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Volcaniclastic sediments, process interaction and depositional setting of the Mio–Pliocene Miura Group, SE Japan

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Volcaniclastic sediments, process interaction and depositional setting of the Mio–Pliocene Miura Group, SE Japan

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Abstract

The Mid-Miocene to Early Pliocene (14–3 Ma) Miura Group exposed on the Miura and Boso peninsulas around Tokyo Bay in southern Honshu comprises at least a 2 km thick succession of volcaniclastic sediments. These accumulated in a forearc basin or basins on the eastern side of a proto Izu–Bonin arc prior to and during accretion of the Miura block onto the Honshu arc and its subsequent dextral transcurrent extension. The basin fill shows a complex admixture of facies that result from multiple processes, which operated on a relatively shallow-slope basin. The main facies groups include dark-coloured, mostly coarse-grained scoriaceous beds; pale-coloured, muddy–silty pumiceous bioturbated sediment; yellowish and whitish-coloured tuffaceous horizons; and chaotic slump, debris flow and injection units. Many of the facies and beds in the older Misaki Formation can be readily interpreted as the result of: (a) direct pyroclastic fall through the air and water; (b) downslope resedimentation via turbidity currents and related processes, in some cases derived from subaqueous base-surge pyroclastic flow or vertical density currents; (c) hemipelagic settling, commonly under the influence of thermohaline bottom currents. In other cases, composite beds are believed to result from the interaction of these processes in more complex events. The younger Hasse Formation is dominated by more shallow-water, marine-currents and storm events and in parts, by fluvial or proximal fan-delta processes. The distribution of these different facies illustrates the evolution and shallowing of the Miura–Boso forearc basins during accretion and emplacement. © 1998 Elsevier Science B.V. All rights reserved.

Keywords: volcaniclastic; turbidites; contourites; Miocene; Japan

1. Introduction

Volcaniclastic, clastic and biogenic sediments of the Miocene to Pliocene Miura Group are present

over much of their Miura and Boso peninsulas adjacent to Tokyo Bay in SE Honshu (Figs. 1 and 2). They are particularly well exposed and their sedimentary characteristics well preserved in coastal areas around the southern parts of both peninsulas, despite extensive deformation associated with their emplacement.

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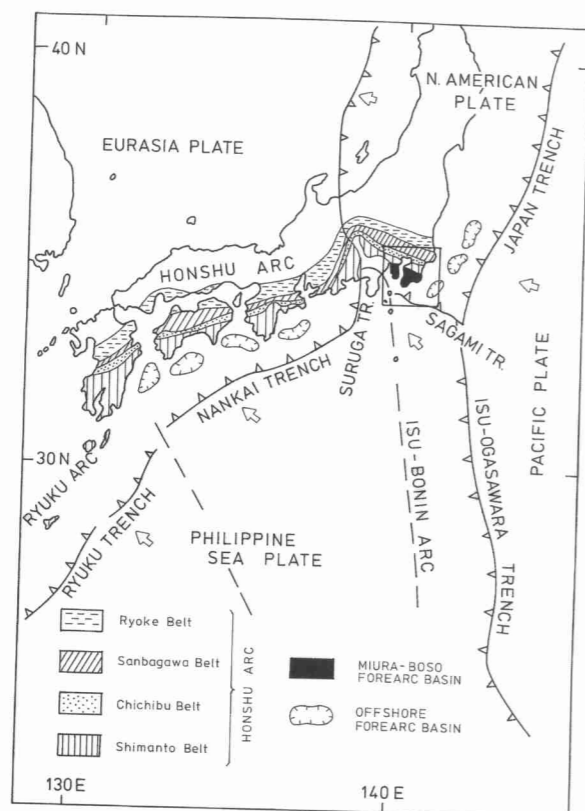


Fig. 1. Regional plate tectonic setting of the Miura-Boso basin. Boxed area is shown in Fig. 2.

The Miura Group represents a shallowing-upward succession deposited over a period of some 11 m.y. (approximately 13 Ma to 2.5 Ma) from the Mid-Miocene to Late Pliocene. Accumulation took place in the forearc to trough region of the arc-arc collision zone between the Izu-Bonin Arc on the Philippine Sea Plate and the Honshu Arc of mainland Japan (Soh et al., 1990).

In this paper, we aim to document in detail the nature and distribution of the wide range of facies that occur in the Miura Group, following extensive fieldwork, careful section logging and subsequent laboratory work, over a period of several years. These facies demonstrate an intriguing and complex interaction of deep-water processes (mass flow, turbidity currents, bottom currents and hemipelagic sedimentation), shallow-water processes (tidal and wave reworking), fan-delta and pyroclastic processes, during basin evolution.

Previous work in this interdisciplinary collaborative study has been published by Ogawa and Taniguchi (1988), Soh et al. (1989, 1990), Pickering et al. (1990, 1993) and reported by Stow et al. (1990) and Stow and Faugères (1990).

2. Geological setting

The general geology of the Miura Peninsula (Akamine et al., 1956; Koike, 1957) and Boso Peninsula (Koike, 1957; Mitsunashi et al., 1976) are well known. Combining this information with offshore geological mapping, Kimura (1977) presented one of the first plate tectonic models of the region, in which it was inferred that the Miura Group volcanics were derived from volcanic banks located offshore west of the peninsulas. Subsequently, other regional syntheses have added to or refined this model (Ogawa and Horiuchi, 1978; Matsuda, 1978; Niitsuma, 1988; Soh et al., 1990). The latest data support the concept of continued collision between the Honshu and Izu-Bonin arcs in the Izu Collision Zone and the accretion of the Miura Group from the Izu-Bonin Arc onto the Honshu Arc at about 2 Ma (Ogawa and Taniguchi, 1988; Soh et al., 1990). This accretion, most probably involving considerable dextral oblique-slip motion, followed the collision of the Izu block with mainland Honshu and the plate boundary jump to its present position in the Sagami Trough south of Miura (Taira et al., 1982; Taira and Ogawa, 1991). In this scenario the Miura Group originated as part of the forearc system formed during the Middle Miocene to Pliocene.

