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THE ARCHITECTURE OF AN ALLUVIAL SUITE: ROCKS BETWEEN THE TOWNSEND TUFF AND PICKARD BAY TUFF BEDS (EARLY DEVONIAN), SOUTHWEST WALES

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The Townsend Tuff Bed and the Pickard Bay Tuff Bed are distinctive ash-fall tuffs traceable within a red-bed sequence over an area measuring about 35 km from west to east by 12 km from south to north. The succession between these markers is a mere 15–30 m thick, but contains six other tuffs which, though not themselves distinctive, can also be traced over the area by virtue of their position relative to the two main falls.

The mudstone-dominated succession between the two main markers contains eight calcretes (pedogenic limestones), most of which extend over practically the whole of the area, and 16 generally local upward-fining or 'coarse' sequences composed of sandstones overlying an erosion surface and passing up into mudstones. The mudstones are massive and seldom laminated, apparently having been organically destratified. The coarser-grained upward-fining sequences involve cross-bedded, parallel-laminated and cross-laminated sandstones, whereas the finer-grained examples normally consist of interbedded mudstones and sharp-based cross-laminated sandstones. Intraformational conglomerates and stringers of mudstone clasts not infrequently accompany the coarser sandstones. Evidence of subaerial exposure is common towards the tops of both the coarser- and finer-grained sorts of upward-fining sequence. The careful tracing of the marker tuffs shows the upward-fining sequences to be of two main kinds. Examples of the least common type occur within localized and relatively deep depressions, probably incised valleys, which they fill to a height less than the depth of the depression. The more frequent variety is also localized but not obviously incised, having apparently grown up in harmony with the accumulation of mud in the area as a whole.

The succession between the Townsend Tuff and Pickard Bay Tuff Beds lies in the transition between a clearly marine-influenced facies below and a clearly fluviatile facies above. It appears to record an extensive but comparatively featureless marginal mudflat influenced by both rivers and the sea. The development of calcretes (fossil soils) within the muddy sediments, and the shifting and valley-building activities of mixed tidal and river channels, could have been under the control of relative fluctuations of sea level perhaps on as short a time scale as of the order of 10^4 years. The channellized currents seem typically to have been vigorous and of low to moderate sinuosity.

1. Introduction

The last 15 years have seen an explosion of interest in the sedimentology of alluvial formations, to the extent that today upward of 200 descriptions exist in the literature. However, because heavy reliance has been placed on one-dimensional methods of analysis (section or borehole logging), without the control provided by closely spaced and rigorous time markers of regional significance, we have so far gained little knowledge of the three-dimensional facies geometry of alluvial rocks, or much understanding of how intrinsic and extrinsic environmental factors shaped that distribution. The architecture of alluvial suites, an issue of practical as well as academic importance, therefore remains a little explored field.

We here describe the architecture of one alluvial suite, a study of which is possible because of the happy accident that today in southwest Wales there exist early Devonian (Lower Old Red Sandstone) rocks with numerous marker ash-fall tuffs, contained in tight and repetitious Variscan folds dissected by a long and intricate marine coastline. This widely exposed suite is no more than 15–30 m thick, yet is divisible vertically by air-fall tuffs into no less than seven intervals. Its accumulation necessitated perhaps less than 10^5 years, suggesting that the suite can be analysed on much the same time scale as such plausible controls as river avulsion, short-term climatic fluctuations, and base-level changes. Most previous work on alluvial architecture has been done at substantially larger thickness and time scales, at least so far as studies of rocks are concerned.

Little detail is available from the stratigraphic record. Several kinds of sand body occur among the Mississippian–Pennsylvanian paralic rocks of the North American mid-continent and the Appalachians, where coals and thin marine limestones provide markers, and outcrop evidence can be combined with densely arrayed subsurface data (Pepper *et al.* 1954; Potter & Glass 1958; Potter 1962, 1963; Potter & Simon 1961; Donaldson 1974). Many of the fluviatile sandstone bodies appear to be valley fills, related to either glacially or tectonically controlled sealevel changes, whereas others wear the aspect of channel-belt sands embedded in overbank or deltaic deposits. Shawe *et al.* (1968) described the two-dimensional geometry and arrangement of floodplain channel-belt sandstones within the Salt Wash and Brushy Canyon Members of the Morrison Formation (Jurassic) of Colorado, using measured profiles closely correlated over the little-obscured walls of canyons and bluffs. Campbell (1976) similarly reconstructed a lengthy two-dimensional section through the Westwater Canyon Member in the same formation. This lithostratigraphic unit consists of numerous intersecting sandstone bodies embedded in finer-grained lithologies. The larger bodies, of the order of 10 km wide, are sufficiently thick and complex internally as to represent either shallow valley fills or large channel belts that remained more or less in one place over a substantial period. The smaller ones have features consistent with a simple channel-belt origin. On a much smaller scale is the work of Nami & Leeder (1978), who recognized two main kinds of fluviatile sandstone body in the Scalby Formation (Jurassic) exposed coastally in northeast England. One is sheet-like, consisting of interlocking sandstone lenses attributable to unstable low-sinuosity streams, whereas the other is narrow and ribbon-like, formed in many cases in association with high-sinuosity channels subject to frequent avulsion.

The field evidence thus suggests that both avulsion, an intrinsic control, and valley cutting and filling, largely governed by extrinsic factors, occurred during the construction of alluvial suites in the past. The relative importance of intrinsic and extrinsic controls, and the scales on which they operated, however, are far from clear.

The limitations of field evidence have prompted attempts to model alluvial architecture. Allen (1965 *a*) developed several generalized schemes, one of which was elaborated (Allen 1974) to show the semiquantitative influence of intrinsic and extrinsic controls on the structure of floodplain and coastal-plain alluvium. The architecture of this type of alluvium was later simulated manually (Leeder 1977; Allen 1978) and, in the most elaborate and successful model so far described, with the aid of a computer (Bridge & Leeder 1979). These models are predicated upon river avulsion as the overriding (intrinsic) control, subsidence being presumed so that a deposit can be accumulated, and include simple extrinsic factors only as secondary or optional determinants. Several quantitative attributes of alluvial suites are amenable to a geometrical approach (Allen 1979), corresponding to the analysis of particle packing. These models yield many exciting insights, for example, into the controls on sand-body connectedness, but continue to demand validation against field evidence, such as we now describe.

2. Geological setting

In association with Ordovician, Silurian and Carboniferous rocks, the Lower Old Red Sandstone in southwest Wales is best exposed to the north and south of Milford Haven (figure 1). Here it is repeated by a series of folds of WNW–ESE strike affected by strike-slip (often conjugate), normal and thrust faults (Hancock 1973). The main anticlinal structures, their cores dominated by Lower Old Red Sandstone, are the Marloes, Winsle and Burton Anticlines north of Milford Haven, and the Castlemartin Corse and Freshwater East Anticlines to the south. The chief faults bounding structural blocks are the Benton and Musselwick Faults north of Milford Haven, the Ritec Fault, thought to extend along Milford Haven itself before crossing the Dale peninsula, and the Flimston Bay Fault in the south. The Variscan structural style changes markedly across the Ritec Fault (Hancock 1973; Hancock *et al.* 1981). The northern anticlines carry large numbers of often steeply plunging parasitic folds, and there is much minor disturbance in the form of low-displacement strike-slip faults and extension or contraction faults. Although of larger amplitude, the southern anticlines are simpler, with very few parasitic folds, and only small-scale faults. The rocks both north and south of the Ritec Fault show a cleavage increasing westwards in strength. In view of the structural complexity of the area, our palaeocurrent readings were corrected for fold plunge as well as for tilt.

Table 1 summarizes the succession of the Lower Old Red Sandstone. North of the Ritec Fault the beds total several kilometres in thickness and range up from late Silurian into the mid or late Lower Devonian (Allen & Williams 1978; Allen *et al.* 1981). The section is most complete in the Marloes Anticline, apparently the site of a broad shallow valley (possibly fault-controlled) in which the earliest Lower Old Red Sandstone accumulated. Here the mudstone-dominated Red Cliff Formation, derived from the south, is overlain by the pink litharenites and interbedded subordinate mudstones of the Albion Sands Formation, transported from a westerly source. In contrast to the remainder of southwest Wales, there is no conglomeratic facies at the base of the red-bed sequence in the Marloes area. Walmsley & Bassett (1976) and Hurst *et al.* (1978) therefore treated the Red Cliff Formation as transitional from presumed Wenlock or Ludlow rocks of marine-deltaic aspect below, and itself as either Wenlock or Ludlow in age. Allen & Williams (1978, 1979) discounted this view, since they found a sharp and substantial facies change marking a depositional break at the base of their Red Cliff Formation, which they consequently assigned to the Post-Ludlow, in conformity with the palaeontological evidence from nearby successions. Interfingering with the Albion Sands Formation are the thick conglomerates and mudstones of the Lindsway Bay Formation, of possible easterly or southerly provenance. A thin representative of this lithostratigraphic unit, lying sharply on shallow-marine Wenlock rocks, commences the red-bed sequence of the

Winsle Anticline (Allen *et al.* 1976), and thus points to northward thinning and overlap within the Lower Old Red Sandstone and to overstep at its base. Above the Albion Sands and Lindsway Bay Formations come the thick mudstone-dominated Sandy Haven Formation, derived largely from the north but with some easterly contributions, and the much sandier Gelliswick Bay Formation, also of northerly provenance. A passage leads up into the sandstone-dominated

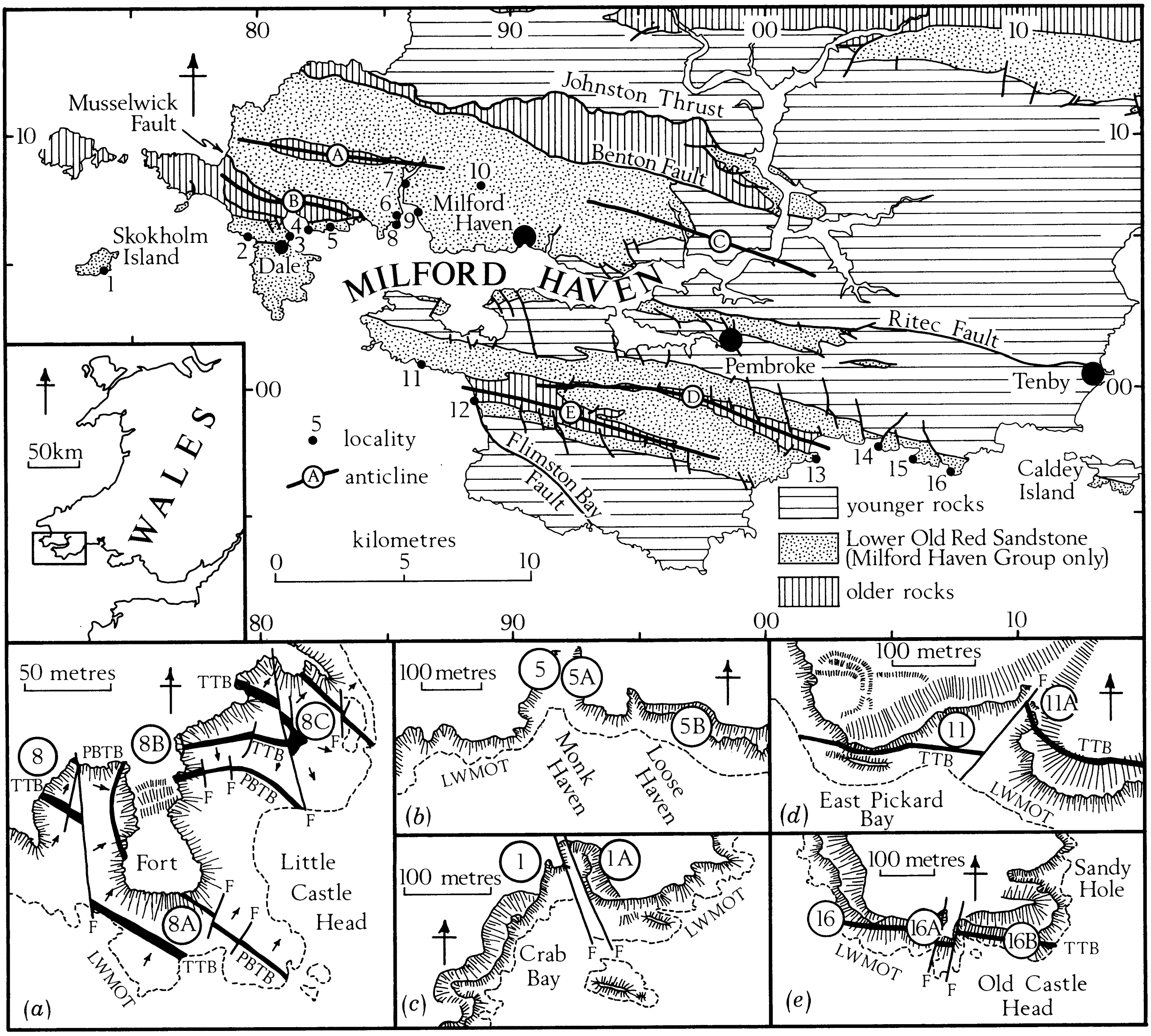


FIGURE 1. Geological sketch map of southwest Wales showing the outcrop of the Milford Haven Group (beneath Cosheston Group) within the Lower Old Red Sandstone, and the localities at which the alluvial suite commenced by the Townsend Tuff Bed is exposed (see also tables 1 and 2). Key to major anticlines: A, Winsle Anticline; B, Marloes Anticline; C, Burton Anticline; D, Freshwater East Anticline; E, Castlemartin Corse Anticline. Localities represented by more than one sedimentological profile are shown in detail, as follows: (*a*) Little Castle Head (locality 8), (*b*) Monk Haven (locality 5), (*c*) Crab Bay, Skokholm Island (locality 1), (*d*) East Pickard Bay (locality 11), and (*e*) Old Castle Head (locality 16). In (*a*–*e*): TTB, Townsend Tuff Bed; PBTB, Pickard Bay Tuff Bed; LWMOT, low water mark of ordinary tides; F, fault.

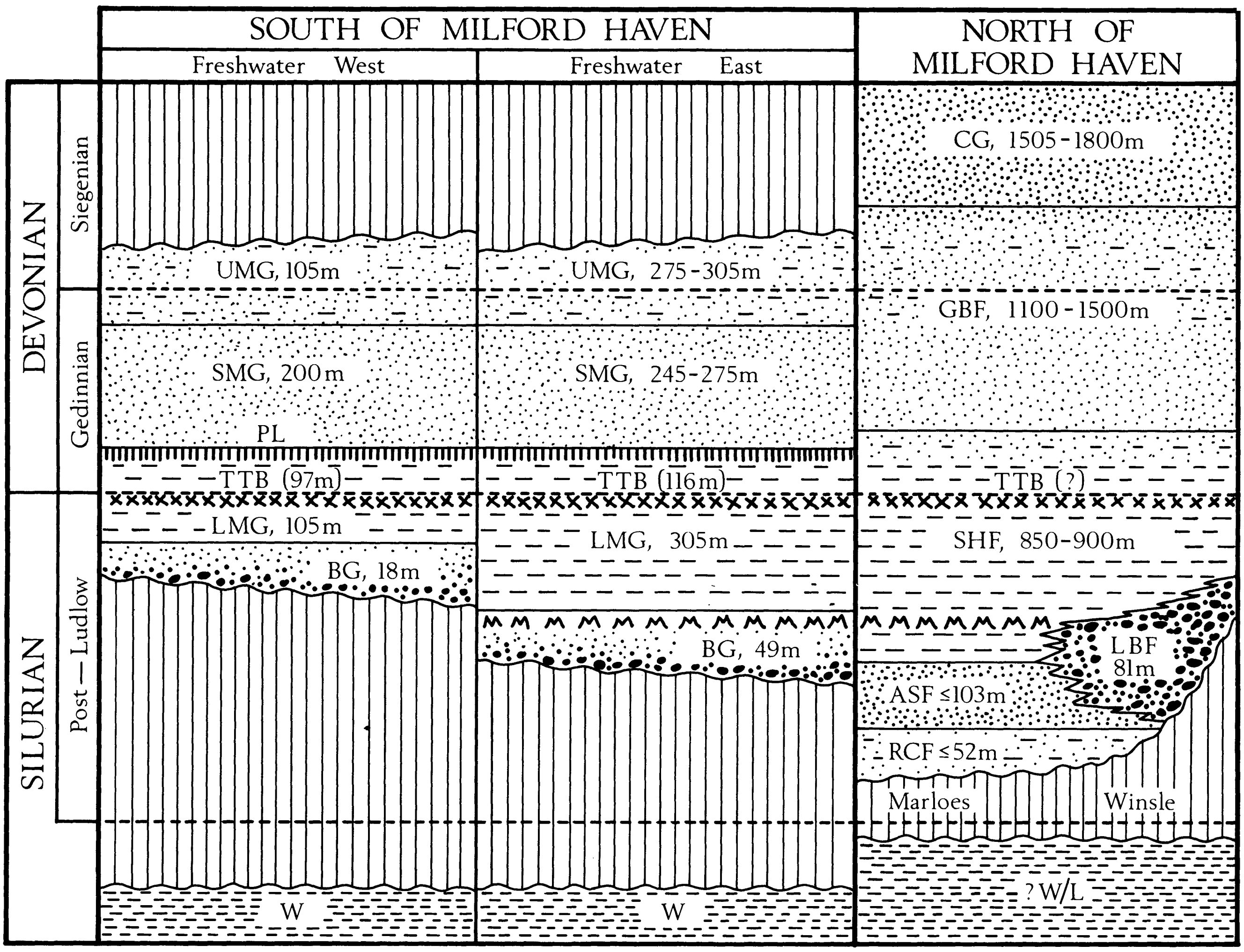
but largely green Cosheston Group, yielding a mid to late Siegenian microflora and possibly ranging into the Emsian (Allen *et al.* 1981).

Near the top of the Sandy Haven Formation, and approximately 930 m above the base of the Lower Old Red Sandstone, lies a thin but unmistakable complex of three ash-fall tuffs called the Townsend Tuff Bed (Allen & Williams 1978, 1981). It is widely exposed both to the north and to the south of the Ritec Fault, and is the pre-eminent regional marker.

The position of this marker shows without doubt that the Lower Old Red Sandstone is also sharply reduced by thinning and overlap southward from the Marloes area, the stratigraphical relations mirroring those from Marloes to Winsle. At Freshwater East (table 1) the

TABLE 1. DIAGRAMMATIC TABLE OF STRATA IN THE LOWER OLD RED SANDSTONE OF SOUTHWEST WALES

(The Milford Haven Group consists of all the rocks of Post-Ludlow, Gedinnian and earliest Siegenian age below the base of the Cosheston Group. ASF, Albion Sands Formation; BG, Basement Group; CG, Cosheston Group; GBF, Gelliswick Bay Formation; LBF, Lindsway Bay Formation; LMG, Lower Marl Group; PL, '*Psammosteus*' Limestones; RCF, Red Cliff Formation; SHF, Sandy Haven Formation; SMG, Sandstone-and-Marl Group; TTB, Townsend Tuff Bed (bracketed figure is stratigraphical distance below the '*Psammosteus*' Limestones, where this is recognizable); UMG, Upper Marl Group; W, Wenlock rocks; W/L, Wenlock or Ludlow rocks. The line of M in the succession north of Milford Haven denotes the lingulid facies of the upper Basement Group and lower Sandy Haven Formation. After Dixon (1921) and Allen & Williams (1978).)



conglomerates graduating up into mudstones and sandstones of Dixon's (1921) Basement Group lie sharply on shallow-marine Wenlock rocks, at no more than approximately 350 m below the Townsend Tuff Bed. Within the Basement Group, however, there is the same lingulid-rich facies of interbedded mainly green mudstones and sandstones (Dixon 1921) that occurs toward the base of the Sandy Haven Formation (Allen & Williams 1978). The reduction is even more at Freshwater West (table 1), where the Basement Group lies within about 25 m below the Townsend Tuff Bed, and again on the marine Wenlock, with the lingulid facies now conspicuously absent. The overlying Lower Marl Group (Dixon 1921) resembles in facies but is much thinner than the Sandy Haven Formation. Its few sandstones are generally finer-grained than those in the Sandy Haven Formation, a feature consistent with the northerly provenance of these correlative strata.

