palmer (1945), based on considerations of the benthic foraminiferal assemblages, speculated that a probable depth habitat of 30 m or slightly more was acceptable. Based on bryozoan faunas, Lagaaij (*in* Rácz, 1971), concluded that a water depth between 12 and 18 m was most likely, and Woodring (1965), noting that the bulk faunas included taxa characteristic of a wide spectrum of non-marine, brackish water and inner and outer shelf habitats, suggested a water depth of over 200 m, possibly up to 500 m.

AUTHOR	PALAEOENVIRONMENT
Vaughan, 1919	< 10 m
Woodring, 1928	< 50 m
Palmer, 1945	~ 30 m
Woodring, 1965	> 200 m
Lagaaij (*in* Rácz, 1971)	12-18 m
Brouwer (*in* Rácz, 1971)	6-21 m
Robinson, 1969a	> 100 m
Goodfriend, 1993	shallow water
Katz and Miller, 1993	upper bathyal (> 200 m)
Robinson, 1994	outer sublittoral (~ 100 m) or deeper

Table 2. Summary of previous palaeoenvironmental interpretations of the Bowden Formation of southeast Jamaica.

Brouwer (*in* Rácz, 1971) concluded that the probable water depth was restricted between about 6 and 21 m. Robinson (1969a, 1994), based on planktic foraminiferal assemblages, interpreted the environment as relatively deep water, in excess of 100 m, a conclusion reiterated by Rácz (1971) and Katz & Miller (1993), who suggested upper bathyal (>200 m) conditions. However, Goodfriend (1993) has recently suggested that the Bowden shell bed may have been deposited in shallow water adjacent to an eroding shoreline deposit containing molluscs, the conglomeratic layers of the Bowden shell bed representing lag deposits following removal of finer-grained material by wave activity.

In view of our conclusions that the coarse-grained units of the Bowden shell bed and associated sandstone layers are products of sediment gravity flows (see also Woodring, 1965; Robinson, 1969a), more particularly turbidity currents, any interpretations of their depositional environment adopting palaeoautecological criteria must be regarded with scepticism. All faunas in these units are clearly allochthonous or, at best, parautochthonous and can in no sense be adopted to interpret the depositional environment. As noted by Aubry (1993), even many of the calcareous nannofossils (planktic and benthic foraminifera and ostracods) in the Bowden shell bed are actually reworked older taxa. Nevertheless, we consider that perhaps the most promising, but to date only broadly broached palaeoecological avenue of research with respect to absolute water depths (Robinson, 1969a; Katz & Miller, 1993), would be a detailed analysis of foraminiferal assemblages in the formation.

Our interpretation of the conglomerate/sandstone lithofacies as turbidites and the volumetrically dominant marlstone and associated micritic limestone lithofacies as products of pelagic and hemipelagic deposition, is indicative of a generally deep-water environment. In contrast to the more recent suggestion by Goodfriend (1993) we find no evidence of wave activity in the entire formation and, hence, deposition was most likely below storm wave base. Storm (and fairweather) wave base depends on a complex interplay of shelf break and width, that may vary considerably from 18-95 m and from a few to >1,000 m respectively (Bouma *et al.*, 1982). Also important is shelf morphology, meteorological regime, magnitude of fluid energy, latitude, etc., and thus wave base is difficult to realistically assess. However, as reviewed in Pickerill & Brenchley (1991), an arbitrary water depth of ± 100 m for mean severe storm wave base is not unreasonable (see also Clifton, 1988; Brett *et al.*, 1993). Indirectly, therefore, the absence of wave structures is in accord with the suggested water depth of >100 m by Robinson (1969a, 1994).

Although both sedimentological and ichnological data from the Bowden Formation are suggestive of a deep-water palaeoenvironment, we reiterate that absolute water depths are impossible to realistically assess using such information. Incorporation, particularly in the Bowden shell bed, of well-rounded, compositionally diverse and variably-sized lithic clasts and terrestrial molluscs and other benthic faunas of an extremely shallow-water marine affinity suggests a coastal or shallow shelf source for the sediment gravity flows. The lithic clasts had undoubtedly been subject to considerable transport and/or reworking prior to their incorporation, and presumably accumulated in a beach (Robinson, 1969a) or perhaps a shoreface environment (see Bourgeois & Leithold, 1984). In contrast, the terrestrial molluscs exhibit no evidence of significant reworking as they are not abraded (Goodfriend, 1993). This suggests they were introduced into the marine realm, perhaps by seasonal or other river floods, and were either rapidly buried prior to re-exhumation and/or quickly resedimented as integral components of sediment gravity flows. Either alternative is also suggested by the absence of borings in these terrestrial molluscs, that is in direct contrast to numerous other shallow marine mollusc species now found in the Bowden Formation (Pickerill & Donovan, 1998).