Although the general age of the Miura Group sediment is known from palaeontological and palaeomagnetic studies (Koike, 1957; Niitsuma, 1976; Tsuchi et al., 1981; Kodema et al., 1983; Yamaguchi et al., 1983; Eto, 1986) together with limited fission track ages, detailed correlation between different outcrops is not yet possible. Recent studies of tephrochronology within the Miura Group have had some success (Mitsunashi et al., 1976; Taniguchi and Ogawa, 1985; Eto et al., 1987), particularly using the trace-element geochemical signatures of different tuff horizons. Although precise correlation between the Miura and Boso peninsulas is not yet possible, we prefer to use the simplified stratigraphy of Soh et al. (1990) for both areas (Fig. 3). Thus the Hasse

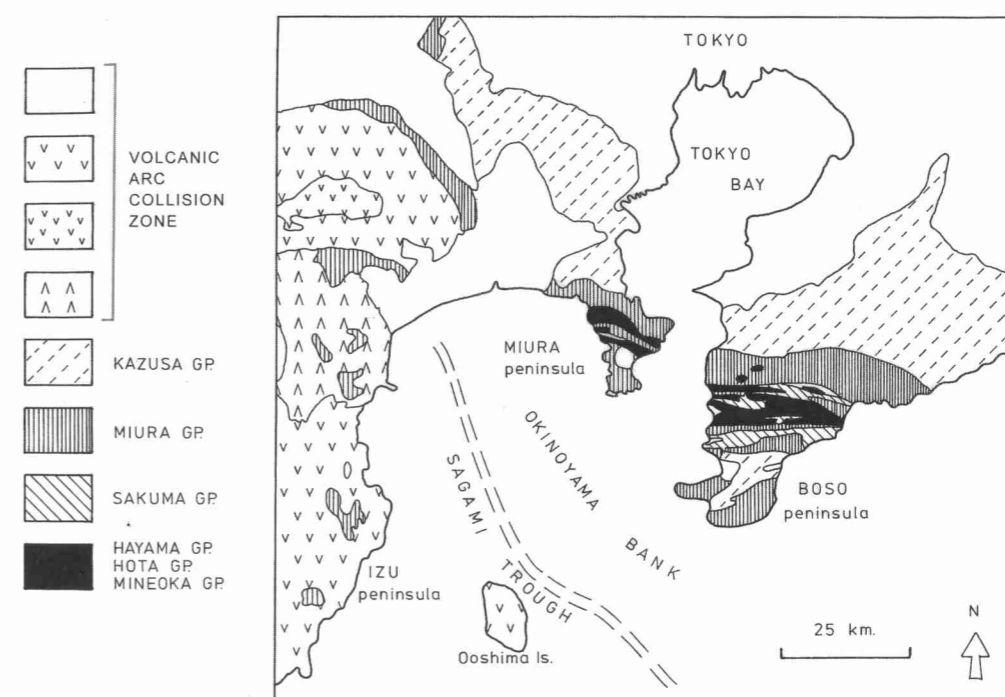


Fig. 2. Generalised geological map of the Miura-Boso peninsulas and adjacent area.

Formation (Late Pliocene) unconformably overlies the thicker Misaki Formation (Mid-Miocene–Early Pliocene), these formations being approximately equivalent to the Nishizaki and Chikura formations formerly used in the Boso Peninsula.

Structural deformation of the area has most recently been documented by Ogawa (1978, 1980), Kodema et al. (1983), and Pickering et al. (1990, 1993). There is a very complex pattern of folds and minor faults set within a dominant W-E tectonic fabric and secondary NW-SE and SW-NE trends. Wet-sediment deformation, including abundant sediment injections and veining, is ubiquitous. Common bedding-parallel and subparallel thrusts have resulted in considerable section duplication so that calculation of the original stratigraphic thicknesses is difficult. The current estimates of formation thicknesses are shown in Fig. 3, but we believe now that these may be between 1.5 and 3 times greater than the original values.

3. Misaki Formation

The Misaki Formation in the southern part of the Miura Peninsula has been measured at over 850 m in thickness, but its basal contact with the Takeyama Formation is not exposed so that its total thickness is not known. Its contact with the overlying Hasse Formation is unconformable in parts but apparently conformable in some of the sections measured. In southern Boso, the Misaki Formation has been measured in excess of 2000 m in thickness and displays apparently conformable lower and upper contacts.

Six main facies groups are recognised, represented by scoriaceous (coarse, medium and composite), pumiceous, tuffaceous and chaotic sediments. However, the wide variety of features evident necessitate further subdivision of these groups into 22 individual facies on the basis of differences in sedimentary structures, textures and composition (Table 1). We summarise below the main characteristics of each of these facies, using a letter code A-F (for facies groups) that is specific to this formation. Individual facies are coded A1, A2, etc., for convenience (Table 1). Depo-

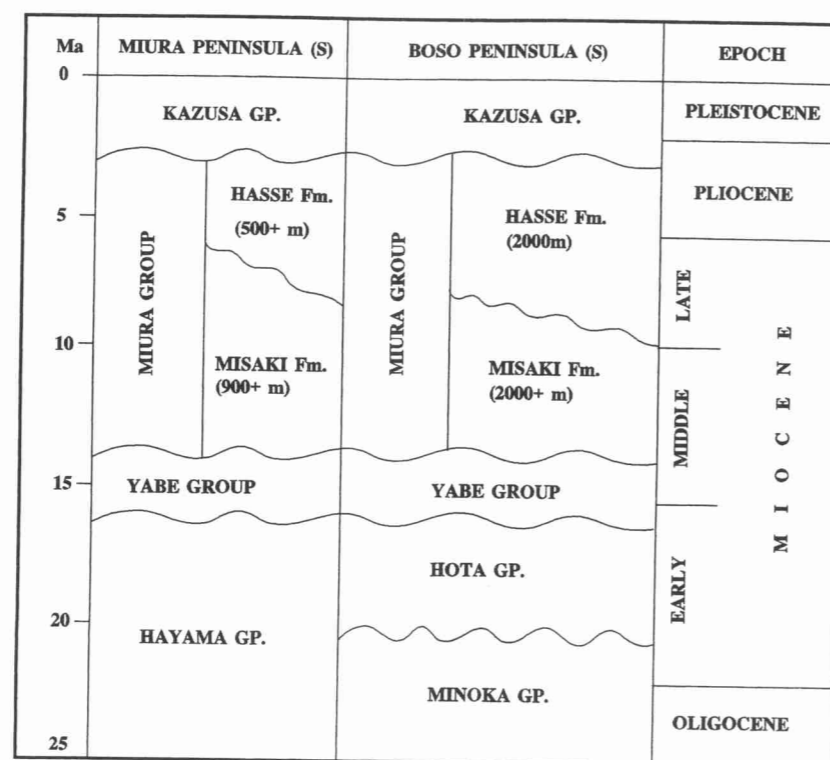


Fig. 3. Summary stratigraphy for the Miura-Boso area.

sitioned processes responsible for their deposition are discussed in the following section.