The alluvial suite here analysed occurs between the top of the Townsend Tuff Bed and the base of a less distinctive ash-fall tuff complex some 15–30 m above, the Pickard Bay Tuff Bed, named after a locality northwest of Freshwater West (Williams *et al.* 1982). The suite is assigned an earliest Gedinnian age, since a level within the Townsend Tuff Bed best represents the base of the Devonian System in South Wales and the Welsh Borders (Allen & Williams 1981). The facies in which it occurs, however, ranges up from possibly early in the Post-Ludlow.

What is the conjectural time scale of the suite? This we estimate from stratigraphical thicknesses as follows. The Silurian portion of the Lower Old Red Sandstone facies, the Red Cliff, Albion Sands and Lindsway Formations, and the Sandy Haven Formation in large part, is most complete in the Marloes area, where approximately 930 m of these beds can at present be measured beneath the Townsend Tuff Bed. The rocks seem largely if not wholly attributable to the Post-Ludlow stage, assigned by McKerrow *et al.* (1980) a duration of 2.5 million years on the basis of radiometric ages. Hence the beds accumulated at an average rate of 1 m of fully consolidated rock every 2688 years. Since the alluvial suite in the Marloes area to which these data apply has an average present thickness when complete of 24.2 m, the suite could represent the elapse at the most of approximately 65000 years. The accumulation of 1 m every 2688 years corresponds to a deposition rate of 3.72×10^{-4} m per year (consolidated thickness), in good agreement with similarly adjusted rates for modern floodplains (Leeder 1975). We have extended this procedure in §5 to obtain estimates of the duration of the seven intervals into which the alluvial suite can be divided with the aid of the marker tuffs.

3. Localities

The suite appears at 16 localities (figure 1; table 2), at five of which more than one sedimentological profile is measurable (figure 1*a–e*). All of the sites, with the exception of St Botolph's railway cutting (locality 10), are coastal. Plate 1 (Trewent Point) gives a good impression of the nature of these generally continuous coastal exposures, of the succession presented by the alluvial suite (at least in its muddier phases), and of the mode of expression both of the major and minor tuff markers (markers designated A–D visible). Trewent Point is the only locality at which, from a single point on land, the suite, with its critical basal marker, can be inspected in its entirety.

On the whole we experienced little difficulty in establishing in full the succession and sedimentological details of the alluvial suite. The coastal rocks are generally wave-polished in the upper intertidal zone and clean and delicately weathered where exposed supratidally. The marker tuffs characteristically weather back in narrow depressions ranging from shallow grooves to deep clefts or slots. At only a few places are the supratidal cliffs blackened or obscured by wash, and it was seldom necessary to examine the weed-covered rocks of the lower intertidal zone. Faulting and bedding-surface shearing introduce an element of uncertainty about the sequence at comparatively few sites (table 2). At Trewent Point (locality 13), the intermediate portion of the alluvial suite was not directly accessible, the log being completed with the help of photographs and inspection with field glasses.

4. Marker beds

The marker ash-fall tuffs, designated markers A–H inclusive, merit brief description as they afford the key to the recognition of the alluvial suite and to its structure as a whole. Their occurrence and thickness are summarized in table 2, and details of their thickness distribution appear in figures 4, 6*a*, 7*a*, 8*a*, 9*a*, 10*a*, 11*a* and 12. Marker H caps the alluvial suite and marker A immediately underlies it.

The suite is recognized by its association with marker A, the Townsend Tuff Bed of Allen & Williams (1978, 1981), a highly distinctive complex of three closely superimposed falls (figure 4; table 2). The lowest is fall 1 (Fall A of Allen & Williams (1981)), resting sharply on a mudstone surface in places marked by faecal pellets and various trace fossils (plate 2, figure 1), and with a tough, green porcellanitic upper part. Fall 2 (Fall B of Allen & Williams (1981)) begins with crystal tuffs that everywhere smother a densely faeces-strewn surface. Above come interbedded dust tuffs and crystal tuffs (plate 2, figure 2) showing parallel lamination, wave-current and wave-ripple marks, cross-lamination, shallow scours and channels, and soft-sediment deformations. The upper part is a thick, tough, green procellanitic muddy tuff and tuffaceous mudstone. Fall 3 (Fall C of Allen & Williams (1981)) has a distinctive irregular and erosional base (plate 2, figure 3) and likewise is graded from crystal up to dust tuff.

Marker H is otherwise called the Pickard Bay Tuff Bed (Williams *et al.* 1982) after its occurrence at East Pickard Bay (locality 11 in figure 1). This ash-fall tuff is less distinctive and somewhat thinner than the Townsend Tuff Bed beneath the alluvial suite, but is much thicker than the other markers associated with the alluvial suite. Marker H seems to consist of at least two falls (possibly three at East Pickard Bay) and is lithologically similar to the uppermost two falls of the Townsend Tuff Bed below (figure 12). Its base is sharp and at locality 2 and in profiles 8A, 11A and 16A reveals abundant faecal debris. Marker H at localities 7 and 10 is unusual in consisting of dust and crystal tuffs in close association with ashy sandstones and with normal terrigenous sandstones and mudstones. Apparently the ash fell into established channels flushed by aqueous currents, but none strong enough entirely to disperse the volcanic debris.

The minor ash falls (markers B–G inclusive) are typified by dusky-pink to deep-purple dust

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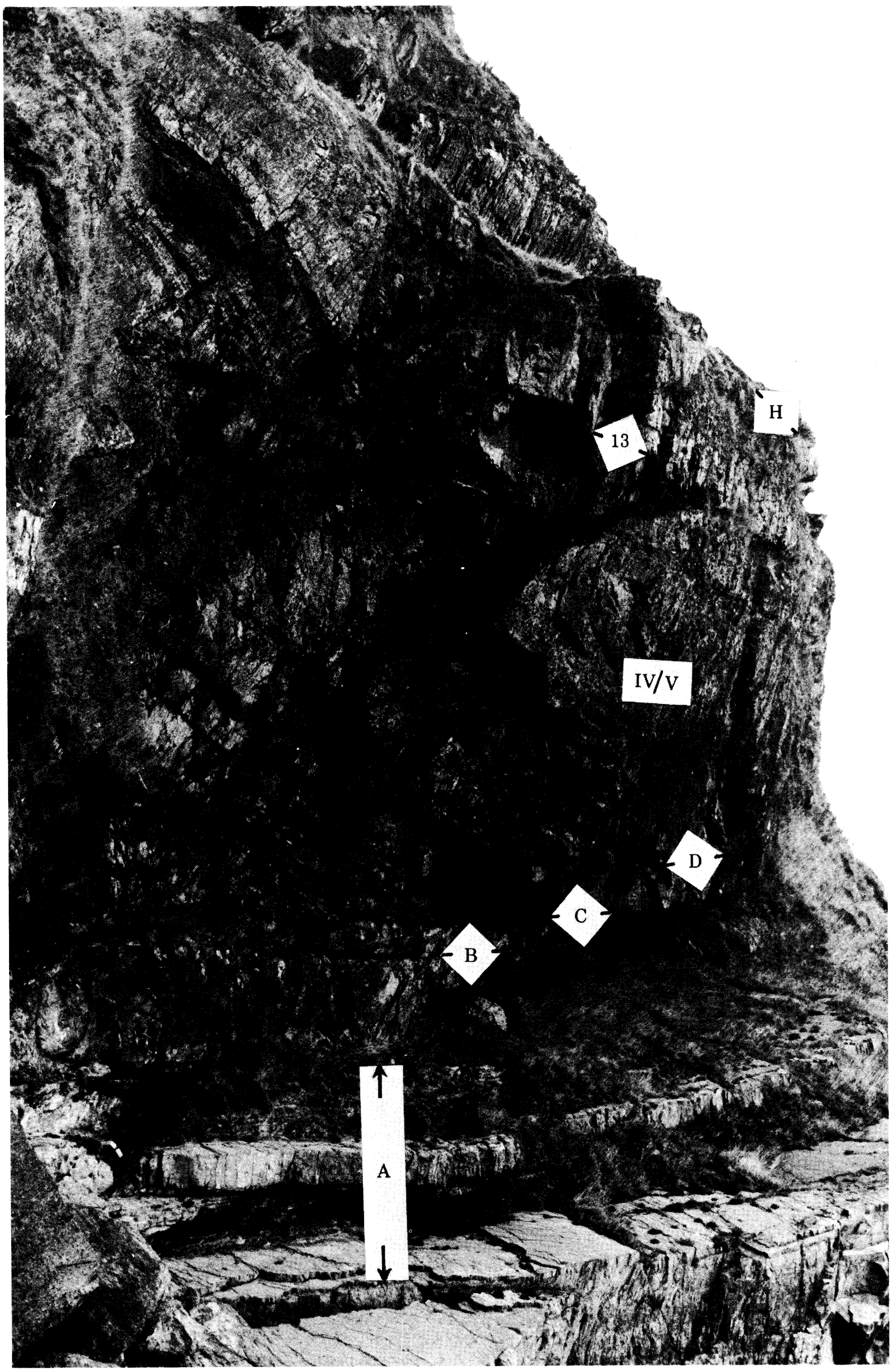
Description of plate 1

The full sequence of the alluvial suite exposed in faulted and steeply dipping rocks on the south face of Trewent Point (locality 13). The sequence in the bottom and right side of the picture is essentially unbroken and continuous, and the photograph has been tilted to give the appearance of flat-lying beds. A, Townsend Tuff Bed (the stout central rib is the porcellanite at the top of fall 2 capped by the parallel-laminated crystal tuffs at the base of fall 3); B, marker B; C, marker C; D, marker D; IV/V, thick mudstones with calcretes IV and V, the lower part showing many pseudoanticlines; 13, base of coarse sequence 13; H, base of the Pickard Bay Tuff Bed (accessible from the cliff top). The person in the bottom left corner is approximately 1.9 m tall.



For description see opposite.

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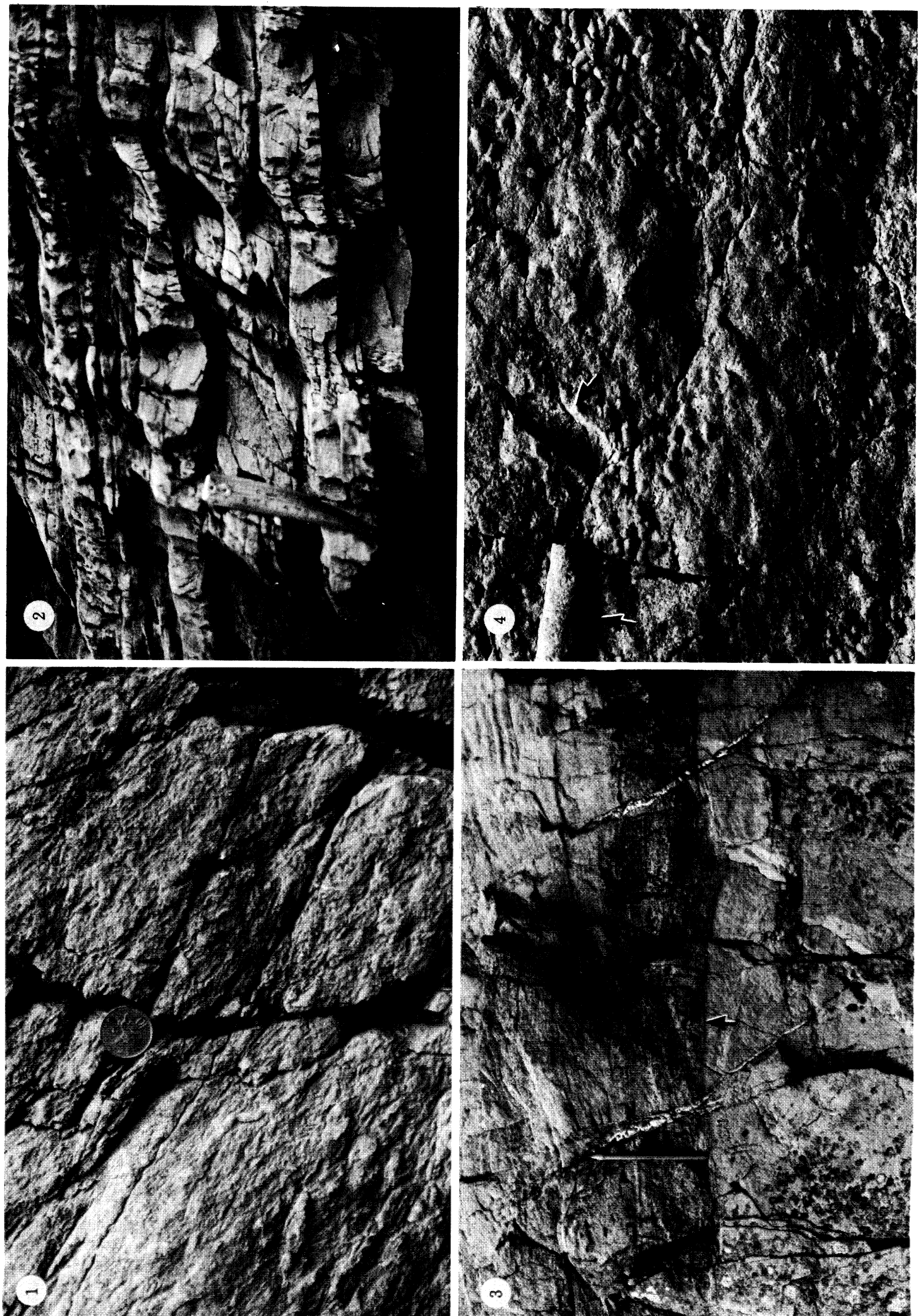


For description see opposite.

Description of plate 2

Sedimentological features of the Townsend Tuff Bed (marker A) and marker C.

Figure 1. Uneven surface underlying fall 1, showing clusters of large faecal pellets and sinuous burrows. Profile 11 A, East Pickard Bay (locality 11). Coin 28 mm across.

Figure 2. Cross-laminated and ripple-marked bands of crystal tuff (weathered slightly back) interbedded with dust tuff, fall 2, profile 11 A, East Pickard Bay (locality 11). Tape measure gives scale.

Figure 3. Erosional contact (arrowed) between parallel-laminated medium-grained crystal tuffs of fall **3** and green porcellanite of fall 2, profile 11 A, East Pickard Bay (locality 11). Pencil gives scale.

Figure 4. Faecal pellets of two sizes (larger arrowed) on the mudstone surface smothered by marker C, profile 8, Little Castle Head (locality 8). Magn. $\times 2.3$.

For description see opposite.

tuffs commonly with green and in places with yellow mottles. They are very variable in thickness (see table 2), as is also true of the Townsend Tuff and Pickard Bay Tuff Beds, partly for sedimentological and partly for structural reasons. Thick developments tend to occupy in places visible hollows (?ponds, channels, moist depressions), the base being smooth and commonly faeces-strewn, as witness marker C in profile 8 (plate 2, figure 4), whereas thin ones normally overlie a sharp but irregular and apparently eroded or even weathered surface. Most of the thinner tuffs show signs of severe organic reworking (plate 3, figure 1). We suspect that, at the more westerly sites in particular, the marker tuffs have been substantially modified in thickness as the result of tectonic flattening associated with the Variscan folding. The tuffs are the least competent beds in the succession and consequently show the most intense cleavage and bedding-surface shear.

5. Introduction to the correlation

To us it seems beyond reasonable doubt that we have correctly identified the same stratigraphical interval (our alluvial suite) at many localities dispersed over southwest Wales. The quality of correlations within the interval, however, depends crucially on our ability correctly to match the subordinate marker ash falls. Here we placed most reliance on similarity of position relative to the bounding Townsend Tuff and Pickard Bay Tuff Beds, but some weight on similarity of lithological sequence, and on the occurrence and character of the stronger calcretes. Similarity of sequence and the character of the calcretes were only exploited locally, however, since the areal lithological pattern is the topic mainly at issue. Table 2 makes it clear that few of the markers can be identified everywhere.

A marker tuff may be lacking (and our sections were measured over generally clean and continuously exposed rocks) for one of four reasons: (i) non-deposition, (ii) deposition with simultaneous current dispersal, (iii) deposition followed by erosion, and (iv) deposition followed by either organic or pedological reworking. These mechanisms have different implications for the problem of correlation.

Non-deposition implies that an ash was accumulated patchily, perhaps due to differences in surface moistness, or to the presence of sheltered hollows, or because a site or group of sites lay outside the bounds of the ash plume. Patchy accumulation as a 'sheet with holes' plausibly explains the local absence of the comparatively thin markers E and F in, respectively, the southeast and northwest parts of the area (figures 9*a*, 10*a*). Their expected positions can none the less be estimated because of a consistent relationship elsewhere between each of them and a more widely developed calcrete.

Description of plate 3

Sedimentological features of the alluvial suite.

Figure 1. Marker F with biogenic mottles of lighter-coloured mudstone, Hook Vale (locality 2). Pencil gives scale.

Figure 2. Cross-bedded and parallel-laminated sandstones, coarse sequence 2, profile 8C, Little Castle Head (locality 8). Hammer gives scale.

Figure 3. Parallel-laminated sandstone, coarse sequence 5, profile 5A, Monk Haven (locality 5). Hammer gives scale.

Figure 4. Thick mudstones with strongly developed calcrete V, Musselwick Point (locality 4). Clipboard gives scale.

TABLE 2. SUMMARY OF THE DISTRIBUTION AND THICKNESS OF THE ALLUVIAL SUITE AND ITS MARKER TUFFS IN SOUTHWEST WALES

number	locality: grid reference	locality: name	marker thickness/m: A	B	C	D	E	F	G	H	thickness between A and H (m)
1	SM 7388 0473	Crab Bay, Skokholm Island	1.94	0.09	0.01	E	E	?	E	0.95	18.02
1A	SM 7393 0476	Crab Bay, Skokholm Island	NM	0.09	0.03	E	E	?	E	0.56+	19.46
2	SM 7958 0604	Hook Vale	1.82+	0.06	NM	E	E	0.01	E	2.01	20.79
3	SM 8126 0610	Townsend, Dale	4.12	0.03	?F	?F	E	0.09	?F	1.27+	14.12+
4	SM 8198 0632	Musselwick Point	4.01	E	E	E	E	0.12	0.09	1.38	27.71
5	SM 8280 0639	Monk Haven	2.54	E	E	E	E	NM	?F	?F	14.87+
5A	SM 8285 0638	Monk Haven	2.09	E	E	E	E	0.14	0.09	0.93	20.94
5B	SM 8298 0635	Monk Haven (Loose Haven)	2.73	E	E	E	E	?F	?F	?F	4.06+
6	SM 8550 0677	Sleeping Bay	2.89	E	E	E	E	0.02	E	0.65+	24.37+
7	SM 8584 0813	Middlekilns Road	3.86	E	E	E	E	0.08	0.11+	1.29	15.12+
8	SM 8541 0652	Little Castle Head	3.96	0.01	0.58+	0.04	E	?	0.02	NM	26.54
8A	SM 8548 0647	Little Castle Head	4.00	0.03	1.10+	0.02	E	?	0.33	NM	26.70
8B	SM 8553 0658	Little Castle Head	3.15	0.73+	E	0.06	E	?	0.09	1.73	20.65
8C	SM 8555 0659	Little Castle Head	4.95	0.05	E	0.03	E	?F	0.28	2.95	22.56+
9	SM 8634 0697	Mun's Mouth	2.11	0.02	E	0.08	E	?	0.07	2.22	17.35
10	SM 8875 0800	St Botolph's railway cutting	3.82	0.07	0.67	0.12	?	E	0.15	1.69	31.52
11	SM 8633 0095	East Pickard Bay	3.38	0.08	0.30	0.07	E	0.03	0.17	1.70	16.95
11A	SM 8646 0096	East Pickard Bay	3.36	0.06	0.35	0.05	E	0.07	0.09	1.30	17.60
12	SR 8847 9946	Freshwater West	2.81	0.01	0.01	E	0.01	0.03	0.11	1.25	13.53
13	SS 0200 9722	Trewent Point	4.14	0.05	0.03	0.02	?	E	0.02	NM	13.76
14	SS 0456 9762	Swanlake Bay	2.80	0.03	0.06	0.01	0.01	E	0.25	1.16	14.55
15	SS 0586 9723	Priest's Nose, Manorbier Bay	2.44	0.05	0.15	0.02	?	0.02	0.04	1.02	15.83
16	SS 0727 9664	Old Castle Head	NM	0.03	0.07	0.06	0.06	0.07	?	0.34	13.87
16A	SS 0741 9664	Old Castle Head	3.39	0.02	0.09	0.06	E	E	0.13	0.43	15.40
16B	SS 0760 9661	Old Castle Head	NM	0.05	0.08	E	0.01	E	0.17	0.38	14.46

E, erosively based course sequence at expected horizon; ?, not detected at expected horizon; NM, present but not measurable; +, abbreviated due to faulting; ?F, not detected because of faulting.