Given an obviously extremely shallow marine source for the sediment gravity flows, particularly those of the Bowden shell bed and associated siliciclastic layers within Section 1, we envisage a palaeoenvironmental setting not too dissimilar to the present-day setting of central southern coastal Jamaica. There, the present-day shelf is narrow and punctuated by the development of large fan-delta and submarine fan systems, and associated proximal-to-shore deep water basins; the shelf break is at 40 m below sea level and the shelf edge is incised by shallow gullies throughout its length (Burke, 1967; Etheridge & Wescott, 1984). Immediately to the south of Kingston (Fig. 1), for example, the Yallahs Basin, seaward of the Hope-Liguanea fan-delta, attains a depth of ± 1,200 m in less than approximately 12 km from shoreline (Etheridge & Wescott, 1984, fig. 5) and contains thick sequences (500 m) of re-sedimented slide and turbidite deposits (Burke, 1967). A broadly analogous environment can easily be envisaged for the Bowden Formation, particularly in view of the inclusion of the aforementioned beach/shoreface lithic clasts and terrestrial molluscs in strata of the Bowden shell bed that would, by necessity, require the former presence of a relatively narrow unstable shelf and perhaps even associated fan-delta systems that were susceptible to periodic, but repeated, failure.

Finally, as previously noted, the occurrence of the conglomerate/sandstone lithofacies essentially in the lowermost horizons of the Bowden Formation, particularly at Section 1 in association with the Bowden shell bed (Figs 2, 3), suggests a relatively 'proximal' palaeoenvironmental regime. Overlying strata in Sections 2-6 (Figs 4, 5) are overwhelmingly dominated by marlstone and associated micritic limestone lithofacies of a more 'distal' aspect characterised by generally slower rates of deposition enabling the production of complex bioturbational fabrics. In Sections 2-6 turbiditic sandstone layers, though present, are only rarely developed. This suggests that the Bowden Formation was deposited in deepening conditions or, alternatively, that the sediment source shifted. Support for the former is provided by Katz & Miller (1993) in their study of benthic foraminiferal biofacies in the Bowden Formation, albeit from supposed Bowden Formation strata on the north coast of the island, but who suggested a deepening from the upper to lower part of the bathyal zone through the formation.

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PLATE 1

PLATE 1

Stratotype of the Bowden Formation, southeast Jamaica, on the eastern side of Port Morant Harbour between the Bowden Wharf (BW) and Pera Point (PP), illustrating locations of Sections 3-6 as described herein.