3.1. Coarse-grained scoriaceous beds

A wide variety of dark greenish, brownish and black-coloured beds composed dominantly of scoria grains and clasts (i.e. dark-coloured lava fragments of basic through intermediate composition) occur throughout the Misaki Formation. These are the 'lapilli beds' of Soh et al. (1990). They make up between about 5% and 45% (more commonly 10%–20%) of any given 100 m section. We have subdivided them on the basis of grain size into three facies groups: (A) conglomerates/pebbly sandstones, (B) sandstones, and (C) composite beds (with complex grading). Both the coarse and medium fine-grained scoria are typically blocky and equant in shape, with subangular to subrounded form. Scoria beds are mostly grain-supported and have four main grain or clast types: dull black and green-black vesic-

ular material (commonly dominant), dull reddish and brownish vesicular material (minor), yellowish, whitish and greyish powdery material (mostly minor, rarely co-dominant), and isolated, typically larger, highly vesicular pumiceous fragments. The matrix is composed mainly of glass and highly altered glass and vitric ash. The dark scoria are typically of low-alkali tholeiite series basaltic andesite, with geochemical characteristics similar to the modern Izu-Oshima Island volcanics (Soh et al., 1990).

3.1.1. Facies A. Scoria conglomerates and pebbly sandstones

Thick-bedded, coarse-grained scoria beds (Facies A1, A2) (Fig. 4) range from 30 cm to over 3 m in thickness, although in the thicker units some amalgamation of beds is locally evident. They are typically parallel-sided or with a slightly irregular loaded and scoured base; more rarely erosional scours of up to 1 m deep have been observed and distinctly lenticular bedforms can occur as the result of dune bedform

Table 1
Misaki Formation: principal facies and process interpretation

Facies Group	Principal Facies	Process Interpretation
Facies Group A	Scoriaceous conglomerates and pebbly sandstones	Turbidites and pyroclastic fall deposits
A1	thick-bedded, structureless	turbidity currents dominant ± pyroclastic fall
A2	thick-bedded, laminated	
A3	thin- to medium-bedded, structureless	
A4	thin- to medium-bedded, laminated	
A5	dispersed beds or horizons	pyroclastic fall
Facies Group B	Scoriaceous sandstones	Turbidites and pyroclastic fall deposits
B1	structureless	turbidity currents dominant ± pyroclastic fall
B2	laminated, ± graded	
B3	dispersed beds or horizons	pyroclastic fall
Facies Group C	Composite scoriaceous beds	Turbidites, debrites and pyroclastic deposits
C1	turbidites	turbidity currents
C2	tripartite units	turbidity currents, debris flow and pyroclastic (flow) fall processes
C3	complex graded units	
Facies Group D	Pumiceous mudstones and siltstones	Hemipelagites and contourites
D1	sandy silty, bioturbated mudstone	hemipelagic processes dominant ± bottom current activity
D2	fine silty, bioturbated mudstone	
D3	laminated or structureless siltstone	
Facies Group E	Tuffaceous beds	Turbidites ± pyroclastic fall deposits
E1	thin-bedded, white, tuffaceous mudstones	pyroclastic fall/fine-grained turbidity currents
E2	thin- to medium-bedded, pale tuffaceous turbidites	turbidity currents dominant
E3	thin- to medium-bedded, speckled sandy tuffs	
Facies Group F	Disturbed and chaotic strata	Slumps, debrites and injection units
F1	contorted and slump-folded units (<2 m)	slumping
F2	contorted/slumped units with clasts (<20 m)	sliding, slumping, debris flow ± injection
F3	chaotic horizons	wet-sediment injection dominant
F4	injected scoriaceous sandstones	
F5	injected/debitric scoriaceous/pumiceous units	

migration. Beds may be completely structureless or show normal, reverse-to-normal and multiple distribution grading. Alternatively they can display poor to well-developed internal parallel and/or cross-lamination, the latter occurring in trough cross-sets of up to 1 m in height.

Structureless, graded and parallel or cross-laminated coarse-grained scoria occurs in thin to medium beds (3–30 cm thick) (Facies A3, A4). Scoria grains and clasts also occur in more dispersed beds or horizons (Facies A5) within the siltstone–mudstone facies. These layers range from very thin (<3 cm) to medium-bedded (15 cm) and have highly irregular shapes. Highly dispersed and moderately dispersed scoria layers can be recognised, together with crude normal grading in some of the less dispersed layers.

A complete range of grain sizes can be observed, from 10% granules in coarse sands to conglomerates

with a mean grain size of about 1–2 cm and a maximum clast size of several tens of centimetres. They are commonly poorly to very poorly sorted but some examples display moderately good sorting. Coarser clast sizes are mostly but not always associated with the thicker beds.

3.1.2. Facies B. Scoria sandstones

Scoria beds with dominant sand-size grains are completely gradational from the coarse-grained A-group facies (Fig. 5) (described above). They tend to occur as medium to thick beds (i.e. up to about 50 cm), that are parallel-sided or with more irregular loaded and scoured bases. Normal and/or reverse grading is common as is parallel and cross-lamination (Facies B2), although in some parts thin structureless scoria beds are the norm (Facies B1). Dispersed scoria sands (Facies B3) are typical within the