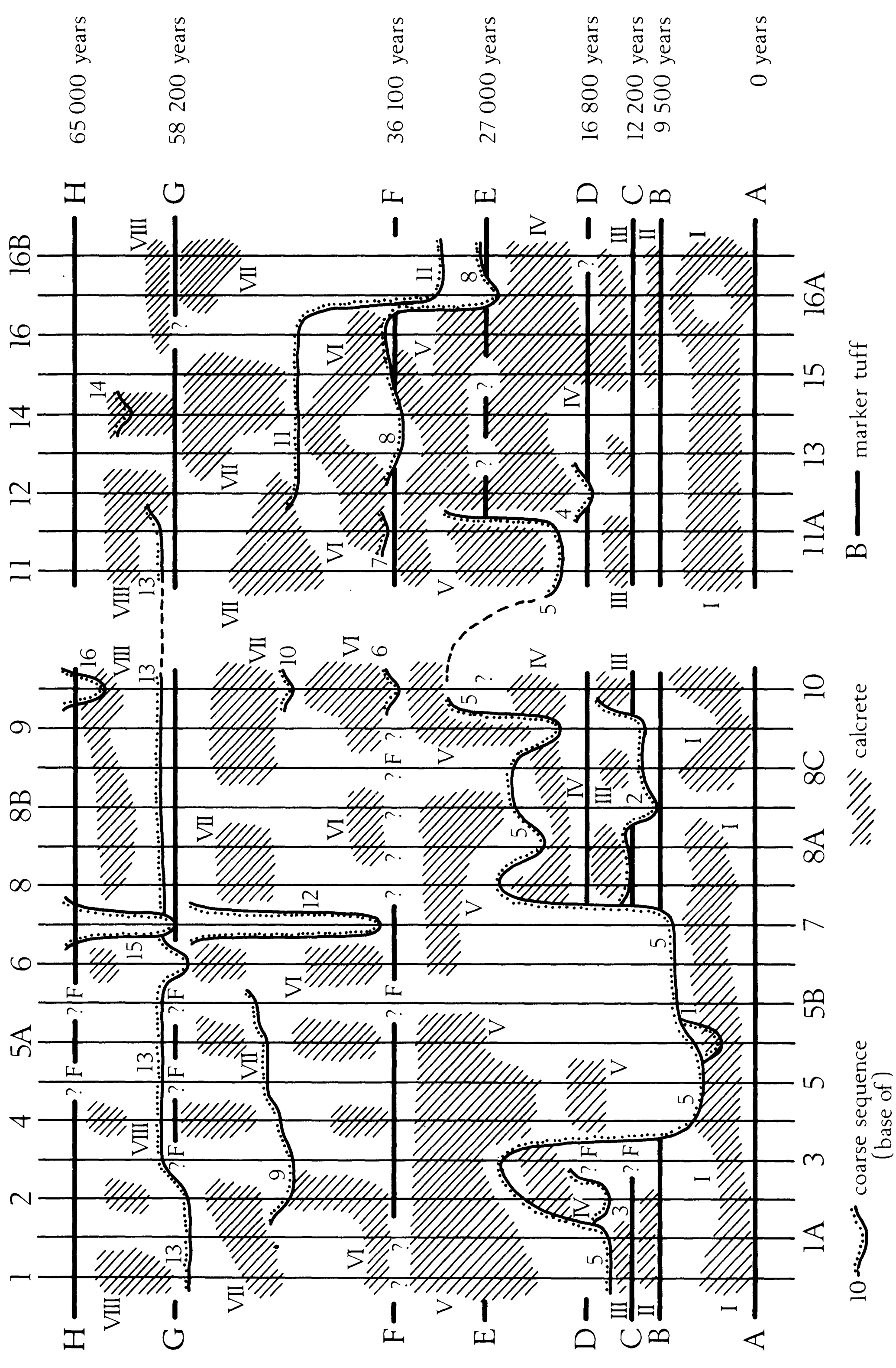


FIGURE 2. Schematic summary of the proposed correlation within the alluvial suite lying between the Townsend Tuff Bed (marker A) and the Pickard Bay Tuff Bed (marker H). See figure 1 for localities and text for explanation of horizontal and vertical scales.

Deposition accompanied by current dispersal implies that the ash fell into a river or tidal flow and was more or less immediately redistributed. That this could not happen with the thicker falls is shown by the association of the Pickard Bay Tuff Bed with ashy sandstones and normal terrigenous sandstones at localities 7 and 10. A few centimetres of ash, however, could perhaps be totally redistributed, leaving no distinguishable trace.

Deposition followed by erosion means that the ash and probably some overlying normal sediment, together possibly with some underlying beds, were subsequently removed by currents or weathering. The deepening of river or tidal channels, the erosion of valleys, or prolonged weathering, could each remove a marker tuff. Tuff fragments preserved in an intraformational conglomerate clearly prove the erosion of a marker, but little weight can be attached to such evidence where tuffs are closely spaced vertically. The absence of these fragments from a conglomerate is not a reliable indication that no marker was subjected to attack.

Deposition followed by organic or pedological reworking means that ash and normal sediment became blended through the action of one or both of these processes during or shortly after deposition. That the terrigenous mudstones of the alluvial suite were extensively bioturbated while soft is shown by the numerous burrows (?root channels) present and by the tuff-smothered faecal debris (plate 2, figures 1, 4). Even the thinnest tuff beds so affected are still recognizable, however, in the form of bands of pink or purple ashy mottles or, in a less advanced stage of destratification, as sheets profusely mottled by normal mudstone (plate 3, figure 1). Calcretization of the mudstones, although involving some churning of the sediment, as well as the pedological introduction of new materials, seems also to have been relatively ineffective as a means of blending ash and normal sediment. At localities 14 and 15, and in profile 16, for example, marker E is well preserved although just a few centimetres thick and contained within or closely associated with strong calcretes.

We accordingly propose the diagrammatic structure sketched in figure 2 as the most plausible for the alluvial suite, having regard to the four factors above and the evidence summarized in figures 4–12. The profiles, representing localities shown in figure 1, appear at an arbitrarily even horizontal spacing. The marker beds are spaced vertically on a time scale determined *pro rata* from the thicknesses of the beds between markers as averaged over the four localities in the southeast of the area, and on the supposition that the alluvial suite accumulated over the 65000 years inferred from north of the Ritec Fault. The marker tuffs are better represented in the southeast than elsewhere (see figure 2) and the suite is muddiest here, whence our stratigraphic method of age determination affords the most complete and reliable time scale. The alluvial suite is divisible into seven unequal intervals and thins southward from the Marloes area (figure 4*b*; table 2) in harmony with the Lower Old Red Sandstone as a whole. Within it we recognize 16 erosively based 'coarse' sequences (numbered 1–16), either sandstones and conglomerates mainly or sandstone-striped mudstones, and eight calcrete profiles (numbered I–VIII).

The correlation of markers B, C, D and G is advanced confidently, as these beds (i) occur at mud-dominated levels, (ii) are widely developed, and (iii) lie stratigraphically close to either the Townsend Tuff Bed or the Pickard Bay Tuff Bed. We are slightly less confident about the correlation of markers E and F, and about the relationships of the coarse sequences in intervals D–E and E–F. Marker F has the wider distribution of the two tuffs and its identity is the more easily resolved. It failed to appear mainly at locality 1 in the extreme west and in a cluster of north-central profiles, where its approximate horizon is assigned on the basis of the calcretes (below calcrete VI). Marker E is lacking over most of the area and in the southeast appears only

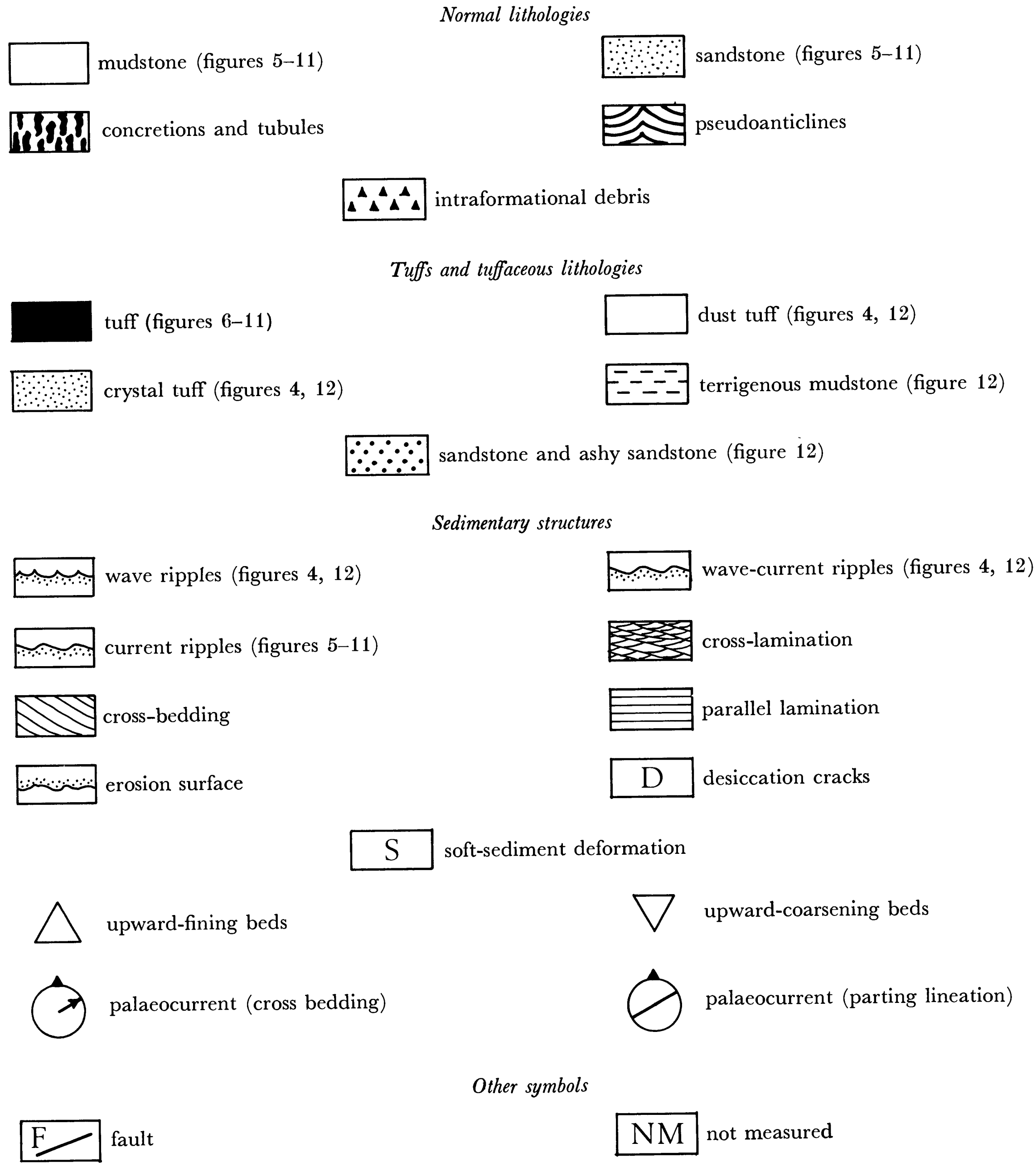


Figure 3. Keys to the sedimentological logs shown in figures 4–12. Where a symbol is restricted in its application to particular figures, the figure number is given in brackets after the description.

locally. In profile 16, and at localities 12 and 14, it seems to be the very thin tuff lying between the strong calcretes IV and V, or near the middle of what seems to be calcrete V overlapping with the earlier profile IV. At localities 4, 5 and 6 recognizable marker tuffs are lacking in the whole of the interval between markers A and F, whereas in locality 2 to the west, and in localities 8 and 9 eastward, an erosional break appears between calcrete V and a profile (taken to be calcrete IV) succeeding marker D. These observations are reconciled in figure 2 by the attribution of the sandstone-capped erosional contact first encountered above either calcrete

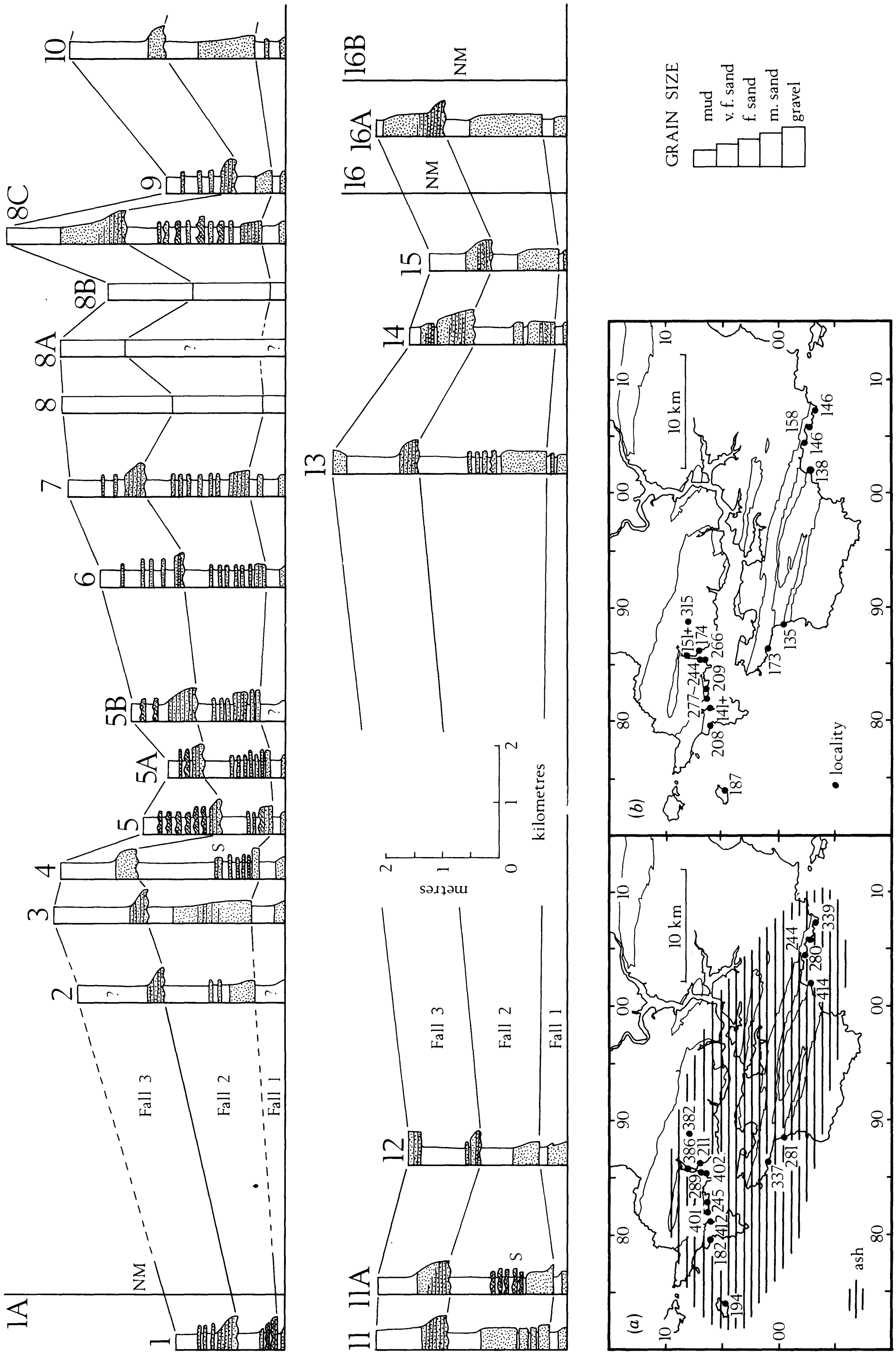


FIGURE 4. Summary of internal stratigraphy and sedimentological features of marker A (Townsend Tuff Bed). (*a*) Thickness in centimetres of marker A. (*b*) Thickness in decimetres of the alluvial suite between marker A (Townsend Tuff Bed) and the Pickard Bay Tuff Bed (marker H).

IV, marker D, or marker A as the case may be, to a single coarse sequence numbered 5. A more complex but still plausible interpretation is that coarse sequence 5 is correctly identified as far east as locality 7, but that the erosional contact seen at localities 8, 9 and 10 should be correlated with that below coarse sequence 6, marker F having been eroded from these last three sites. Sequences 6, 7 and 8 all occur just below calcrete VI, however, and plausibly record the same broad sedimentary event. If our second interpretation is correct, calcrete V should appear in at least one of profiles 16A and 16B. Its lack, combined with the question then raised of the absence of marker E at localities 4–6, makes us prefer our first proposal.

6. Interval A–B (?9500 years)

(*a*) *Main facts*

This consists of roughly 2 m of red mudstone (figure 5) with no clear thickness variation (figure 5*a*). The beds are massive, unlaminated and coarse-grained, with silt (in total predominating over clay) and some sand grains and mica flakes clearly visible under the hand lens. Green blotches and streaks, and some mottles of tuff, are present near the base in the passage up from fall 3 of the Townsend Tuff Bed. Locally the mudstones show long, subvertical and somewhat winding mud-filled burrows (?root channels), with a circular to irregular cross section about 5 mm across and occasional downward branches. Many are surrounded by a halo of mauve to blue shading off into red. The only deviation from this lithological monotony is afforded by coarse sequence 1 (profile 5B). It consists of a lower upward-fining succession of very coarse, horizontally laminated red mudstone with lenses of cross-laminated clean silt, overlain by a second and slightly down-cutting succession begun by horizontally laminated clean silt. We link it to interval A–B because at least the lower part is calcretized along with the underlying mudstone.

Interval A–B includes calcrete I, best developed in the north and centre of the area (localities 1–6, 9, 11). The profile consists of small calcareous concretions becoming common or abundant upward, accompanied by calcite 'tubules' 5–10 mm across, apparently a calcified form of the burrows described. Locally there are weakly developed pseudoanticlines (Allen 1973, 1974). At several localities calcrete I is of tubules only.