PLATE 2

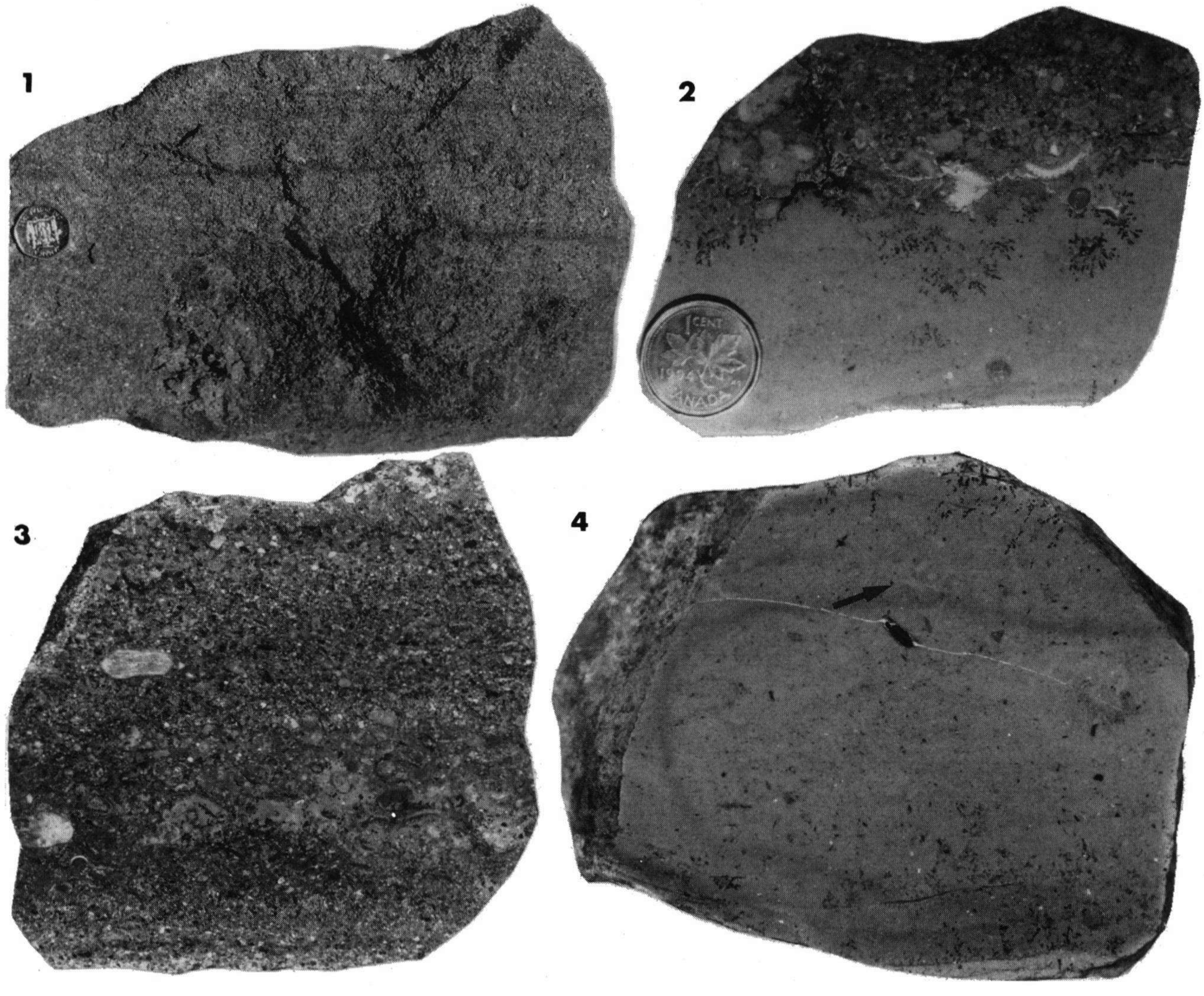


PLATE 2

Fig. 1. Medium-to coarse-grained sandstone from Section 2 illustrating a Bouma Ta-b sequence of internal structures. Coin diameter is 1.7 cm.

Fig. 2. A micritic limestone/sandstone couplet from Section 2. Note the internally structureless nature of the micritic limestone and the erosional base of the sandstone. Coin diameter is 1.9 cm.

Fig. 3. Polished vertical slab of an apparently massive pebbly sandstone from Section 1, x 1.

Fig. 4. Polished vertical slab of part of a laterally continuous micritic limestone layer from Section 2. Note the absence of internal structure apart from poorly discernible bioturbation structures, such as that arrowed, x 1.3.

PLATE 3

Fig. 1. Typical outcrop of massive marlstone lithofacies from the stratotype of the Bowden Formation. The arrow indicates a thin layer of micritic limestone. Notebook is 19 cm in length.

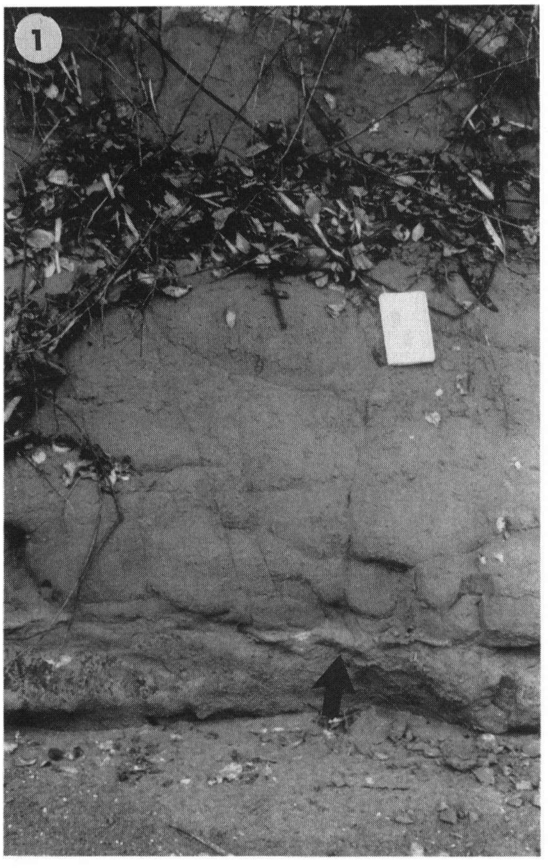
Fig. 2. Rare example of laminae and thin layers preserved in the marlstone lithofacies from the stratotype of the Bowden Formation. Lighter (at left) is 8 cm in length.