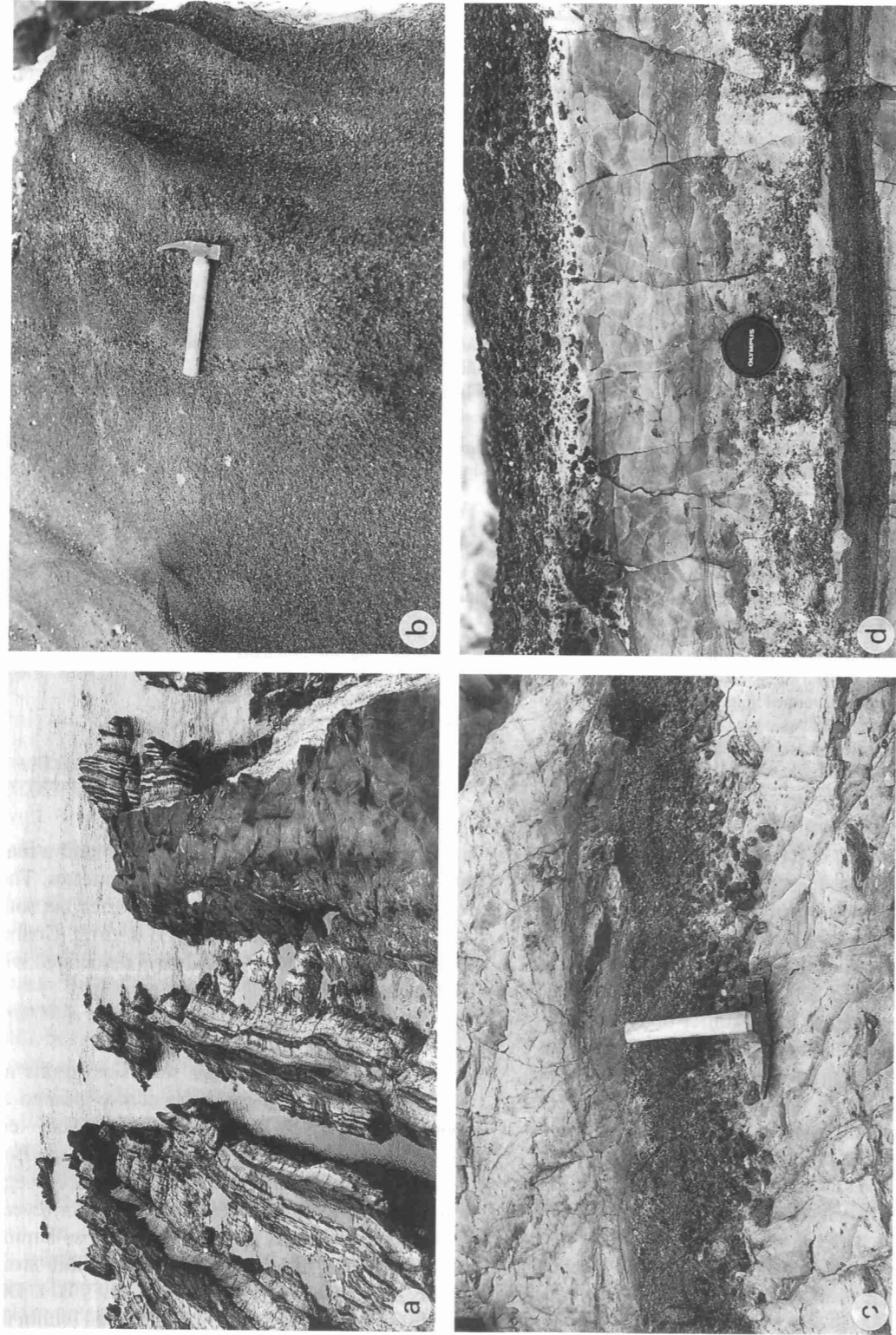


Fig. 4. Photographs of Facies Group A: scoriaceous conglomerates and pebbly sandstones. (A) General view with very thick A1/A2 unit near base overlain by scoriaceous sandstones (Facies B, C) and pumiceous mudstones (Facies D). (B) Detail near base of very thick A1/A2 pebbly sandstone unit seen in (A). Note indistinct stratification. (C) Dark graded scoriaceous bed (Facies A3) — probable pyroclastic fall deposit — within hemipelagic pumiceous mudstones (Facies D). (D) Dark graded scoriaceous bed (Facies A3, top), pale hemipelagic pumiceous mudstone (Facies D2, mid) with dispersed scoriaceous horizon (Facies A5, near base). Thin, parallel-dominated scoriaceous sandstone at bottom of photo (Facies A4).

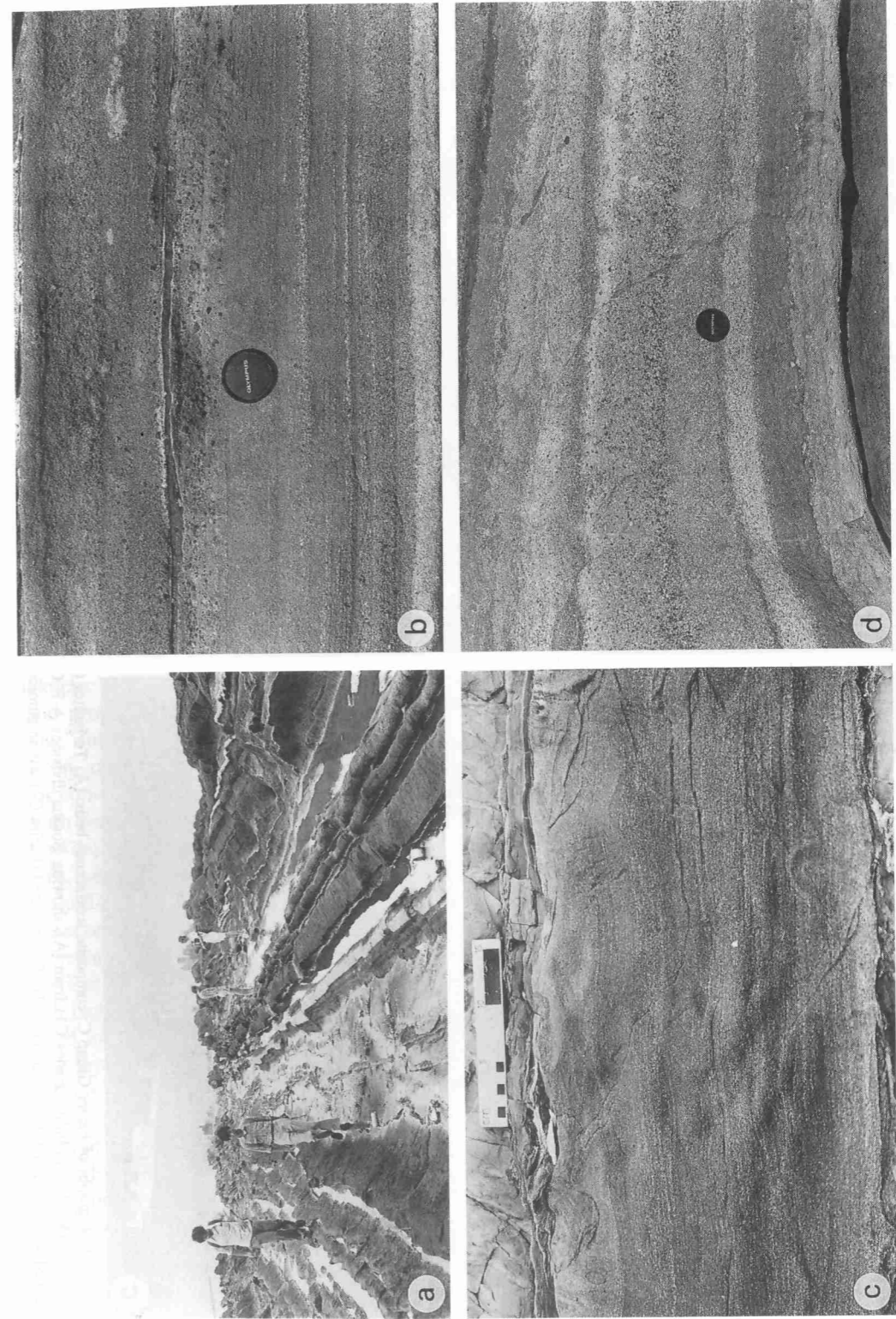


Fig. 5. Photograph of Facies Group B: scoriaceous sandstones. (A) General view of interbedded coarse-grained scoriaceous sandstones (Facies A, B and C) and fine-grained pumiceous mudstones (Facies D). (B) Parallel laminated scoriaceous sandstone (Facies B2) with thin horizon of dispersed pebbles (Facies A5). (C) Parallel and wavy laminated scoriaceous sandstone (Facies B2). (D) Mainly structureless scoriaceous sandstone beds (Facies B1) with some dispersed sandstone/granule horizons (Facies B3, A5).