(*b*) *Interpretation*

The confinement of these mudstones between two stratigraphically close and areally extensive (12.5 km by 35 km) marker beds implies a monotonously uniform and virtually featureless depositional environment. To judge from the prevalence of quartz silt, the associated clay minerals were introduced as suspended fluccules, by currents at times strong and turbulent. The massive and unlaminated character of the mudstones demands the penecontemporaneous operation of some process of destratification, either organic or pedological. Destratification by organisms is consistent with the burrows (?root channels) observed, and with the abundant and commonly large faecal pellets locally smothered at other levels by such as markers A, C and H. Possibly some destratification accompanied the calcretization, as the pseudoanticlines and concretions imply relative movements within the affected mud. Coarse sequence 1 reveals that locally on the monotonous surface there operated stronger currents, perhaps contained in a belt of gullies or shallow channels (figure 5*b*). Shortly afterwards the muds were very widely but not strongly calcretized, an event suggesting the virtual cessation of mud supplies and the brief

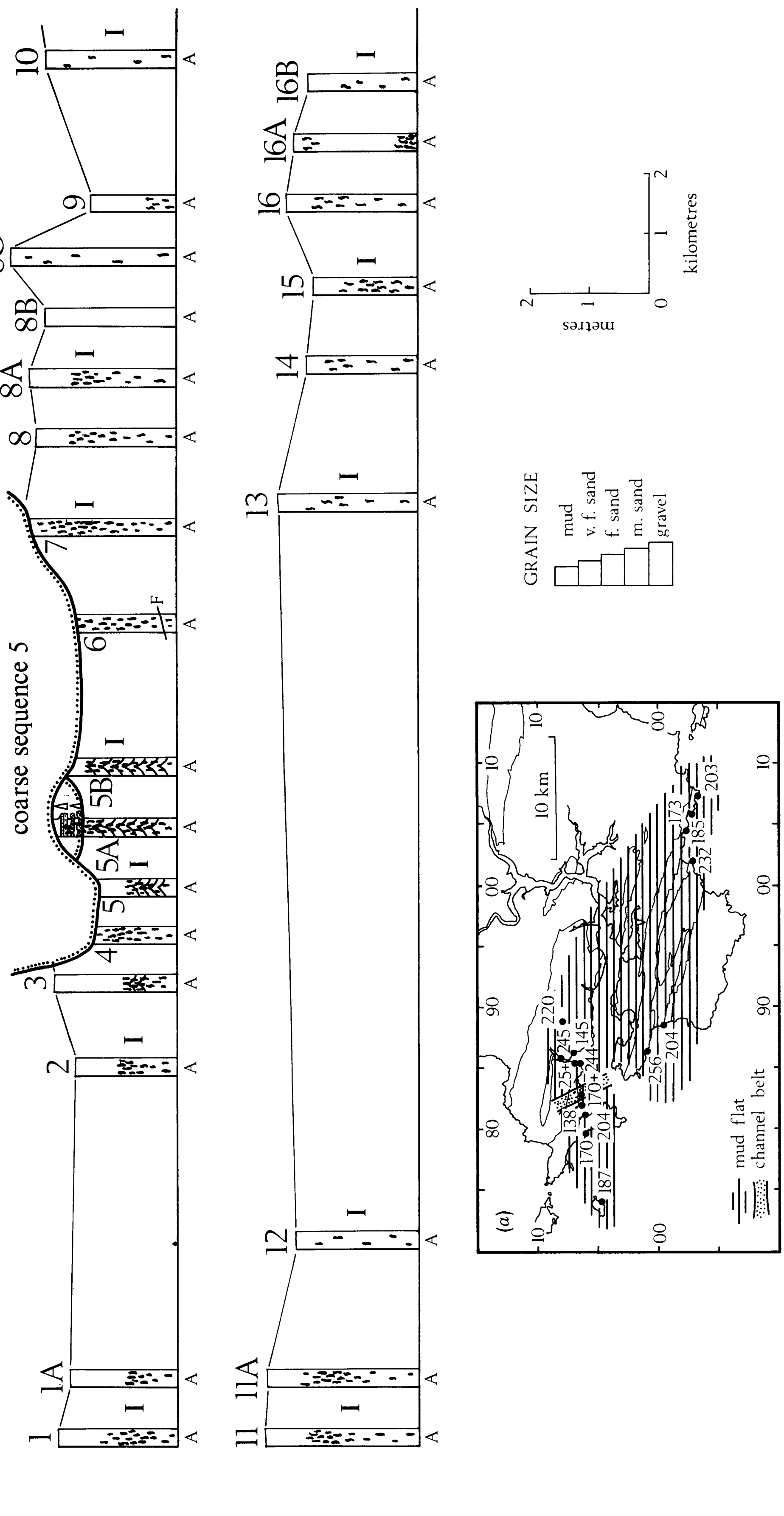


FIGURE 5. Summary of the internal stratigraphy and sedimentological features of the rocks between marker A (Townsend Tuff Bed) and marker B (interval A–B), with (a) the thickness in centimetres and an environmental interpretation of the rocks in the interval. See figure 3 for key to symbols.

appearance of soil-forming conditions under a warm semi-arid climate (Allen 1974; Leeder 1975).

There are no direct proofs for the subaerial exposure of the sedimentary surface during the accumulation of interval A–B, but we suggest that the environment was a continuation of the extensive coastal mudflats blanketed by the Townsend Tuff Bed (Allen & Williams 1981). Allowing for age differences, a broad parallel can be drawn between the mudstones of interval A–B and the intertidal and supratidal grading to distal fluvial muds of the modern Colorado Delta (Gulf of California) (Thompson 1968; Meckel 1975). The supratidal flats in particular consist of poorly laminated to unlaminated silts. Like the better laminated intertidal muds, they underlie a huge virtually featureless area. Soil-forming conditions could have come to interval A–B in response to a slight fall in sea level, though we lack direct evidence for this (e.g. deep sand-filled channels) in the area examined.

7. Interval B–C (?2700 years)

(*a*) *Main facts*

These beds seem to thin toward the south and east (figure 6*b*). As in interval A–B, the rocks are massive, coarse, micaceous red mudstones lacking internal lamination (figure 6). Burrows (?root channels) are fairly common and in places have blue haloes. Marker C in profile 8 sharply smothers a mudstone surface richly strewn with oval to rod-shaped faecal pellets about 1 mm long but with occasional much larger forms (plate 2, figure 4). Calcrete II is restricted to the west and southeast, consisting at its strongest of a thin profile with abundant small calcareous concretions and calcite tubules. Elsewhere the mudstones are carbonate-free.

(*b*) *Interpretation*

Interval B–C, conjectured to have lasted the brief period of 2700 years, records similar environmental conditions to the rocks immediately preceding it. Deposition on a featureless mudflat was resumed, possibly after a slight sealevel rise terminated the episode of soil formation that gave calcrete I, but there was subsequently another though more localized attempt at soil generation. The chance preservation of abundant faecal debris beneath marker C is powerful evidence that the massive and unlaminated character of the mudrocks reflects more or less continuous organic reworking.

8. Interval C–D (?4600 years)

(*a*) *Main facts*

These rocks are thickest in a central northeast–southwest belt, where coarse sequence 2 is developed (figure 7*b*), and thin off considerably southeastward. The beds are also reduced to the west of this belt, but in consequence of coarse-sequence erosion.

Away from the central belt, the sediments are thick, massive red mudstones with much quartz silt and some sand and mica (figure 7). Only locally are the lowermost mudstones horizontally laminated (locality 11) or sand-striped (locality 13). Burrows (?root channels) often with blue haloes are widely prevalent. The mudstones are lightly calcretized toward their base, tubules being abundant and small concretions in places common (calcrete III).

Coarse sequence 2 in two parts occurs in interval C–D, in places eroding marker C (figure 7).

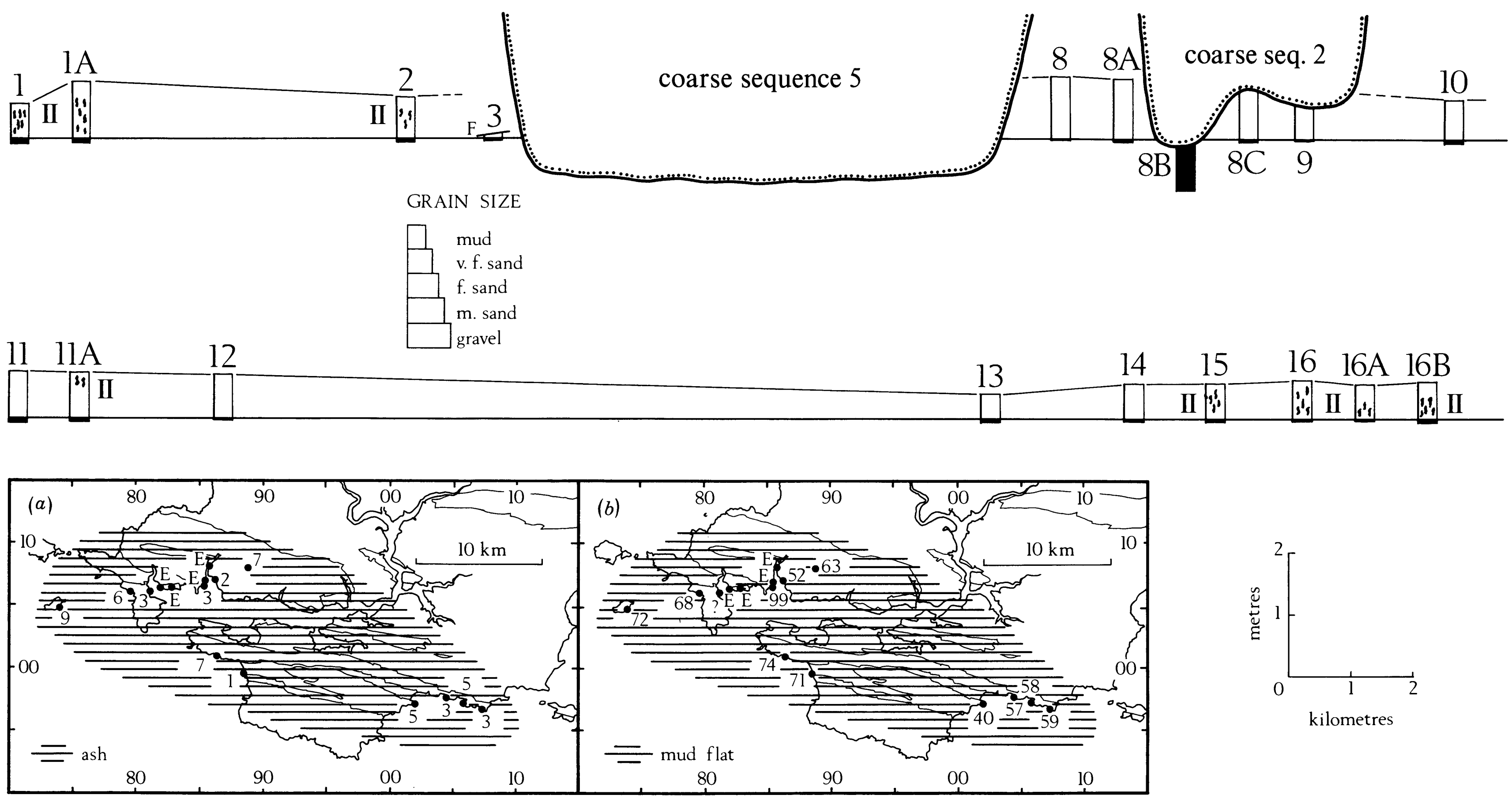


Figure 6. Summary of the internal stratigraphy and sedimentological features of the rocks from and including marker B up to marker C (interval B–C). (*a*) Thickness in centimetres of marker B. (*b*) Thickness in centimetres of the rocks in interval B–C, with an environmental interpretation. See figure 3 for key to symbols.

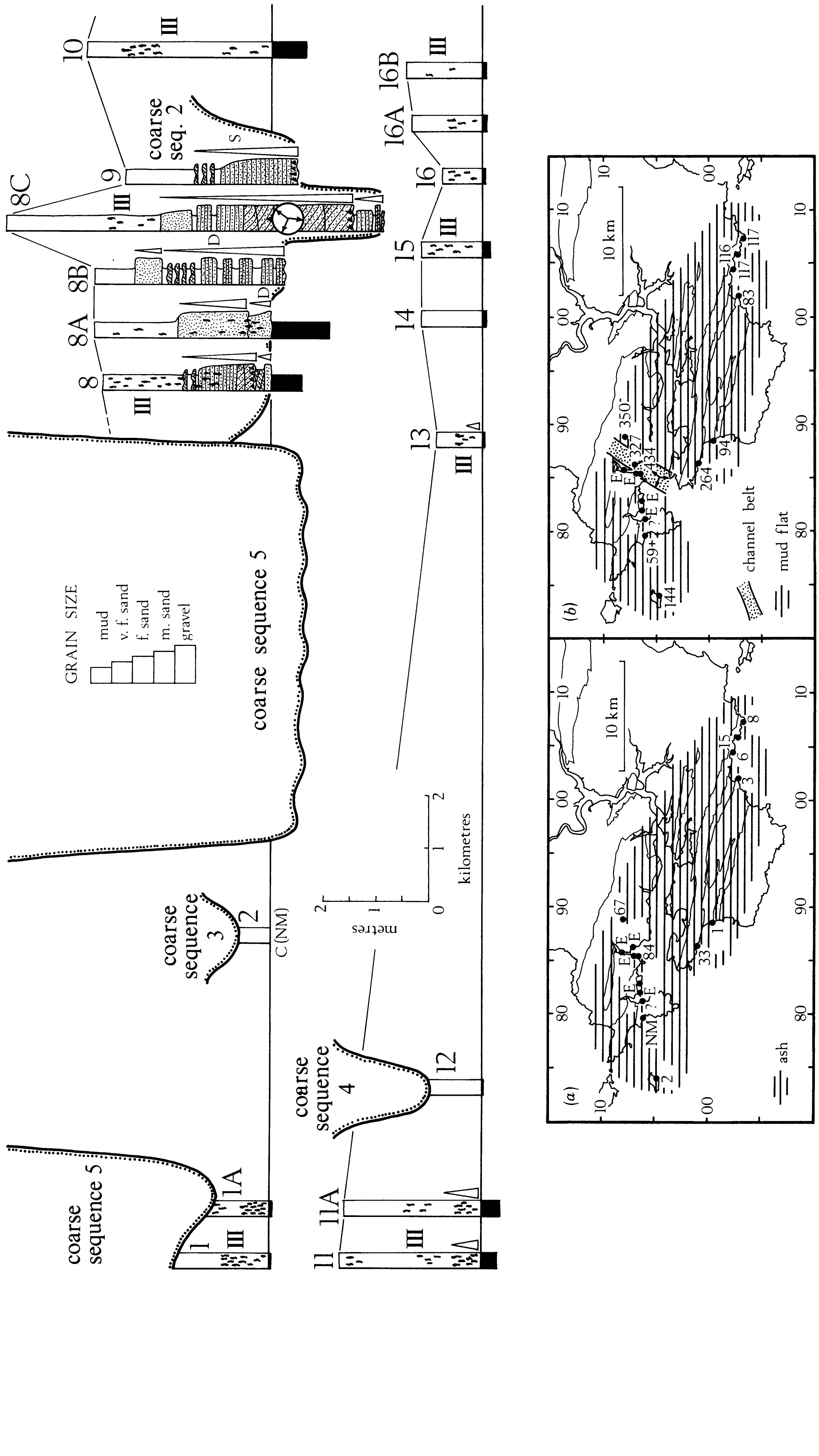


FIGURE 7. Summary of the internal stratigraphy and sedimentological features of the rocks from and including marker C up to marker D (interval C–D). (*a*) Thickness in centimetres of marker C. (*d*) Thickness in centimetres of the rocks in interval C–D, with an environmental interpretation. See figure 3 for key to symbols.

Neither part shows signs of lateral accretion. The lower part, best seen in profiles 8B and 8C, consists of an upward-fining succession of alternating sandstone and massive mudstone beds. The sandstones are very fine- to fine-grained, with generally sharp and regular bases and sharp to rapidly gradational tops. Basal features include desiccation cracks, irregular erosional welts, and small load casts. Several sandstones appear massive and homogeneous, though with locally faint traces of parallel lamination. The highest sandstones toward the top are very fine-grained and cross-laminated. The higher upward-fining succession comprises most of the coarse sequence in profile 8C, possibly most of that in profile 8, and probably all of the sequence at locality 9. The beds overlie an erosion surface strewn with mudstone clasts and consist mainly of fine-grained, cross-bedded or parallel-laminated sandstones (plate 3, figure 2). Toward the top occur soft-sediment deformations, desiccation cracks, and thin sharp-based normally graded sandstones. The small calcareous concretions and calcite tubules present in coarse sequence 2 are interpreted as calcrete III.

The purple sandstones of the second upward-fining succession appear among the more northerly sites at Little Castle Head (figure 1*a*), dying out southeastward along the northeast limb of the parasitic anticline by rise of the base. Two of the available three cross-bedding azimuths are consistent with the channel margin implied by this pattern of distribution and thinning.

(*b*) *Interpretation*

Interval C–D may have lasted about 4600 years. The thinning of the mudstones southeastward from coarse sequence 2 suggests their spread from the same channels as those that received the sandstones (figure 7*b*). In support of this view, the mudstones seem coarsest and best laminated closest to the projected channel belt (e.g. locality 11).

Did the channels hold only fresh water or were they tidally influenced? Downcutting and lateral wandering could have produced the clast-strewn erosional bases, and the currents were at times powerful, to judge from the sedimentary structures (Allen 1970, fig. 2.6). Dune fields underlain by cross-bedded sand arose in many places and in others there formed smooth shoals with parallel-laminated sand beneath. Currents weak enough to have formed asymmetrical ripple marks were restricted either to a late stage in channel filling, or to marginal shallows, to judge from the restriction of cross-lamination to very fine-grained sandstones in the higher parts of the two upward-fining successions. The currents, although strong at times, were also markedly unsteady and variable in direction. Infilled desiccation cracks occur within 0.25 m of the base of the lower upward-fining sequence in one profile and near the top of the second in another. The cross-bedding azimuths suggest diametrically opposed flows, but the sandstones include no mud drapes pointing conclusively to tidal influences. Whatever the salinity, the channellized flows were of no great sinuosity, to judge from the lack of evidence for lateral accretion. The thickness of coarse sequence 2 suggests that any rivers involved were of small or intermediate size.

The two upward-fining successions differ substantially. The lower, with its alternating coarse and fine beds, is reminiscent of the interbedded muds and sands flooring estuarine channels in the Niger Delta (Allen 1965*b*), but also invokes the processes and to some extent the deposits of flashy or ephemeral streams (McKee *et al.* 1967; Patton & Schumm 1981). Were the channels tidal, however, they must have lain high in the intertidal zone, for their muddy floors to have become dried out (?neaps), a microtidal régime being at once excluded. The higher upward-fining sequence resembles in all but scale some of the tidally influenced channel deposits described from the South Carolina marshlands (Barwis 1978), as well as those reported from the Colorado River Delta (Meckel 1975). In the absence of faunal criteria, however, the beds can just as satisfactorily be matched in modern river channel deposits, particularly where channel sinuosity was low (see, for example: Harms & Fahnestock 1965; Shelton & Noble 1974). The diversity of cross-bedding azimuths (admittedly few) is the only evidence that specifically favours a tidal influence.

Channel activity eventually gave place to the calcretization of the sandy fills and laterally equivalent muds. Calcrete III is nowhere strongly developed, however, pointing to brief pedogenesis, consequent on either river diversion or a slight lowering of sea level accordingly as coarse sequence 2 is interpreted.

9. Interval D–E (?10200 years)

(a) *Main facts*

These rocks are thickest at north-central sites, despite some removals during the emplacement of younger coarse sequences (figure 8*b*).

Coarse- to very-coarse grained massive red mudstones predominate (see figure 8). Lamination is restricted to the coarsest rocks, which form the lower parts of thin sharp-based normally graded mudstone sequences (profiles 8, 8A, 8C). Burrows (?root channels) with blue to mauve haloes are widespread and the beds reveal an intense calcretization.

Calcrete IV is a thick profile of common to very abundant large calcareous concretions and calcite tubules generally associated with large intersecting concave-up sheets of irregularly interlaminated mudstone and calcite up to 0.03 m thick and spaced vertically a decimetre or so apart. Locally the pseudoanticlines assume a boxwork style (profile 8, localities 12 and 16). Calcrete IV at localities 12 and 16 includes another type of deposit (vein calcrete), formed of closely spaced irregular bedding-parallel calcite sheets united vertically by short veins.

Two coarse sequences antedate calcrete IV (see figure 8). Sequence 4 is the thinner and finer-grained of the two, apparently eroding marker D. It consists of a sharp-based and locally laminated very coarse sandy mudstone passing up into coarse mudstone. Sequence 3 appears above a thin green-striped mudstone and consists of two upward-fining successions, the lower resembling the earlier part of coarse sequence 2 (profile 8B). Above lies a thick red mudstone with numerous stripes and sharp-based bands of very fine grained sandstone. The second upward-fining succession consists of cross-laminated very fine-grained sandstones interbedded with massive mudstones in beds thickening upward. The sediment transport direction is unknown.