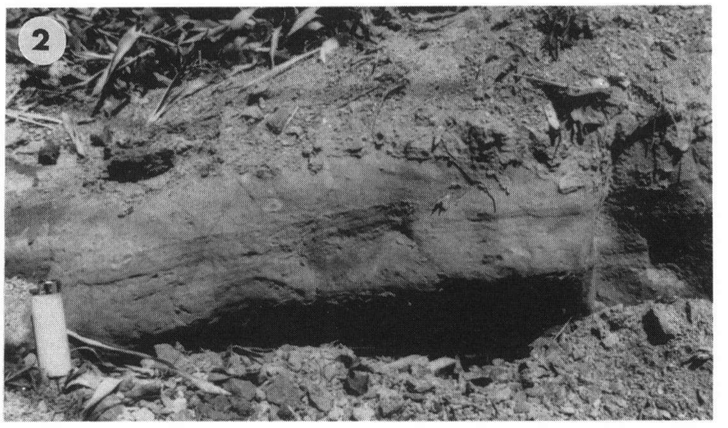
Fig. 3. Photomicrograph of silty marlstone from Section 4 illustrating small-scale erosional scour infilled by form-concordant laminated marlstone. x 6.4.

Fig. 4. Massive marlstone lithofacies with nodular micritic horizons from Section 2. Hammer is 35 cm in length.

Fig. 5. Large metasedimentary siltstone clasts enveloped in typical marlstone lithofacies from Section 2. Hammer is 35cm in length.

PLATE 3





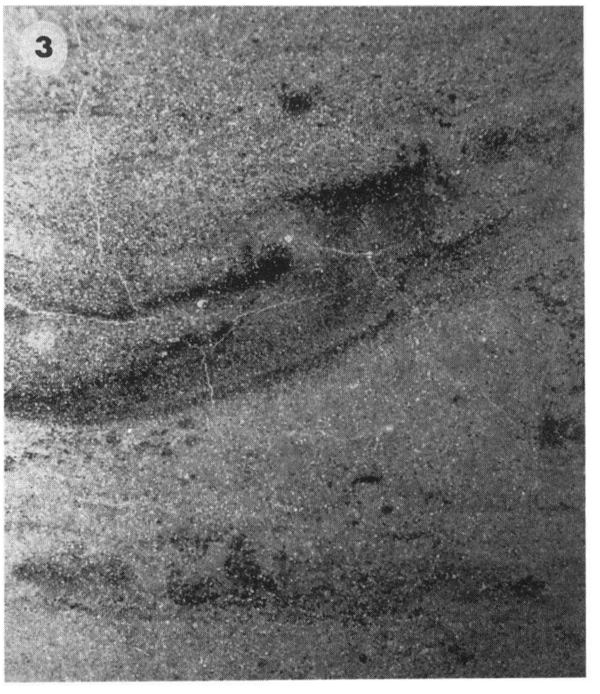


PLATE 4

Fig. 1. Outcrop photograph of marlstone in vertical section exhibiting typical bioturbated fabric (for example, immediately above coin that is 2.4 cm in diameter).

Fig. 2. Vertical polished slab of marlstone exhibiting *Teichichnus rectus* Seilacher, 1955 (upper arrow), *Phycosiphon incertum* von Fischer-Ooster, 1858 (recurved arrow) and *Planolites* isp. (lower arrow). Scale bar is 1 cm.

Fig. 3. Outcrop photograph of marlstone in vertical section exhibiting *Phycosiphon incertum* and *Planolites* isp. (above coin) and a partial *Chondrites* isp. (to left of coin). Coin diameter is 2.4 cm.

Fig. 4. *Ophiomorpha*? isp. in outcrop photograph of marlstone in vertical section. Scale bar is 1 cm.

Fig. 5. *Thalassinoides*? isp. segment reburrowed by a dense array of *Planolites* isp. and *Phycosiphon incertum* in outcrop photograph of marlstone in vertical section. Scale bar is 1 cm.

Fig. 6. *Chondrites* isp. in outcrop photograph of marlstone in vertical section. Arrow indicates initial sub-vertical mastershaft. Scale bar is 1 cm.

PLATE 4