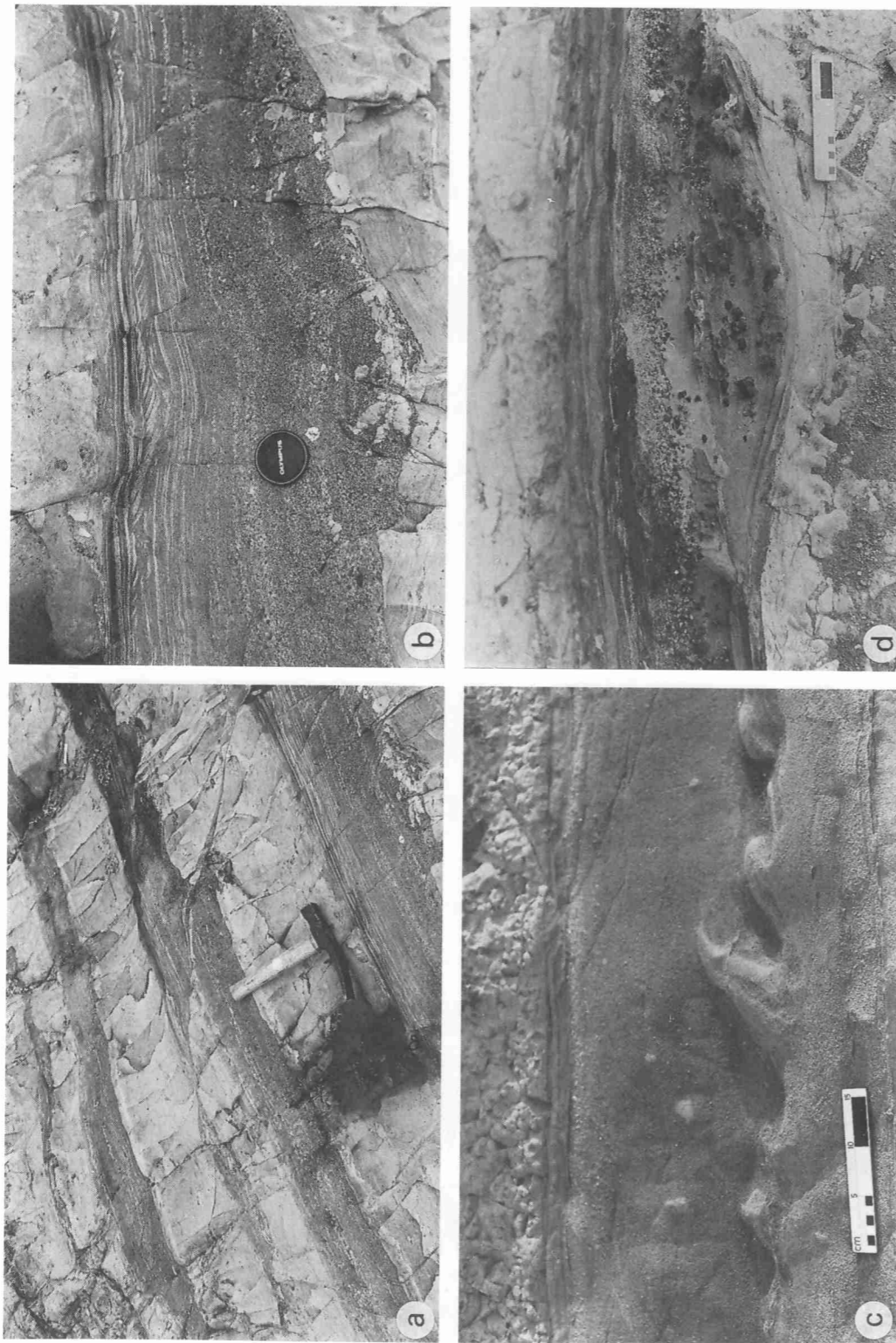


Fig. 6. Photographs of Facies Group C: composite scoriaceous beds. (A) Turbidites (Facies C1) interbedded with pumiceous mudstones (Facies D2). Note low-angle thrust fault. (B) Detail of turbidite (Facies C1) from (A), showing Bouma divisions A B C D E. (C) Turbidite (Facies C1) overlying pumiceous mudstone (Facies D1/D2) with marked load, scour and flame structures. (D) Tripartite bed (Facies C2) within pumiceous mudstones (Facies D2).

siltstone–mudstone facies, although in many cases it is probable that extreme dispersion has destroyed any coherent vestige of the original layer. Grain size ranges from granular to silty sandstones, mostly being poorly to moderately well sorted.

Rare scoria sandstone beds display reversed polarity cross-lamination and others an apparent hummocky cross-stratification. Completely reverse-grading through a 15 cm thick bed and a completely convolute laminated horizon, 12 cm thick, have also been observed.

3.1.3. Facies C. Composite scoria beds

Three distinctive scoria bed types are recognised that display more composite sequences of sedimentary structures and grain sizes (Fig. 6). The most widely distributed of these are graded conglomerate–sandstone–mudstone and sandstone–mudstone beds with complete and partial turbidite structural sequences (Bouma, 1962) (Facies C1). Bed thicknesses of up to 2 m and as little as 3 cm have been recorded, displaying the range of coarse-grained to fine-grained turbidite features noted by Stow (1985a, 1986). More commonly, beds range from 5 to 30 cm in thickness. Different beds display differing thickness and proportions of the various Bouma (1962) divisions, some having a thick, parallel-laminated B-division, others with well-developed cross-laminated or convolute-laminated C-divisions, and so on. Beds with water-escape structures are perhaps better related to the Lowe (1982) model for coarse-grained turbidites, whereas relatively few very thin-bedded siltstone and fine sandstone turbidites are recognised.

The second composite facies (Facies C2), described separately by Soh et al. (1989), comprises three distinct elements: element I, a lower laminated unit with isolated volcanic clasts; element II, a middle graded and laminated unit; and element III, a thin overlying layer rich in volcanic glass. Both elements I and III are mostly thin (1–5 cm) and one or other may be absent. Element II is the thicker (decimetre scale) unit of coarse-grained scoria.

The third facies in this group (Facies C3) occurs only rarely but is important in demonstrating the interplay of depositional processes involved (see later section). It is a complex scoria bed type with elements of both reverse and normal grading, parallel and cross-lamination and small to large pumice clasts incorpo-

rated into the dominant scoriaceous composition. Bed thickness typically ranges from 0.5 to 1.5 m.