(b) *Interpretation*

Coarse sequences 3 and 4 point to the local development of channellized currents before the growth of calcrete IV. As in interval C–D, channel activity seems to have coincided largely if not wholly with mud deposition. The sharp-based laminated mudstones at locality 8 hint at the presence nearby of a third source of turbulent currents and coarse sediment. The salinity of the waters is in doubt. Variable and at times powerful currents are suggested by the interbedded sandstones and mudstones starting coarse sequence 3, but there is neither faunal proof for tidal influence nor the evidence of frequent desiccation to support a river origin. The sandstones above, and the very coarse mudstones of sequence 4, are consistent with less vigorous currents,

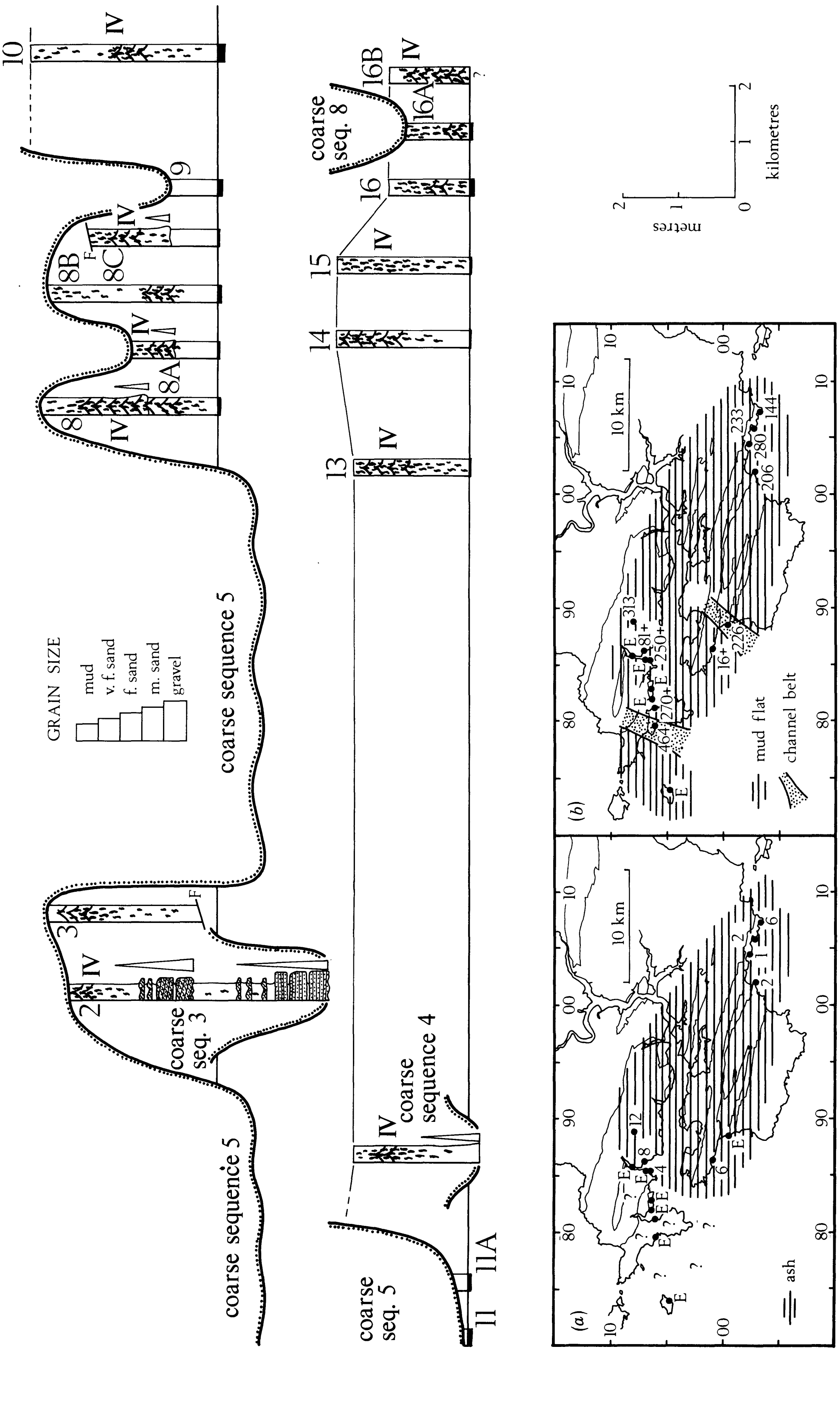


FIGURE 8. Summary of the internal stratigraphy and sedimentological features of the rocks from and including marker D up to marker E (interval D–E). (*a*) Thickness in centimetres of marker D. (*b*) Thickness in centimetres of the rocks in interval D–E, with an environmental interpretation. See figure 3 for key to symbols.

but there is again no decisive evidence for their salinity. In general, environmental conditions were not significantly different from those that earlier prevailed.

Calcrete IV is much thicker and richer in calcite than any of the three immediately preceding fossil soils and is one of the strongest two in the whole alluvial suite. Pedogenesis was evidently prolonged, in response either to the massive diversion or drying up of rivers entering the area or to a sufficient lowering of sea level that former tidally influenced mudflats were rendered wholly terrestrial. The growth of calcrete IV could have accompanied the incision of the structure later occupied by coarse sequence 5 of the next interval.

10. Interval E–F (?9100 years)

(a) *Main facts*

These rocks are very variable in thickness, because of the dominance of coarse sequence 5 and its supervening mudstones, apparently emplaced as deep down into the suite as interval A–B (figures 2, 9*b*).

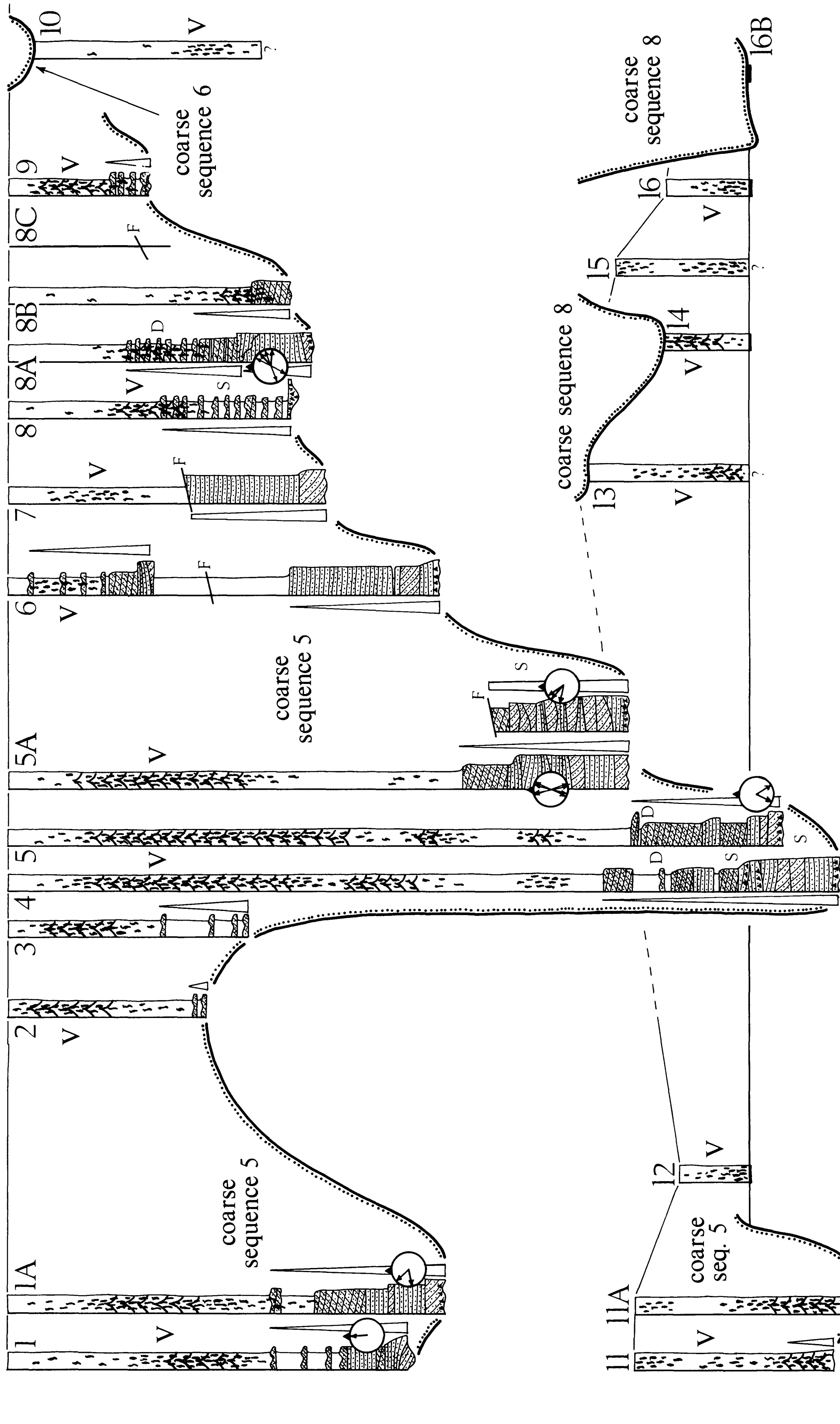
Where coarse sequence 5 is lacking (see figure 9), interval E–F comprises massive unlaminated coarse red mudstones devoid of sandstone stripes. Burrows (?root channels) are plentiful, locally with blue haloes. The mudstones are intensely calcretized, but only at locality 15, where marker E is thinly developed, is calcrete V wholly distinguishable from calcrete IV below. The profile overlapping that is visible elsewhere is not related to the absence of marker E, however, since this ash fall occurs at localities 12 and 14, as well as at locality 15 (figure 2).

Coarse sequence 5 (figure 9) reaches down lowest at four west-central sites (localities 4–7), where up to 4 m of sandstones with a little interbedded mudstone pass up into an intensely calcretized thick mudstone. Mudstone and calcrete fragments are strewn over its erosional floor. The coarser sandstones (plate 3, figure 3) are either cross-bedded or parallel-laminated in mildly cross-cutting sets with clast-strewn bases. Cross-lamination typifies the very fine-grained and generally higher rocks, among which are thin desiccated mudstones. The palaeocurrent directions are almost diametrically opposed. Signs of lateral accretion are lacking. Overlying the sandstones are red coarse massive thickly calcretized mudstones with frequent and often blue-rimmed burrows (?root channels) (plate 3, figure 4). Calcrete V at locality 4 and in profiles 5 and 5A seems to comprise no less than three partly overlapping profiles, of which the topmost is the thickest. It is weak at locality 6, where an upward-fining succession of interbedded mudstones and fine to very fine grained parallel-laminated or cross-laminated sandstones is affected.

In the far west (locality 1) coarse sequence 5 erodes beds down to interval C–D (figures 2, 9). Here the sandstones and calcrete V are thinner than in the centre of the area, and sediment transport took place only toward the west and northwest.

In the ground between locality 1 and localities 4–7, coarse sequence 5 is represented only by mudstones with normally graded sandstone stripes and bands. Calcrete V is however quite well developed.

A strong development of coarse sequence 5 erodes the calcretized mudstones of interval D–E at locality 8 (figure 9). The two upward-fining successions found at locality 8 are divided in profile 8A by a laterally extensive convex-up erosion surface (plate 4, figure 1). The upper succession, preserving signs of its lateral accretion, includes many sharp-based normally graded thin sandstones (plate 4, figures 2, 3), at least two horizons of locally incompletely filled


1
1A
coarse sequence 5
2
3
4
5
5A
coarse sequence 5
6
7
8
8A
8B
8C
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15
16
coarse sequence 8
16B

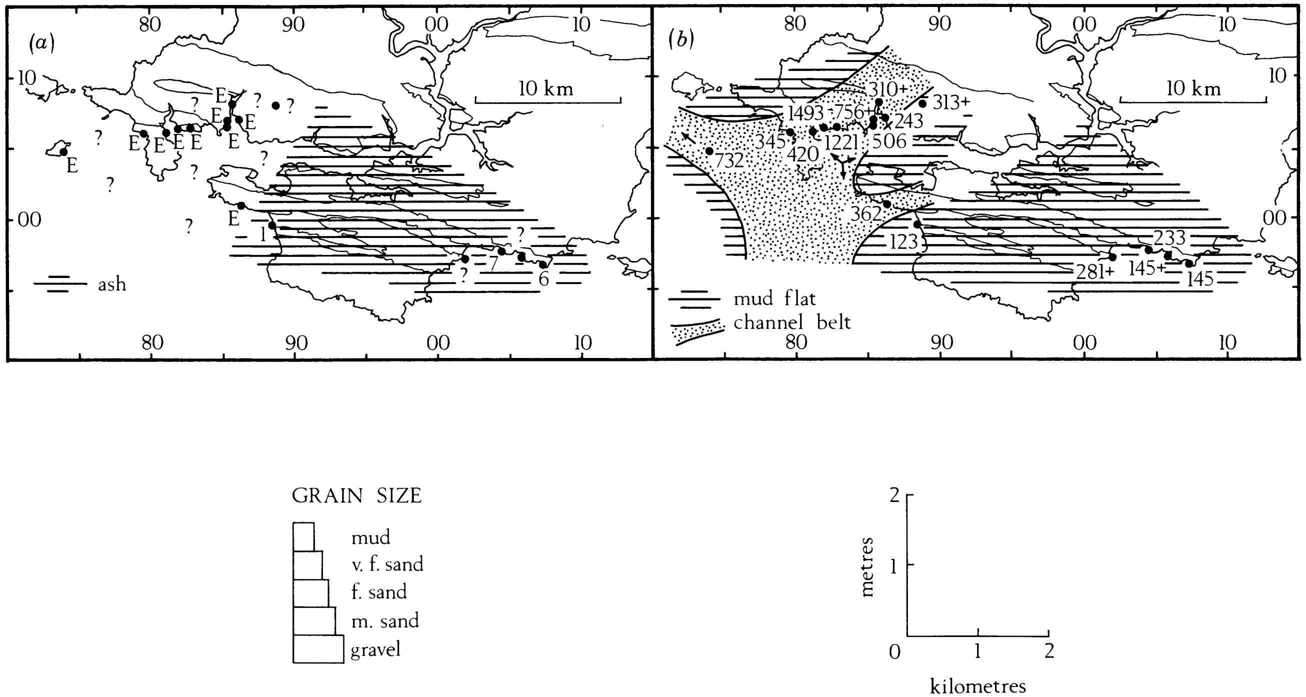

FIGURE 9. Summary of the internal stratigraphy and sedimentological features of the rocks from and including marker E up to marker F (interval E–F). (*a*) Thickness in centimetres of marker F. (*b*) Thickness in centimetres of the rocks in interval E–F, with an environmental interpretation. See figure 3 for key to symbols.

desiccation cracks (plate 4, figure 4), and some soft-sediment deformations. Sediment transport (lower succession) was toward the east and northeast. Calcrete V is strongly developed within the uppermost sandstones and the lower part of the overlying thick mudstone. Eastward (locality 9) and southward (locality 11) from locality 8, coarse sequence 5 fades away to mudstones with sandstone stripes and bands, and to very coarse laminated mudstones resting on an erosion surface strewn with calcrete debris. Among these rocks calcrete V is locally of the vein type but otherwise formed of large concretions associated with pseudoanticlines (boxwork in places) (plate 5, figures 1, 2).

(*b*) *Interpretation*

The conjectured duration of interval E–F is 9100 years, about average for the alluvial suite as a whole. Coarse sequence 5, dominating the interval, could record either a complex of unusually large deep channels or the incision and subsequent aggradation of connected valleys during a cycle of sealevel change (figure 9*b*). The choice of interpretation rests on the character of the fill.

Whereas the downcutting is roughly 10 m at the greatest, the sandstones that commence the deepest-reaching part of coarse sequence 5 are a mere 3–4 m thick. Since the transition from sandy upward to muddy sediments in both river-floodplain and tidal-flat environments broadly defines the channel rim, and therefore the height of the river at bankfull, or of the tide at or not much below high water, the sequence cannot record a complex of channels introduced without there having been a substantial lowering of sea level. The same conclusion is demanded by the desiccation cracks high up in the lowest-lying sandstones, and by the subordinate calcretes within calcrete V at localities 4 and 5. Hence coarse sequence 5 must record the perhaps episodic infilling of a group of connected valleys incised by shifting channels in response to a substantial sealevel lowering. The subsequent aggradation apparently involved the accumulation of progressively finer grained and more widely spread sediments. Thus the upward-fining sandstone complexes at localities 4–7 are thicker and coarser-grained overall than those at locality 8, which in turn are coarser and thicker than the successions at localities 2, 3, 9 and 11. The upward-fining succession high up at locality 6 could represent a channel belt active near the end of the interval, when mud was accumulating over the area as a whole. The isolation of this succession suggests its avulsive emplacement.

Although the upward predominance of mudstone in coarse sequence 5 compares with the upward-fining seen in the aggradations of river valleys at times of post-glacial sealevel rise (see,

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Description of plate 4

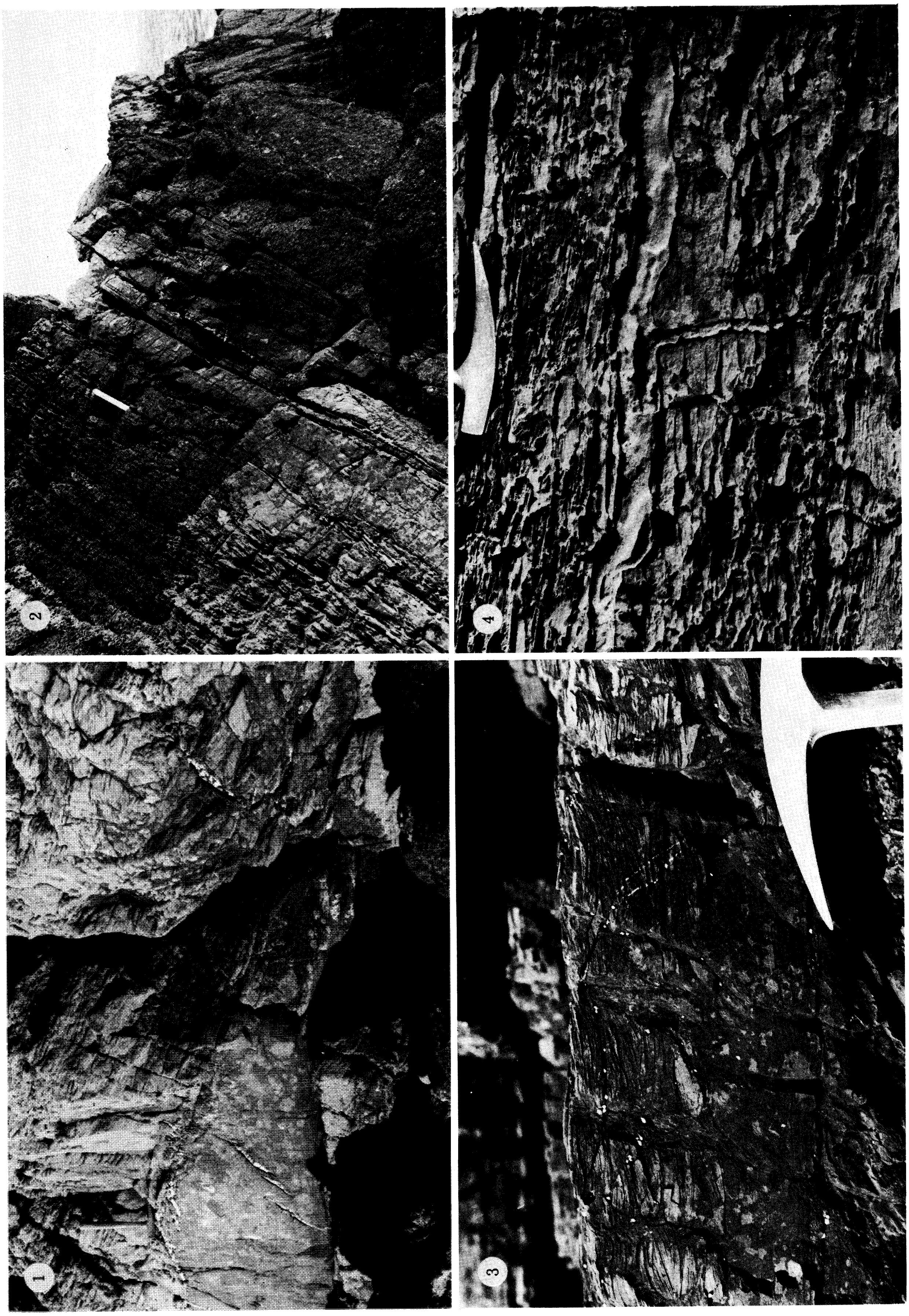
Sedimentological features of the alluvial suite.