3.2. Fine-grained pumiceous beds

The dominant facies (55–95%) of the Misaki Formation is light-coloured, greyish-yellow or buff, fine-grained pumiceous sediments of mud and silt grade (Fig. 7). These sediments generally show ill-defined bedding, but occur in intervals of up to decimetres thick between the darker scoria beds or dispersed scoria horizons. Two main facies are defined, mainly to emphasise the range of grain sizes, being a complete gradation from sandy silty mudstone (Facies D1) to fine silty mudstone (Facies D2). In the coarser-grained Facies D1, the size of individual isolated grains typically ranges up to several millimetres (rarely 10 mm). Rhythmic to more random variation of mean and maximum grain occurs on a decimetre scale through thick sequences of these poorly sorted mudstones.

Although both pumiceous facies (D1 and D2) in this class appear generally structureless, apart from extensive bioturbation, there are a number of significant microstructures and remnant structures that can be identified in parts. These include discontinuous discrete silty laminae and very rare micro-cross-lamination and parallel lamination within a thin lenticular laminated layer. These features tend to be more common in decimetre-scale zones or horizons within otherwise structureless, bioturbated sediment. In such zones the sediment appears to have a more oriented fissile fabric than in the surrounding mudstones.

A third facies (D3) occurs more rarely, but particularly on Boso Peninsula. This is a better-sorted, buff-coloured siltstone (to very fine silty sandstone), without scattered scoria and lacking significant bioturbation, that occurs in thin to thick structureless or finely laminated beds. Although distinct from the other facies in this class it is grouped with them because of its similar composition and grain size.

One of the most striking features of the D1 and D2 pumiceous facies is their intense bioturbation. It appears that any original sedimentary structures of fabric have been largely destroyed by a thorough working and reworking of the sediment by an active macrobenthos. Several overlapping tiers of infaunal burrows can be identified in layers between adja-

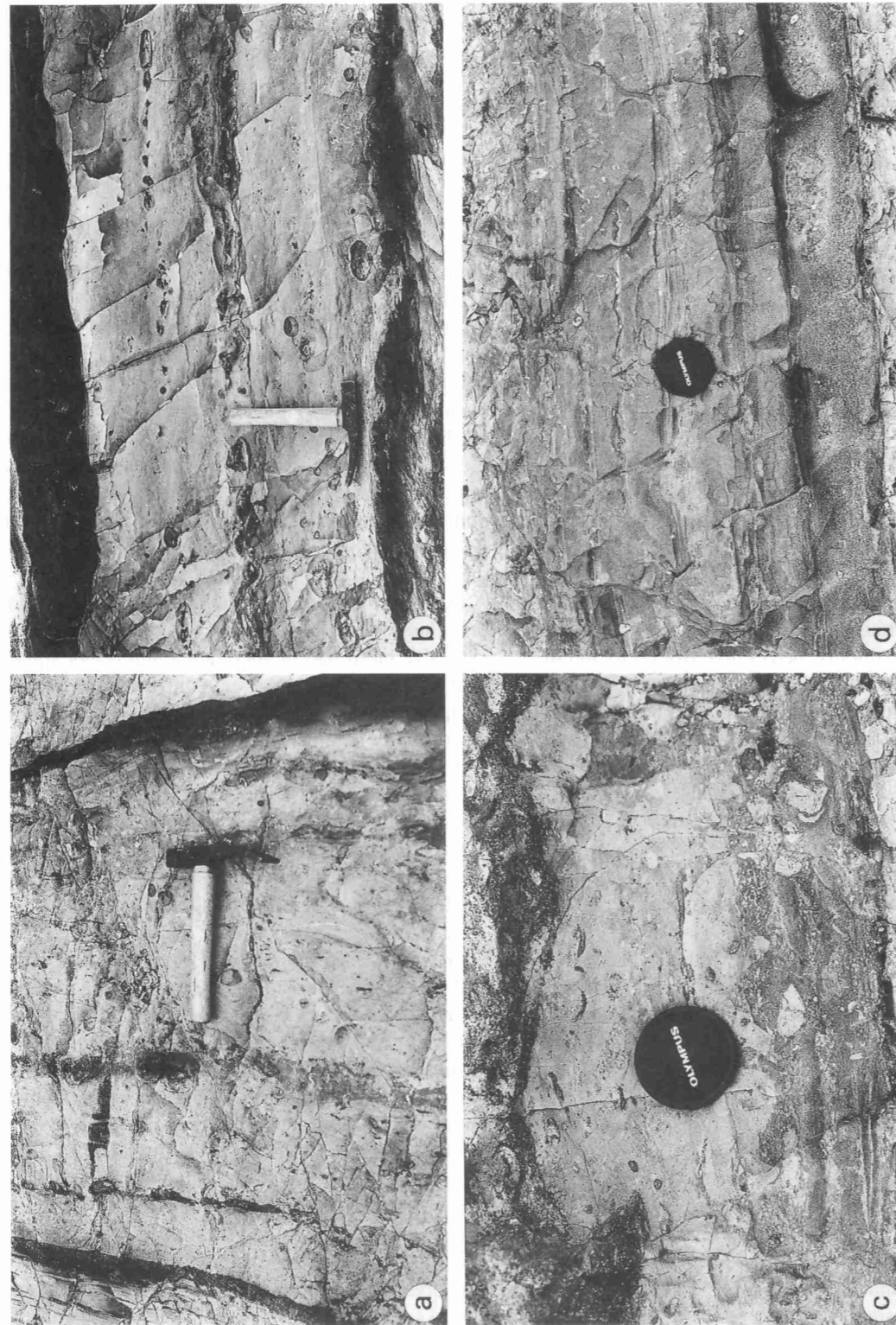


Fig. 7. Photographs of Facies Group D: pumiceous mudstones and siltstones. (A) Pumiceous sandy silty mudstone (Facies D1) over fine silty mudstones (Facies D2) (right). Note bioturbation and thin intercalated scoriaceous horizons. (B) Pumiceous silty mudstone (Facies D2) dominant. Note sideritic concretions and indistinct lamination in parts (possible contourites). (C) Pumiceous silty mudstone (Facies D2) intensely bioturbated between dispersed scoriaceous horizons (Facies B3 and B2). (D) Laminated pumiceous siltstone facies (Facies D3) dominant (middle), with bioturbated pumiceous mudstone above (Facies D2) and (?) scoriaceous sandstone below (Facies B2).

cent scoria beds. These include *Zoophycos*, *Chondrites*, *Helminthoides*, *Planolites* and particularly in the coarser-grained (D2) facies, large mounds and overlapping *Zoophycos* traces are dominant. In these sections, there are also many scattered sideritic concretions, some of which occur in bedding-parallel and sub-parallel bands.

These fine-grained pumiceous facies are composed of variable admixtures of pumice, clay minerals, biogenic material and scattered scoriaceous debris. The biogenic fraction is dominated by ma-

rine foraminifers and nannofossils, together with a minor proportion of other microfossils including sponge spicules, radiolarians and diatoms. The volcanic fraction has partially altered to smectite clays.

3.2.1. Facies E. Tuffaceous beds

Interbedded with the scoriaceous and pumiceous volcanoclastic sediments are light-coloured, acidic, tuffaceous beds, that form a minor (1–5%) but persistent and distinctive facies class (Fig. 8). We recognise three tuff facies on the basis of sedi-

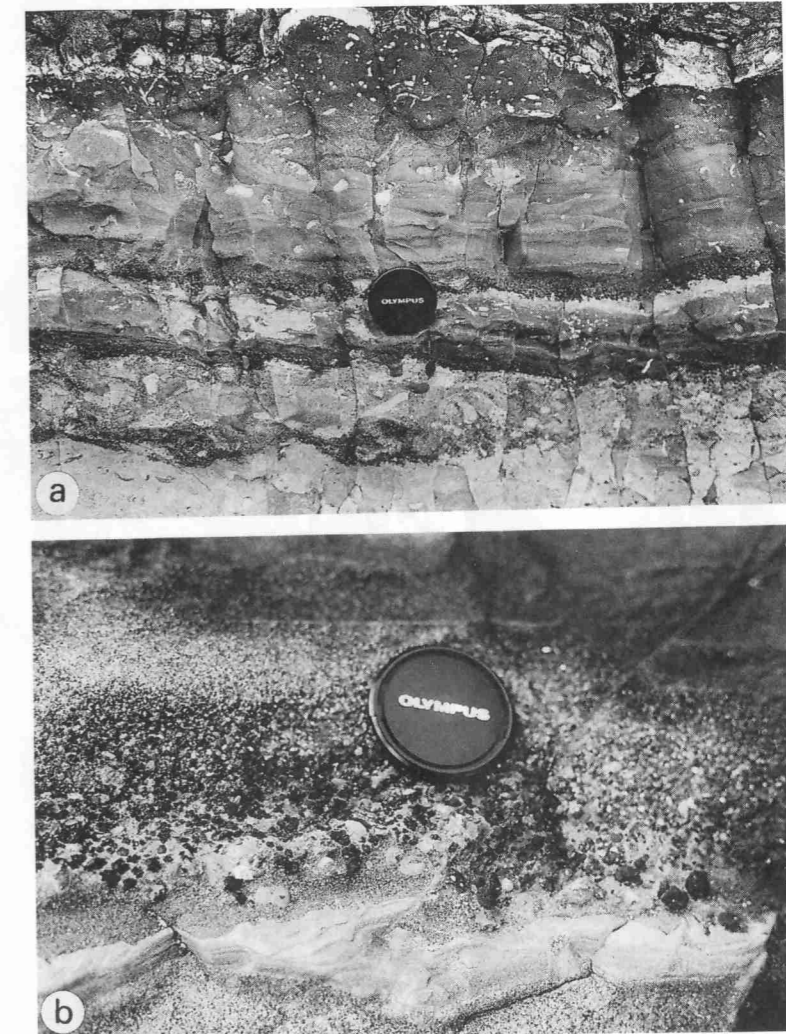


Fig. 8. Photographs of Facies Group E: tuffaceous beds. (A) Two thin-bedded white tuffaceous mudstones (Facies E1) near top and at level of lens cap, both bioturbated down into underlying scoriaceous sandstones (Facies B, C). (B) Thin-bedded white to speckled tuffaceous turbidite (Facies E2, E3) near base of photo below graded scoriaceous conglomerate.