Figure 1. Convex-up erosion surface within the lower part of coarse sequence 5 in profile 8A, Little Castle Head (locality 8). Hammer gives scale.

Figure 2. Coarse sequence 5 on cliffs 35 m west of the site of profile 8A, Little Castle Head (locality 8). The lower sandstones are parallel-laminated and close to the north toward the erosion surface at the base. Upward these rocks graduate into interbedded mudstones and sharp-based, normally graded, very fine-grained sandstones with cross-lamination and current-ripple marks. Scale given by measuring rule 0.15 m long.

Figure 3. Sharp-based normally graded sandstone passing from parallel-laminated up to cross-laminated, upper part of the upward-fining succession shown in figure 2 above. Hammer gives scale.

Figure 4. Fine- to medium-grained sandstone bridging and infilling one of a row of desiccation cracks, mudstones above sandstones shown in figure 2 above. Hammer gives scale.



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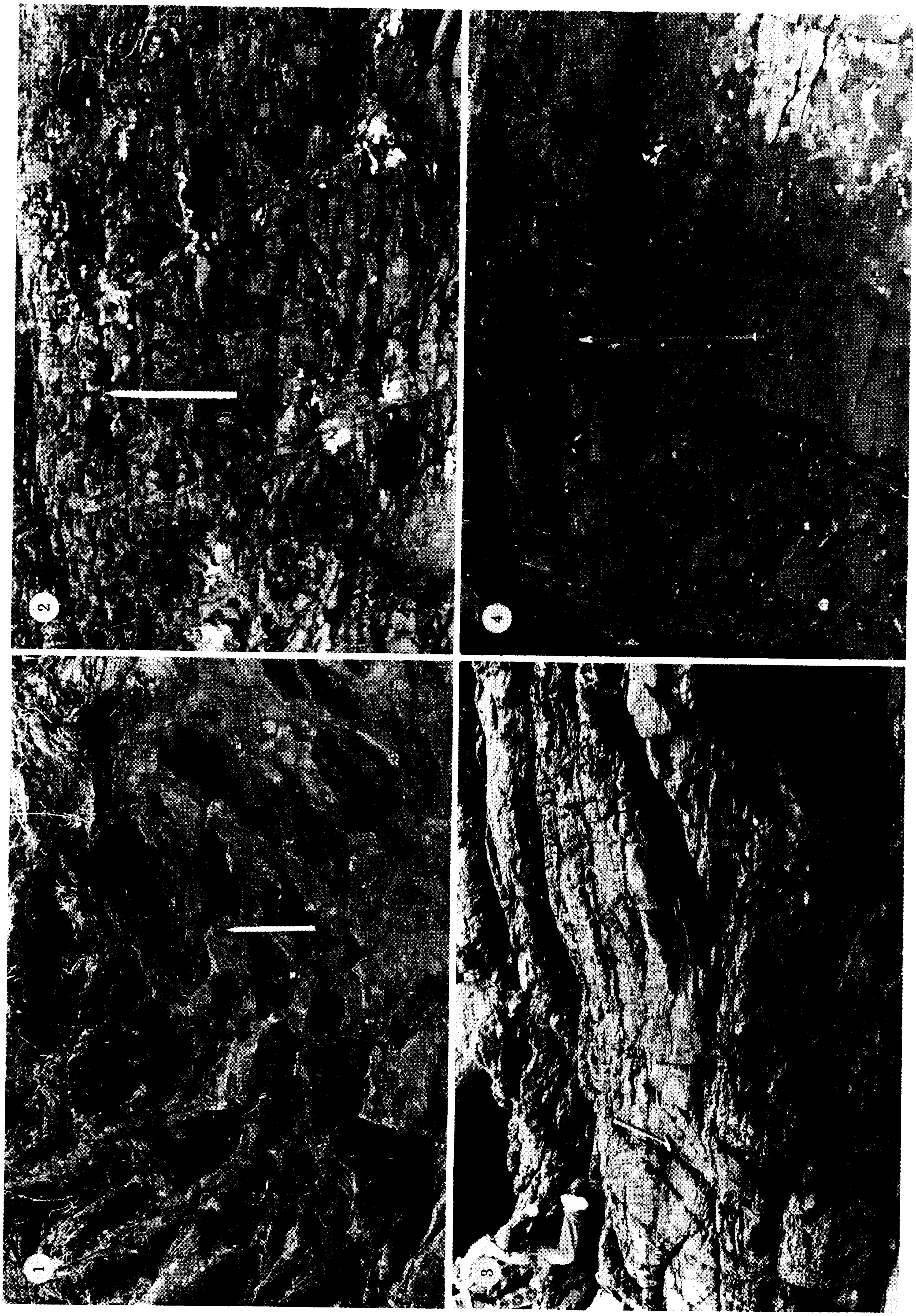


For description see opposite.

for example: Fisk 1947; Zagwijn 1963), this character contributes nothing to the question of whether the complex is fluviatile or tidally influenced. The only features directly suggesting tidal effects are the burrowed and massive nature of the mudstones, the variable current directions (locality 5) reminiscent of Meckel's (1975) observations from tidal channel sands, and the contradictory flows provided by localities 1 and 8. The upward-fining rocks are otherwise difficult to distinguish from the deposits of modern low-sinuosity sand-bed streams (see, for example: Ore 1963; Harms & Fahnestock 1965; Smith 1970, 1971, 1972; Shelton & Noble 1974). Several of our localities provide excellent lateral control on the sandstones, but at only one is there the slightest evidence for their lateral accretion.

Aggradation of the valley complex and the completion of interval E–F by the spread of mud over the area as a whole was followed by a second long period of soil growth during which calcrete V accumulated. Sea level may once again have fallen.

11. Interval F–G (?22100 years)

This interval is the thickest and most variable in the entire suite (figure 10*b*), representing about one-third of its speculative duration. Profiling revealed two widely developed calcretes and several local coarse sequences.

(*a*) *Deposits antedating calcrete VI: main facts*

West of localities 10 and 11 these rocks are coarse massive red mudstones with frequent burrows (?root channels) normally with mauve to blue haloes (figure 10). Calcrete VI is very variable, ranging from a profile of tubules and scattered concretions (most localities) to a strong horizonation of abundant concretions (profile 8B) locally with pseudoanticlines (locality 6, profile 8A).

Two minor coarse sequences numbered 6 and 7 occur centrally (figure 10). Neither involves sediment coarser in grade than very fine sand.

Coarse sequence 8 (localities 12–16), the main sandy development antedating calcrete VI, coarsens and seems to cut down more deeply eastward (figure 10). It involves interbedded sharp-based graded sandstones and locally desiccated mudstones. Burrows (?root channels) commonly with blue haloes abound and in profile 16A are accompanied by the giant trace fossil *Beaconites antarcticus* (Gevers *et al.* 1971). Small symmetrical ripple marks were found 0.27 m above the base in this profile, the only examples that we saw within the alluvial suite during our survey. Calcrete VI is as variable in coarse sequence 8 as over the rest of the area.

Description of plate 5

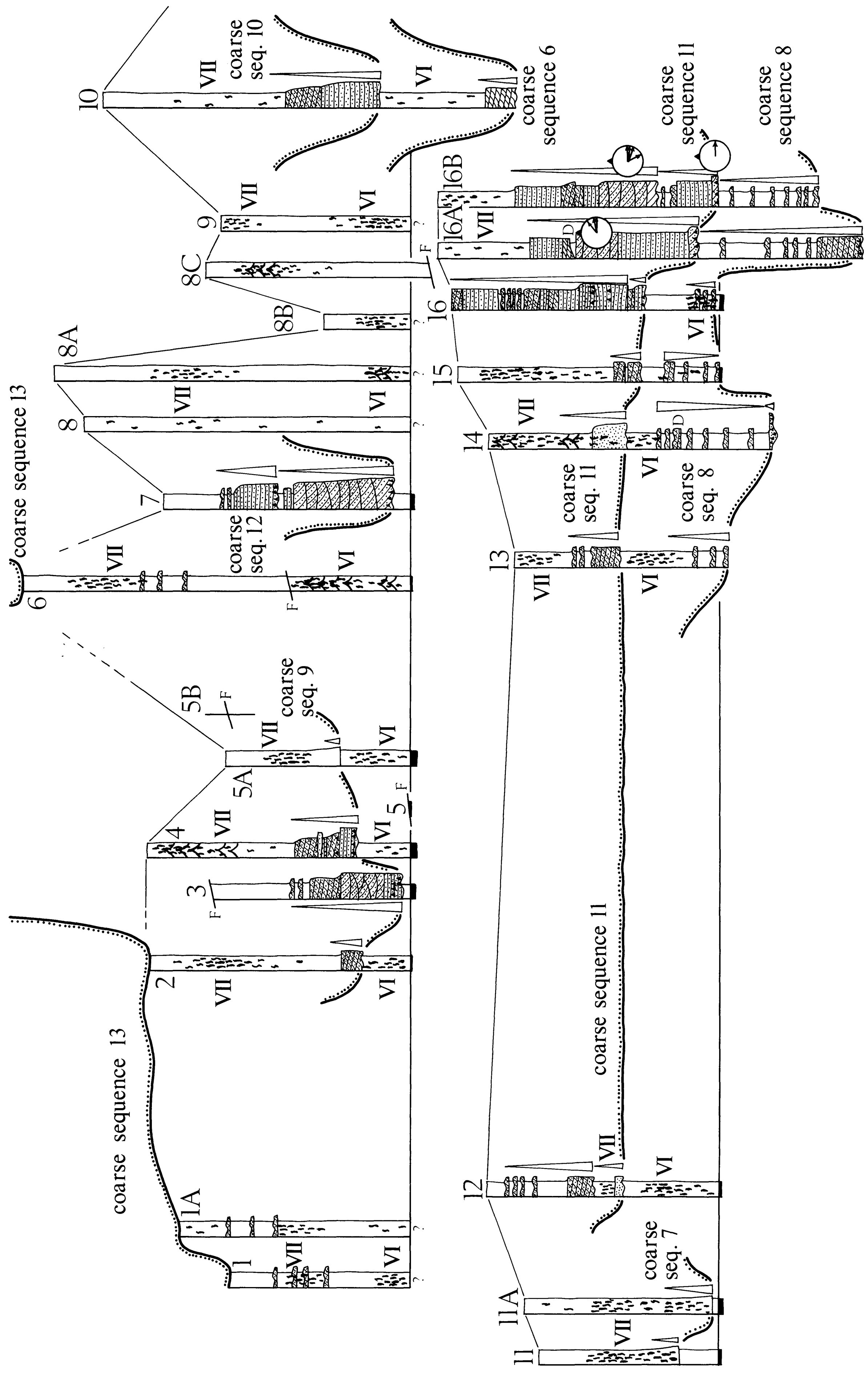
Sedimentological features of the alluvial suite.

Figure 1. Pseudoanticlines formed of interlaminated mudrock and calcite, calcrete VII, profile 11, East Pickard Bay (locality 11). Pencil gives scale.

Figure 2. Calcrete in vein form, calcrete VII, profile 11, East Pickard Bay (locality 11). Pencil gives scale.

Figure 3. Coarse sequence 13, Hook Vale (locality 2). The upper part of the upward-fining succession consists here of a large concave-up scour infilled from left to right (east to west) with cross-bedded sandstone. Hammer gives scale.

Figure 4. Thick mudstones with interbedded graded cross-laminated sandstones, coarse sequence 13, Musselwick Point (locality 4). Pencil gives scale.



coarse sequence 13
coarse sequence 13
coarse sequence 11
coarse seq. 12
coarse seq. 9
coarse seq. 10
coarse sequence 6
coarse sequence 11
coarse sequence 8
coarse seq. 11
coarse seq. 8
coarse seq. 7
1
1A
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3
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5
5A
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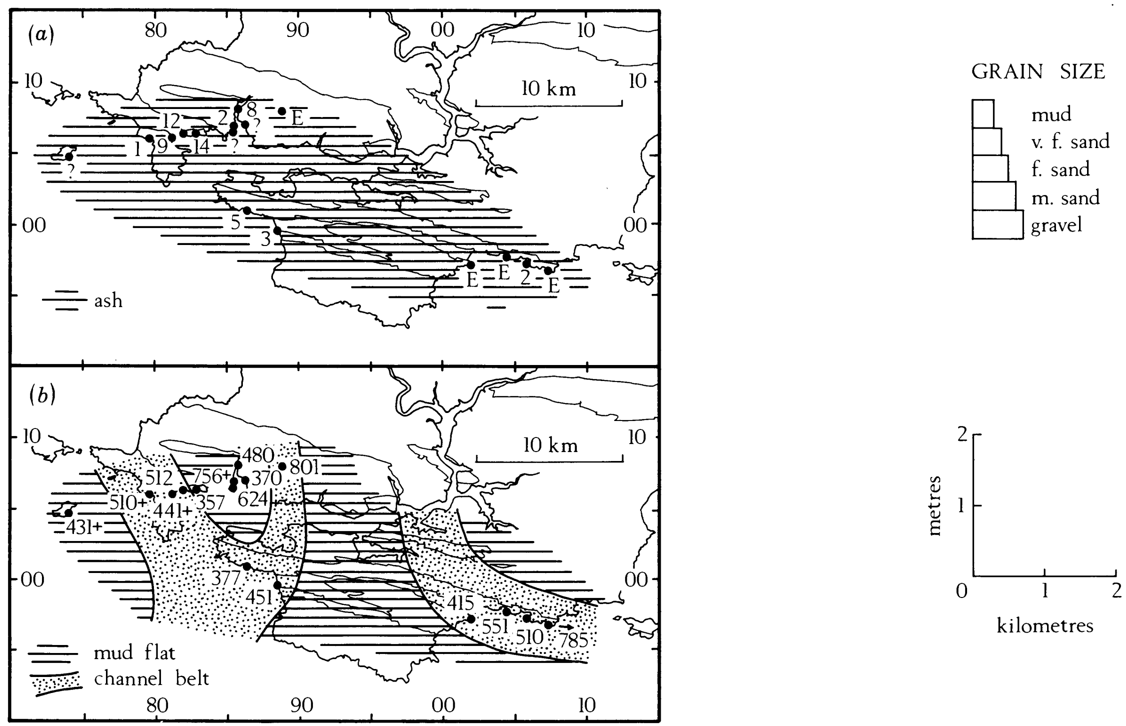

FIGURE 10. Summary of the internal stratigraphy and sedimentological features of the rocks from and including marker F up to marker G (interval F–G). (*a*) Thickness in centimetres of marker F. (*b*) Thickness in centimetres of the rocks in interval F–G, and an environmental interpretation. See figure 3 for key to symbols.

(*b*) *Deposits antedating calcrete VII: main facts*

This part of interval F–G is essentially a complex of coarse sequences of mainly local significance.

Coarse sequence 9, sited west-centrally (figure 10), is coarser and thicker at localities 3 and 4 than on its flanks at locality 2, where there is a thin very fine-grained sandstone, and in profile 5A, where a laminated very coarse mudstone appears. The sand stripes and bands at locality 1 to the west may be related to coarse sequence 9.

Coarse sequence 10 is restricted to locality 10 and consists of fine-grained parallel-laminated sandstones overlain by cross-laminated very fine-grained sandstone.

Coarse sequence 11 is widely distributed in the east and seems to reach into the centre of the area (figure 10). Like coarse sequence 8 below, it both coarsens and cuts down deeper eastward. Locally, two upward-fining successions are developed. A rare find of a single *Onchus* spine was made among the mudstone clasts at the base of the sequence in profile 16A. Sediment transport occurred in directions ranging between roughly northeast and southeast.

Calcrete VII is widely but variably developed in the thick massive locally burrowed mudstones capping coarse sequences 9–11 (figure 10). Calcite tubules and carbonate concretions range from scattered to abundant and locally there are pseudoanticlines.

Coarse sequence 12 (locality 7) is among the more substantial, and may postdate calcrete VII, for it underlies marker G but lacks a calcrete.

(*c*) *Interpretation*

The beds record a complex series of events extending over possibly as long a period as 22100 years (figure 10*b*).

The incision in the east which extensively cuts marker F and locally removes marker E still lower (localities 12–16) could have been formed during the regional growth of calcrete V in the upper part of the immediately preceding interval (figures 2, 10). The spreading aggradation of the incision by coarse sequence 8 led to the regional re-establishment of a featureless mudflat, on which channel activity remained localized. Calcrete VI bears witness to the cessation of deposition on these flats, possibly in response to a renewed lowering of sea level.

Coarse sequence 11 has a similar relation to calcrete VI as sequence 8 to calcrete V, except that no markers are cut. It too may record the infilling and eventual swamping of a shallow valley cut below a land surface that elsewhere was experiencing pedogenesis. The presence of sequences 8 and 11 in the same group of localities suggests either continuity of channel activity throughout the period of change implied by calcrete VI or the persistence of depressions, potentially exploitable by new drainage, from before the production of that calcrete. Coarse sequence 9 and 10 denote the presence of channel belts at other places on the mudflats implied by the rocks in the upper part of interval F–G. Mudflat-building ceased during the production of calcrete VII, when coarse sequence 12 may possibly have begun to form.

The salinity of the environment is uncertain, in the absence of direct faunal evidence. The coarse sequences resemble those formed earlier in the history of the alluvial suite and on comparative grounds could represent either river (see, for example: Harms & Fahnestock 1965; Shelton & Noble 1974) or tidal (see, for example: Meckel 1975; Barwis 1978) channels. The currents were generally sluggish during the growth of coarse sequence 8, to judge from the prevalence of cross-lamination and mud interbeds, but vigorous when coarse sequences 9, 10 and 11 were emplaced, as witnessed by the extensive development of parallel lamination and cross-bedding. Signs of lateral accretion are totally lacking, and the channels cannot have been of large sinuosity. The coarse massive mudstones, with their abundant burrows and general lack of evidence for desiccation, point to an extensive and uniform watery environment richly supplied with suspended and probably flocculated mud. The symmetrical ripple marks at locality 16 afford the only direct proofs of wave action. Their wavelength is small, however, and consistent with extensive but ponded very shallow waters, such as occur as commonly in river floodbasins as on intertidal mudflats.

12. Interval G–H (?6800 years)

(a) *Main facts*

These rocks are thickest in a north-central zone, showing some reduction westward and a drastic thinning toward the southeast (figure 11*b*). Dominating them is coarse sequence 13, distributed over the entire western sector (figures 2, 11).

In the centre and east of the area (localities 12–16), where coarse sequence 13 is lacking, interval G–H is represented by mainly coarse red massive mudstones locally with laminations (figure 11). Coarse sequence 14, of interbedded mudstones and sandstones, marks a distinct coarsening of these monotonously fine-grained deposits.

Coarse sequence 13 involves two probably intergrading kinds of sandy development, distinguished on the basis of overall thickness and sedimentary structures and grade (figure 11). A similar dual development is less clearly distinguishable in intervals E–F and F–G below (figures 9, 10).

One kind consists of an upward-fining and erosively based succession of cross-bedded and/or parallel-laminated sandstones, typically of fine grade (plate 5, figure 3). Generally only the uppermost parts of these sandstone bodies reveal cross-laminated very fine-grained sandstones and burrowed (?root-channelled) mudstone interbeds. This type of sandy development marks sequence 13 at localities 2, 9 and 10 and in profile 5A, as well as the upper part at locality 4. The cross-bedding points to almost diametrically opposed currents on broadly southwest–north paths.

The second, finer-grained, and generally thinner kind of sandy development marks coarse sequence 13 at localities 1, 6, 8 and 11, and low down at locality 4 (figure 11). It is represented by upward-fining successions of, in most places, interbedded very fine-grained sandstones and massive red mudstones. The lowermost sandstone bed, resting sharply on an erosional surface, may be as much as 1 m thick, to be followed by mudstones and sharp-based normally graded cross-laminated sandstones interbedded on a centimetre to decimetre scale (plate 5, figure 4). Locally, there is no thick basal sandstone.

Calcrete VIII appears in places within coarse sequence 13 but is mainly developed in the overlying or laterally equivalent mudstones. It is highly variable, ranging from calcite tubules sparsely accompanied by small concretions to a short profile with abundant concretions and tubules. Locally the calcrete is absent.

(b) *Interpretation*

An interval of perhaps only 6800 years is recorded, during which deposition on an extensive mudflat was again resumed, following the termination of the conditions that led to calcrete VII.

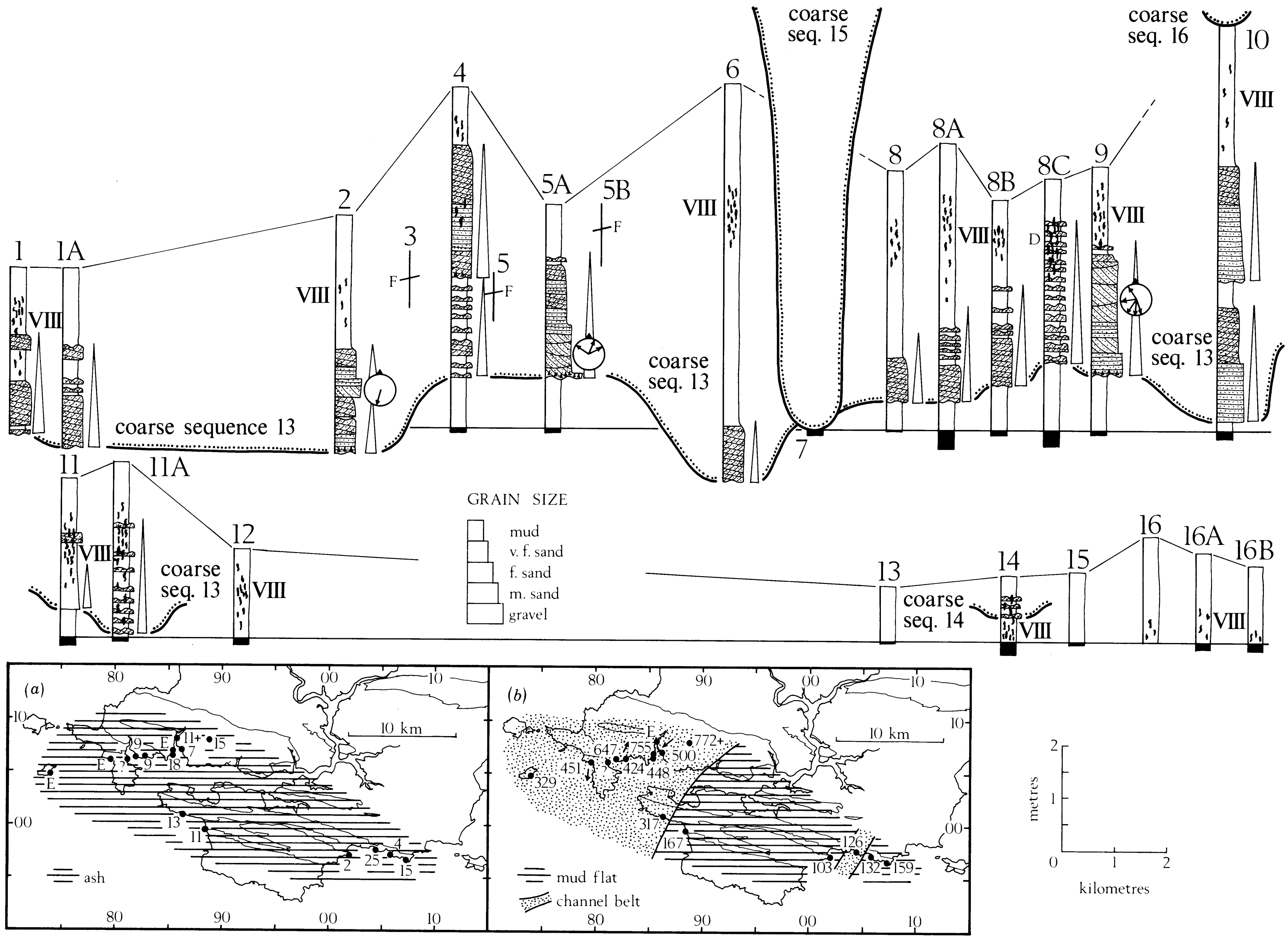

FIGURE 11. Summary of the internal stratigraphy and sedimentological features of the rocks from and including marker G up to marker H (Pickard Bay Tuff Bed) (interval G–H). (a) Thickness in centimetres of marker G. (b) Thickness in centimetres of the rocks in interval G–H, with an environmental interpretation. See figure 3 for key to symbols.

Channel activity dominated the west (see figure 11*b*). Probably a cluster of shifting channel belts was present, to judge from the vertically and horizontally dispersed occurrence of the coarser and thicker sandy developments (see figure 11). The thinner and finer-grained sandstone bodies appear to record sites somewhat remote from the principal effluents. Were those sites fed by distributaries that split off from the main rivers, or were they reached through dendritic alternately distributary and contributary tidally influenced channels such as stem from fluvial effluents where they cross tidal flats today? Tidal influences cannot be excluded, in view of the almost diametrically opposed (but admittedly few) palaeocurrents measured. Little coarse sediment reached the southeastern part of the area, where the mudstones are substantially thinner than the mixed deposits in the west. The massive quality of the mudstones, and the lack of desiccation cracks despite the frequent supplies of sand, point to a watery environment. Calcrete VIII records another return to soil-forming conditions, perhaps in response to a change of sea level.

13. Coarse sequences linked to marker H

The Pickard Bay Tuff Bed (marker H) is closely associated with two coarse sequences, most of the fallen ash apparently having survived current reworking (figure 12).

Coarse sequence 15 lies erosively on marker G and consists of two upward-fining successions, in the higher of which marker H is an ashy sandstone overlain by dust tuffs and laminated very fine-grained crystal tuffs. Coarse sequence 16, which postdates calcrete VIII, in its upper part includes interbedded ashy sandstones, muddy tuffs, and dust tuffs streaked with ashy sandstone.

These sequences point to the continuation or repetition of channel activity in the general vicinity of coarse sequence 13. Away from the channels, where marker H rests on mudstones, there were extensive watery mudflats abounding in organisms, to judge from the faecal debris smothered by the marker (localities 8, 9, 11 and 16) and the local occurrence (profile 11A) of bedding-surface piercements suggestive of *B. antarcticus* (Allen & Williams 1981).

14. Concluding discussion

The alluvial suite contained between the Townsend Tuff and Pickard Bay Tuff Beds is but 15–30 m thick yet falls on the basis of marker ash falls into seven intervals traceable over an area measuring approximately 12 km by 35 km. A period of 65000 years may have been the most that was necessary for its accumulation, if one assumes a constant deposition rate over the formation containing the suite. The architecture of the alluvial suite is accessible in unusual detail.

The suite contains eight calcretes, all but one of which is developed over practically the entire area. These closely resemble calcretes developed elsewhere in the Lower Old Red Sandstone, which Allen (1974) on comparative grounds interprets as pedogenic and implying a subtropical setting and a warm semi-arid climate. Even if the calcretes are non-pedogenic, that is, of the groundwater variety (see, for example, Mann & Horwitz 1979), which is unlikely in view of their profile characteristics, the climatic implication is the same, as is their implication that a vadose zone was for a substantial period established in the uppermost few decimetres or metres of the sediment. The sedimentary surface itself during these periods received little fresh sediment (Allen 1974; Leeder 1975) and would have been subjected to atmospheric weathering and probably slight erosion. Emergence into the vadose zone occurred on the average perhaps every 8000 years during the accumulation of the suite.

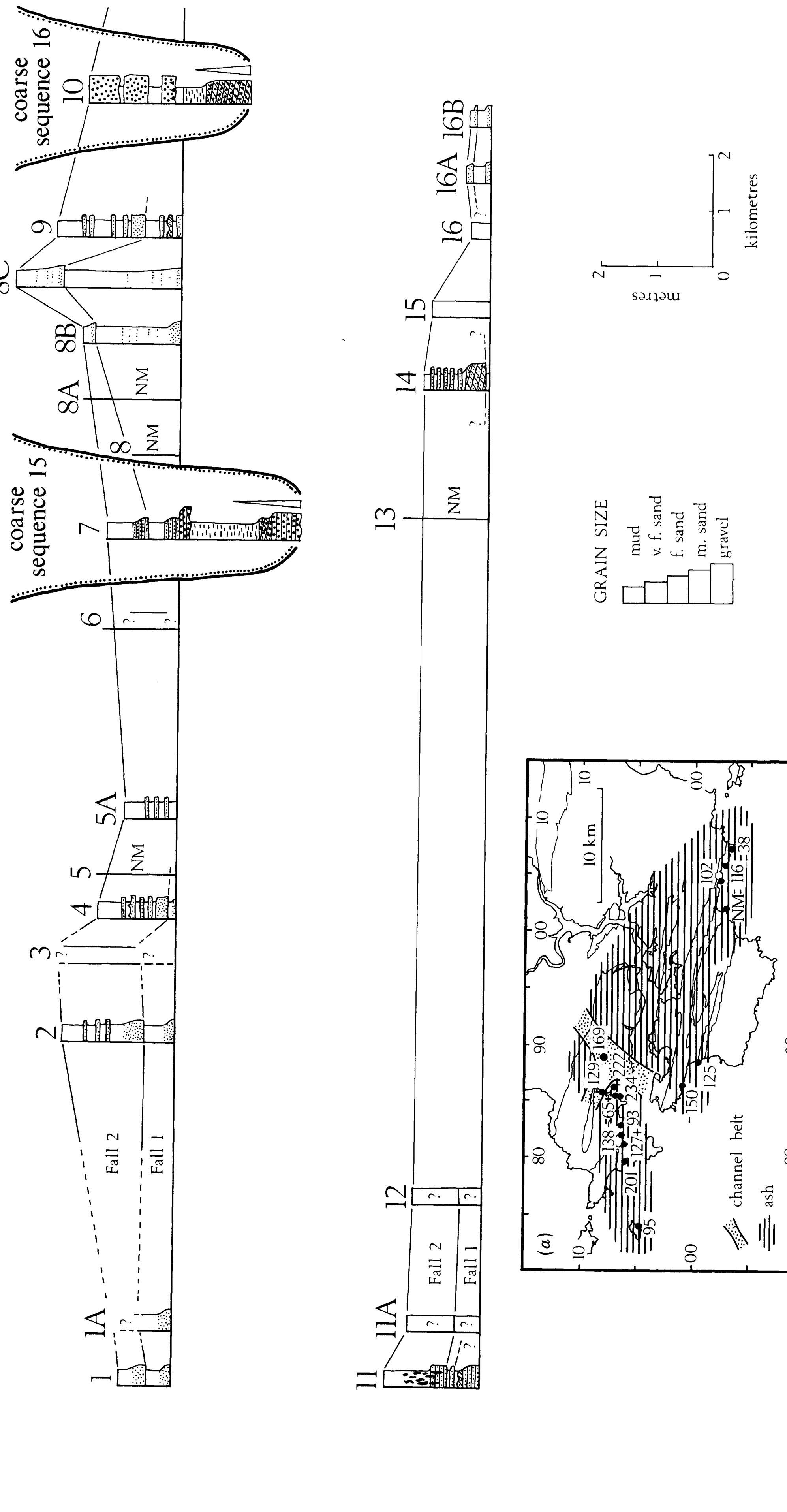

FIGURE 12. Summary of the internal stratigraphy and sedimentological features of marker H (Pickard Bay Tuff Bed) and the channel-belt coarse sequences with which it is associated. (*a*) Thickness in centimetres of the Pickard Bay Tuff Bed and its associated channel-belt coarse sequences, with an environmental interpretation. See figure 3 for key to symbols.

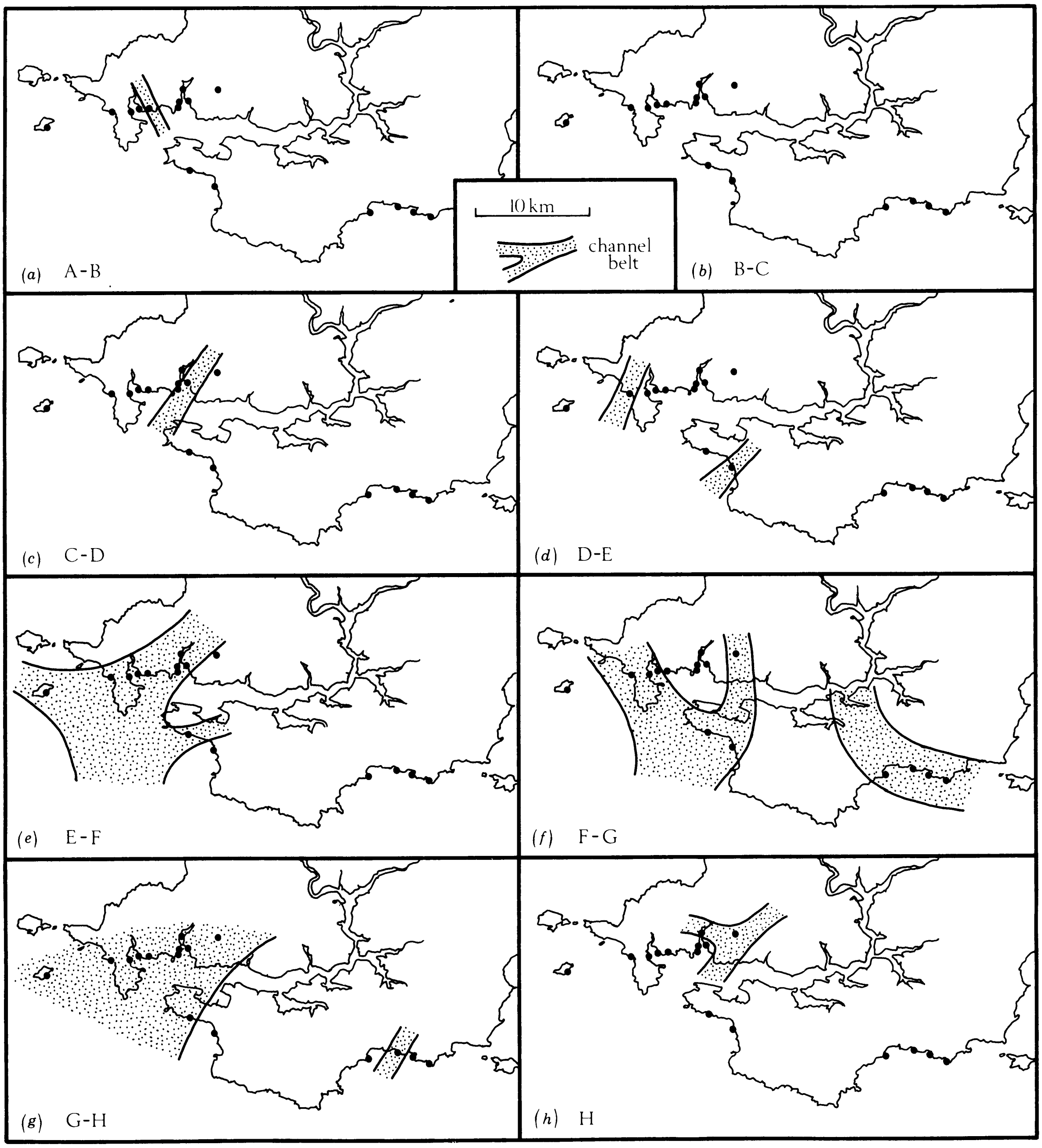

FIGURE 13. Summary of the inferred succession of channel belts within the period of time (?65000 years) represented by the alluvial suite contained between the Townsend Tuff and Pickard Bay Tuff Beds.

Between episodes of calcretization, the area was the site of extensive and virtually featureless watery mudflats traversed by generally sparse channel belts. The mudstones deposited on these flats are coarse and massive, generally lacking internal lamination. The burrows (?root channels) extensively preserved in them, together with the smothered faeces-strewn surfaces preserved beneath some of the tuffs, hint at the soft well watered nature of the flats and suggest that the mudstones owe their massive quality primarily to organic destratification.

The tracing out of beds between markers leaves no doubt as to the laterally restricted nature of the coarse sequences interpreted as channel-belt deposits, as summarized in figure 13. There seem to be two main sorts. Coarse sequences such as 2 and 9 (figure 2) are rather local and probably record channel belts established during and active within periods of upbuilding of the mudflats. Hence they could have contributed to that upbuilding. Sequence 13, apparently also of this type, is by contrast relatively extensive and heterogeneous, and so may represent more than one main effluent. Sequences of this sort are of the order of 2 m thick and scour down little. In sharp contrast is sequence 5, which cuts down many metres through several marker tuffs, spreading over about half the area, and including sandstone bodies up to 4 m thick. Their thickness is only about one-half the inferred depth of incision, however, which suggests that the sequence infills and ultimately spreads away from a valley system incised into older mudflat and channel-belt deposits. The less deeply cut sequences 8 and 11 may have a similar origin. Their close association despite an intervening calcrete suggests that channel belts could persist from one episode of mudflat-upbuilding to the next. Mudstone is so prevalent between the Townsend Tuff and Pickard Bay Tuff Beds that contacts and even near approaches between coarse sequences are likely to be very rare. There are nonetheless some indications of the avoidance of older coarse sequences by younger ones, as required by models of alluvial architecture (Allen 1978; Bridge & Leeder 1979). Thus sequences 8 and 11 occur in the east, while sequence 5, largely avoiding sequence 2, and sequence 13 are restricted to the west.

In summary, a long-lived vadose zone was established many times during the upbuilding of a watery mudflat crossed by sparse channel belts, a few of which persisted from one episode of upbuilding to another.

The possible controls on this pattern, most of which Allen (1974) lists, are (i) channel diversion, (ii) climatic change leading to a changed sediment and aqueous channel discharges, (iii) change of sea level or other base level (e.g. lake level), and (iv) tectonism, which may act through its effect on either discharges or base level (or both). Whereas the first of these is an autocyclic or intrinsic factor, the others are extrinsic or allocyclic (Beerbower 1964).

The environmental setting of the alluvial suite, a series of river-influenced transitional mudflats ranging from supratidal and possibly non-tidal through intertidal to possibly subtidal, is suggested as much on general as on specific grounds. The suite occurs in a mud-dominated succession lying stratigraphically in the transition from the undoubtedly marine lingulid facies toward the base of the Sandy Haven Formation and equivalent rocks, up to the unquestionably fluviatile Gelliswick Bay Formation and correlative strata, with their frequent upward-fining sequences and close similarity to modern fluvial deposits (Dixon 1921; Allen 1963; Allen & Williams 1978, 1979). An environment like a tidal flat, in which strong currents can occur repeatedly and widely, is also implied by the character of the Townsend Tuff Bed, which the Pickard Bay Tuff Bed described here closely resembles. The sand-grade ashes in these markers contain a wide variety of high-energy sedimentary structures (figures 4, 12), strongly suggesting that the area was a mudflat only because it was denied *terrigenous* sand (Allen & Williams 1981). A further implication of the high-energy structures preserved in markers A and H is that the régime was mesotidal if not macrotidal, for it seems unlikely that tidal currents of the required strength could have arisen under microtidal conditions. We imagine that the tidal range was measured in metres and the tidal currents in at least decimetres per second. In this kind of high-energy setting, richly supplied with fine-grained material but ordinarily denied the coarse grades, relative changes of sea level by a matter of metres seem to us to provide the simplest means of accounting for the widely developed calcretes and the apparent incision of some of the coarse sequences we describe.

The direct evidence for tidal influences, mainly the variability of sandstone palaeocurrents, is admittedly weak and therefore it would be wise to consider other possible settings. A lacustrine environment similar to Lake Rudolf in the Rudolf Basin (east Africa) has some attractions (Butzer 1971). The level of this shallow lake has fluctuated considerably in response to climatic and other changes on time scales ranging from hundreds to tens of thousands of years. Sandy channel belts and deltas have been incised and built forward over the former lake floor with each lowering. A rise in lake level has resulted in the transgression of these environments, the aggradation of former river valleys, and the renewal of widespread mud deposition over areas that for a time experienced pedogenesis. Two defects are nevertheless apparent. One shared by our tidally influenced mudflats is the comparative lack of evidence for wave action, unless it be argued that organic destratification of the mudstones has resulted in its total elimination. The other is the scarcity in the alluvial suite of upward-coarsening sequences indicative of prograding delta distributaries. If neither the tidal nor the lacustrine setting is accepted, and a distal fluvial model remote from any marine influence is preferred, severe climatic change and/or repeated avulsion seem to become the only acceptable ways of explaining the calcretes that we find to be so widespread. There then remains the overriding difficulty of accounting for the pervasive strong currents revealed by each chance introduction of air-borne sand-grade ash.

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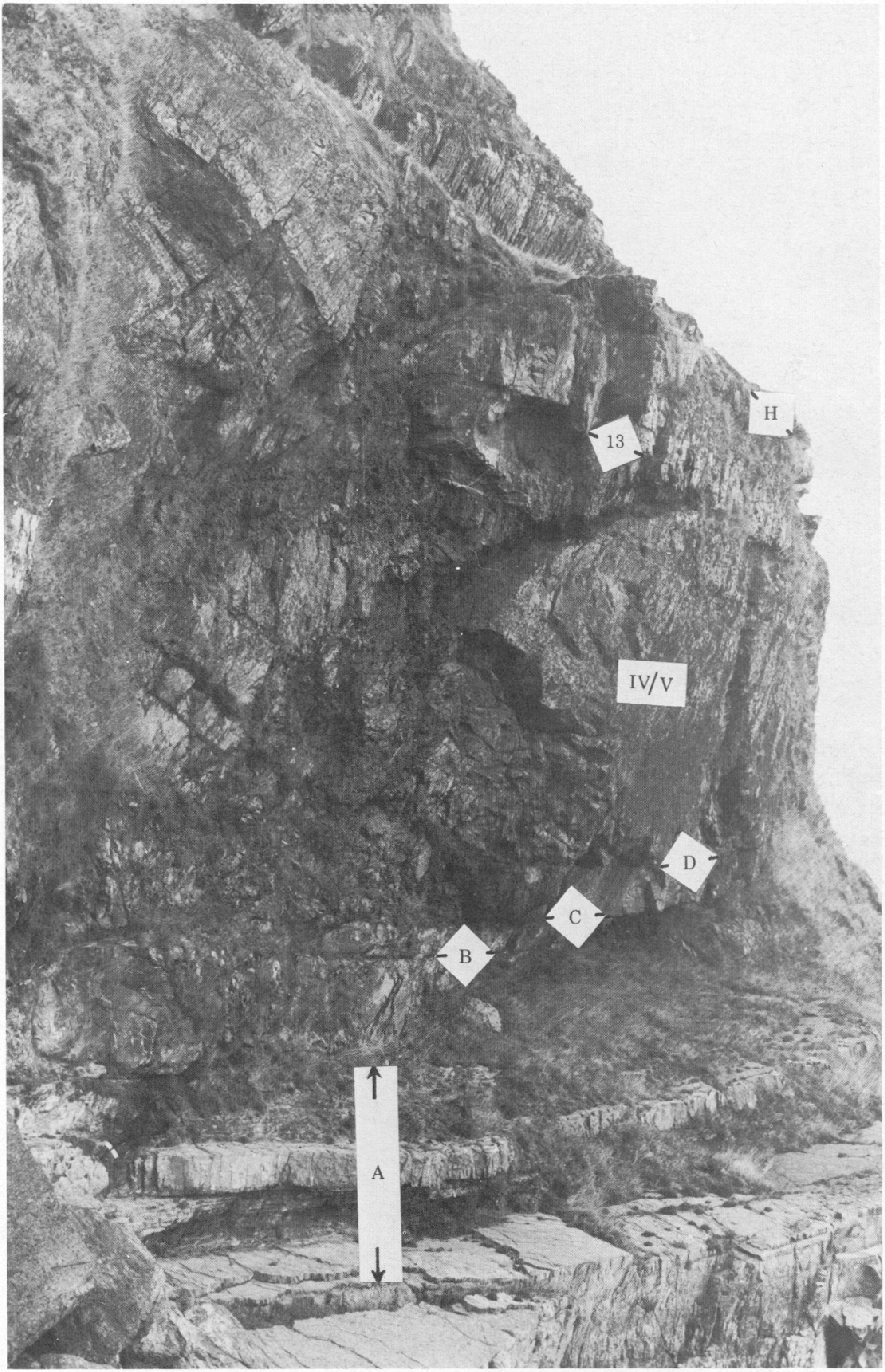

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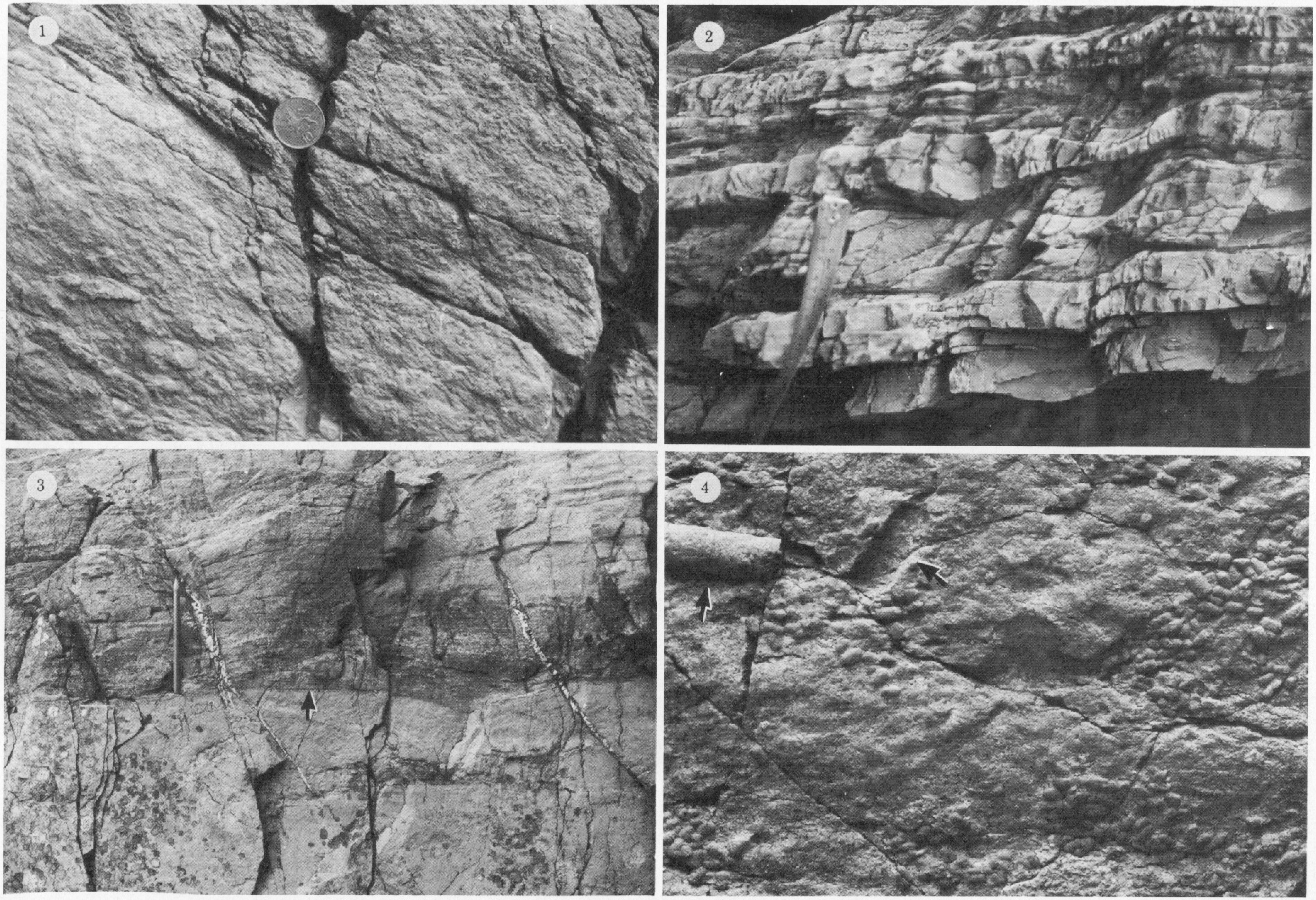

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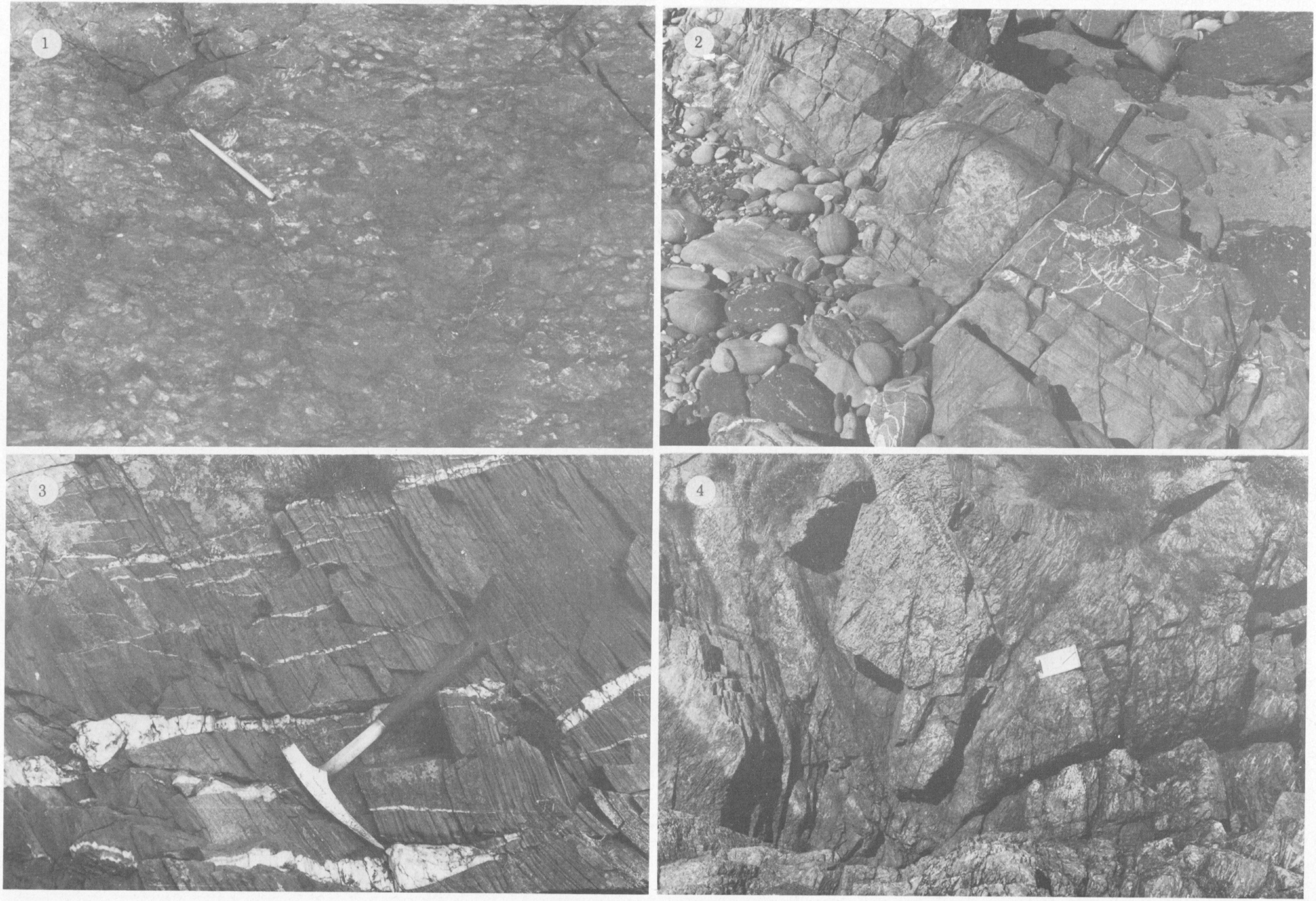

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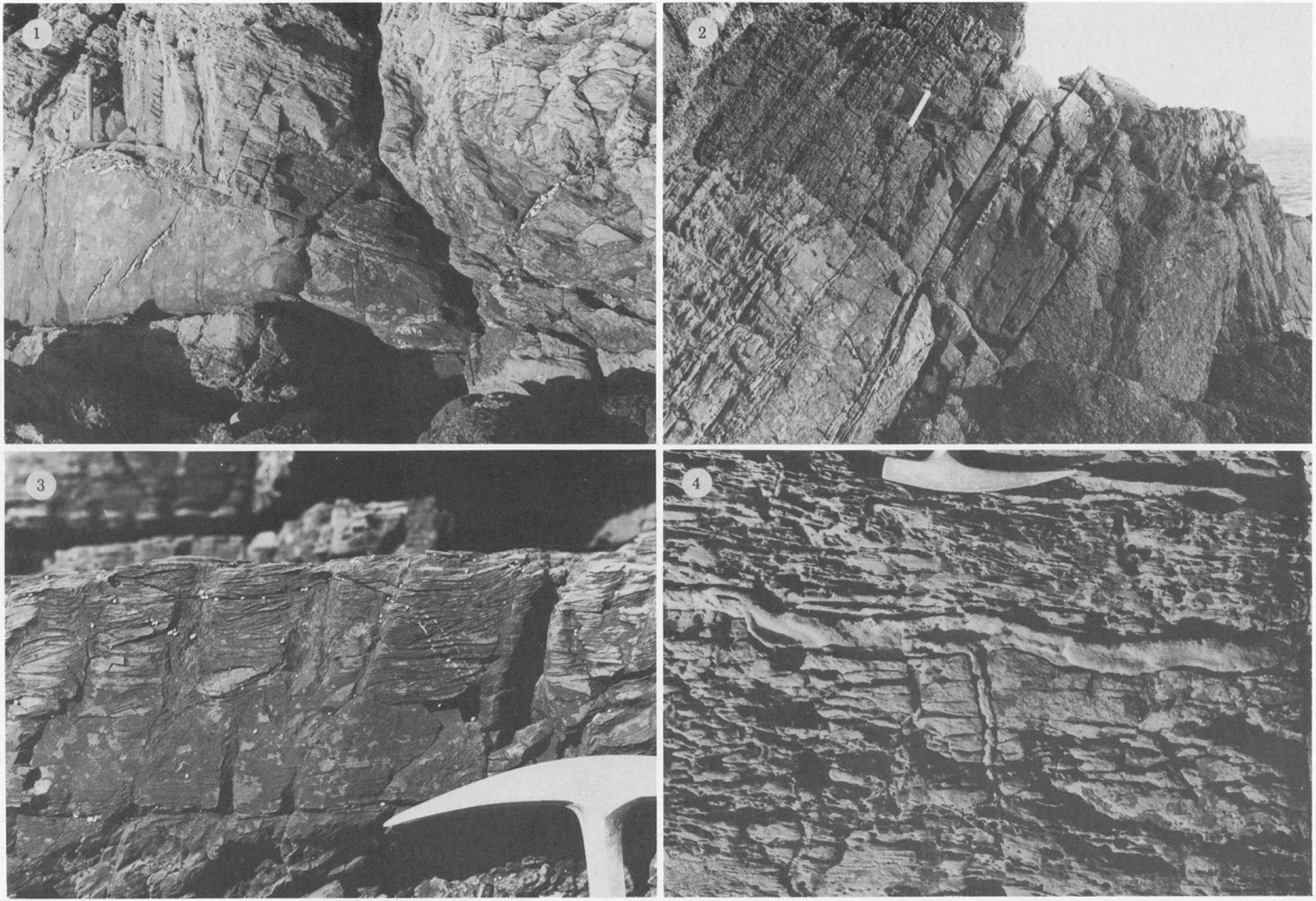

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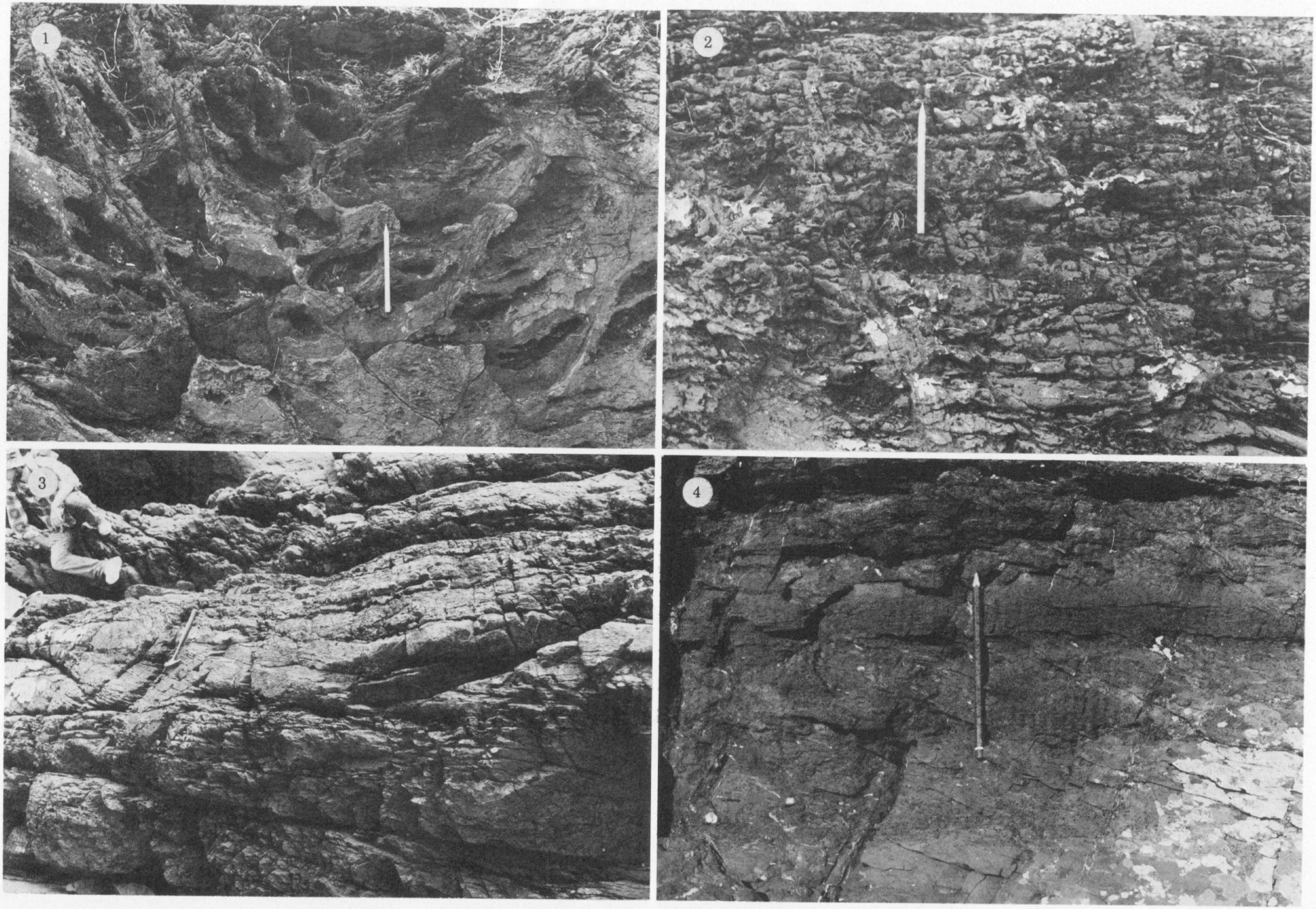

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