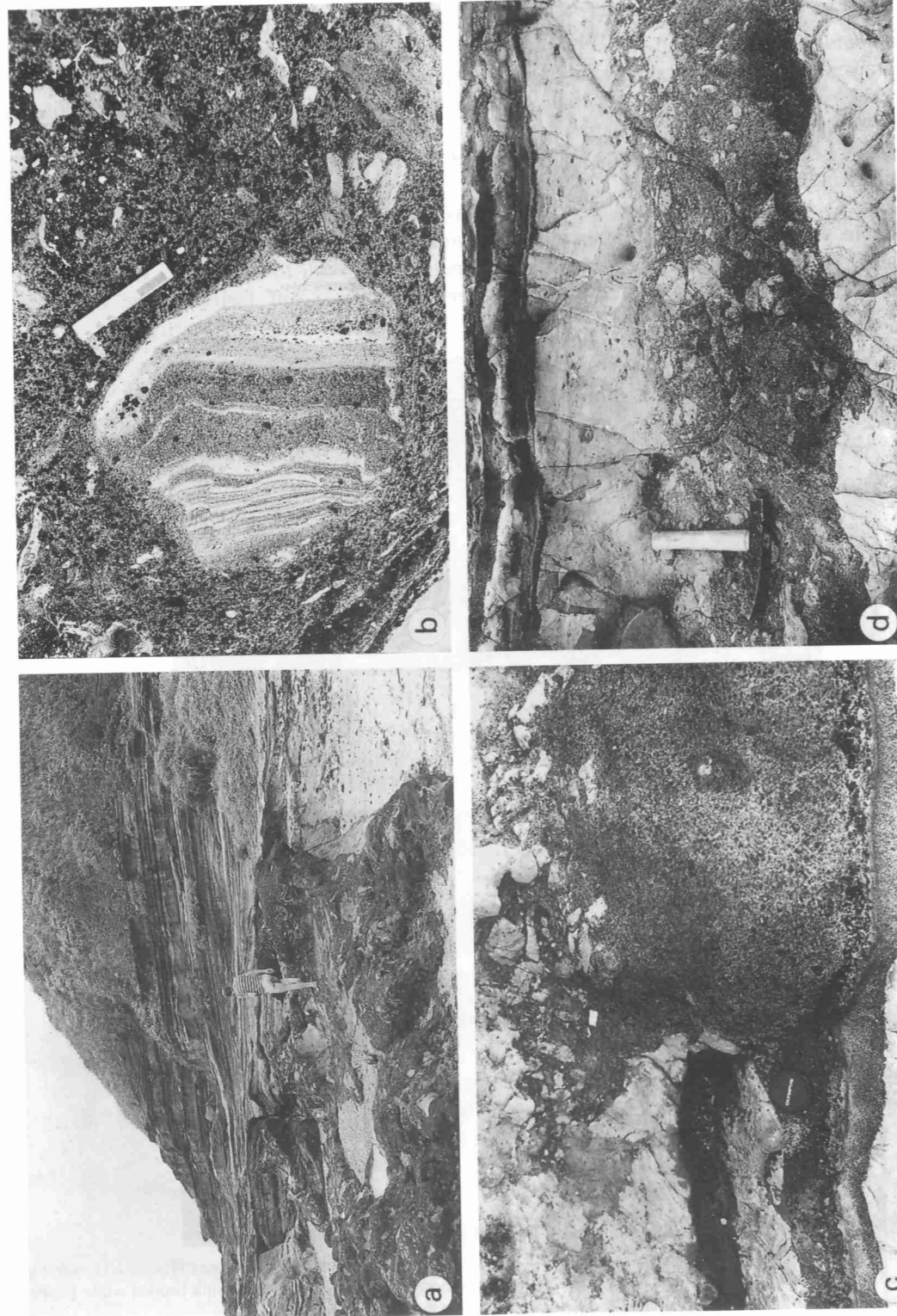


Fig. 9. Photographs of Facies Group F: disturbed and chaotic strata. (A) Large area chaotic horizon (Facies F3) of mixed-composition wet-sediment injection into well bedded strata. (B) Detail of chaotic facies in (A) (Facies F3). (C) Injected scoriaceous sandstone (Facies F4) showing abrupt irregular termination against interbedded pumiceous scoriaceous facies. Note probable F5 facies at top. (D) Injected/debritic unit (Facies F3) within pumiceous mudstone (Facies D2).

mentary structures and grain size. The first (Facies E1) comprises thin-bedded (<10 cm), fine-grained powdery white layers that are generally normally graded but otherwise structureless. The second (Facies E2) comprises thin to medium (3–30 cm), silt- to medium-grained sandstone-graded tuff beds. These commonly show parallel lamination passing upwards into convolute lamination; cross-lamination and structureless intervals also occur. The bases of beds are typically loaded and scoured with common flame injection features and the tops gradationally bioturbated with the overlying pumiceous facies. In some cases, two or more tuff beds are stacked together forming a thicker (<1 m) composite tuff unit.

The third facies of this class (Facies E3) is represented by medium and coarse-grained sandstone tuffs with a black and white speckled appearance. They occur in thin and medium beds and are less clearly graded. Parallel and cross-lamination is commonly present but indistinct.

3.2.2. Facies F. Disturbed and chaotic strata

There has been considerable post-depositional disturbance to the Misaki Formation sediments, mostly assumed due to the processes of euduction and accretion of the Miura Basin to the Honshu Arc mainland (Fig. 9). This disturbance includes intense folding, high-angle faulting, bedding plane faulting and the development of associated veins and gashes (Pickering et al., 1990).

In addition to these features, which are not the concern of this paper, there are five different types or aspects of sediments noted during detailed section logging that deserve consideration as 'sediment facies'. Most of them have been interpreted by previous workers and some are still considered here to be of syndepositional origin, although we are now only confident in interpreting Facies F1 in this way (see later discussion).

Facies F1 comprises thin to moderately thick (up to 2 m) zones with contorted and slump-folded beds sandwiched between adjacent parallel and undisturbed beds. Similar contorted features can be seen at a larger scale (up to 20 m thick) where the folded strata are commonly associated with a jumbled assortment of metre-scale blocks, all of the surrounding lithologies (Facies F2). In the latter facies it has not been possible to identify both the top and bottom

enclosing strata so that the exact relationships are less clear. Facies F3 is represented by a still more chaotic assortment of clasts of all sizes (up to several metres), both intraformational and exotic in nature, set in a finer-grained sandy matrix. These zones can be at a scale of a few metres to a few tens of metres and both bedding parallel and cross-cutting relationships are observed.

Facies F4 and F5 both have characteristics of sediment injection bodies. The first (F4) is more obvious being composed of a uniform mix of mainly scoriaceous sand-size grains that can be seen to intrude both laterally and vertically into adjacent strata. The second (F5), however, is more equivocal in nature. It is composed of rounded to angular clasts of the pumiceous facies in a matrix of scoriaceous/pumiceous sediment. It commonly occurs in 'beds' from 20 cm to 2 m thickness sandwiched between a light-coloured pumiceous and dark-coloured scoriaceous bed. More rarely this facies can be seen to cross cut obliquely to the strata and very rarely to be injected vertically.

4. Hasse Formation

The Hasse Formation in the southern part of the Miura Peninsula has been measured at about 460 m thick over the Misaki Formation, whereas in southern Boso, it is over 2000 m in thickness. These values assume no sequence repetition and so are most likely over-estimates. However, bedding-parallel thrust faults have not been noted in this formation to the same degree as in the underlying strata.

The five main facies groups recognised are similar to those of the underlying formations, including scoriaceous (coarse and medium), pumiceous, tuffaceous and chaotic sediments. However, many of the nine individual facies identified are significantly different from the Misaki facies (Table 2) and must therefore be considered separately. The letter codes G–K are specific to the Hasse Formation; depositional processes are discussed in the following section and summarised in Table 2.

4.1. Mixed scoriaceous/pumiceous beds

The Hasse Formation is immediately distinguished from the Misaki Formation by the dom-

Table 2
Hasse Formation: principal facies and process interpretation

<i>Facies Group G</i>		<i>Mixed composition conglomerates and pebbly sandstones</i>	
G1	very thick-bedded, very coarse-grained		complex interaction of fan-delta processes with shallow-marine processes (tides, waves, shelf currents)
G2	thick-bedded, coarse-grained, \pm structures		
G3	medium- to thick-bedded, pebbly sandstones, cross-stratified		
<i>Facies Group H</i>		<i>Mixed-composition sandstones</i>	
H1	structureless		
H2	medium- to thick-bedded, laminated		
H3	thin-bedded, laminated		
<i>Facies Group I</i>		<i>Mudstones and siltstones</i>	
I1	mudstones, thin units/partings		
I2	siltstones, thin units/partings		
<i>Facies Group J</i>		<i>Tuffaceous mudstones</i>	
J1	pale-coloured, acidic tuffs		pyroclastic fall \pm reworking by currents
<i>Facies Group K</i>		<i>Disturbed and chaotic strata</i>	
K1	contorted and slump-folded		slump-slide processes
K2	chaotic horizons		slump-slide debris flow or injection processes

inance in the former of coarse-grained, stratified and cross-stratified beds of greenish and brownish colours. These commonly form 80–95% of any given section. They are composed of a varied suite of clasts, including approximately equal admixtures of darker scoriaceous and lighter pumiceous material as well as rare exotic elements in some units that have been derived from the Honshu Arc. There seems to be a sharp natural division into two facies groups on the basis of grain size.

4.1.1. Facies G. Mixed-composition conglomerates and pebbly sandstones

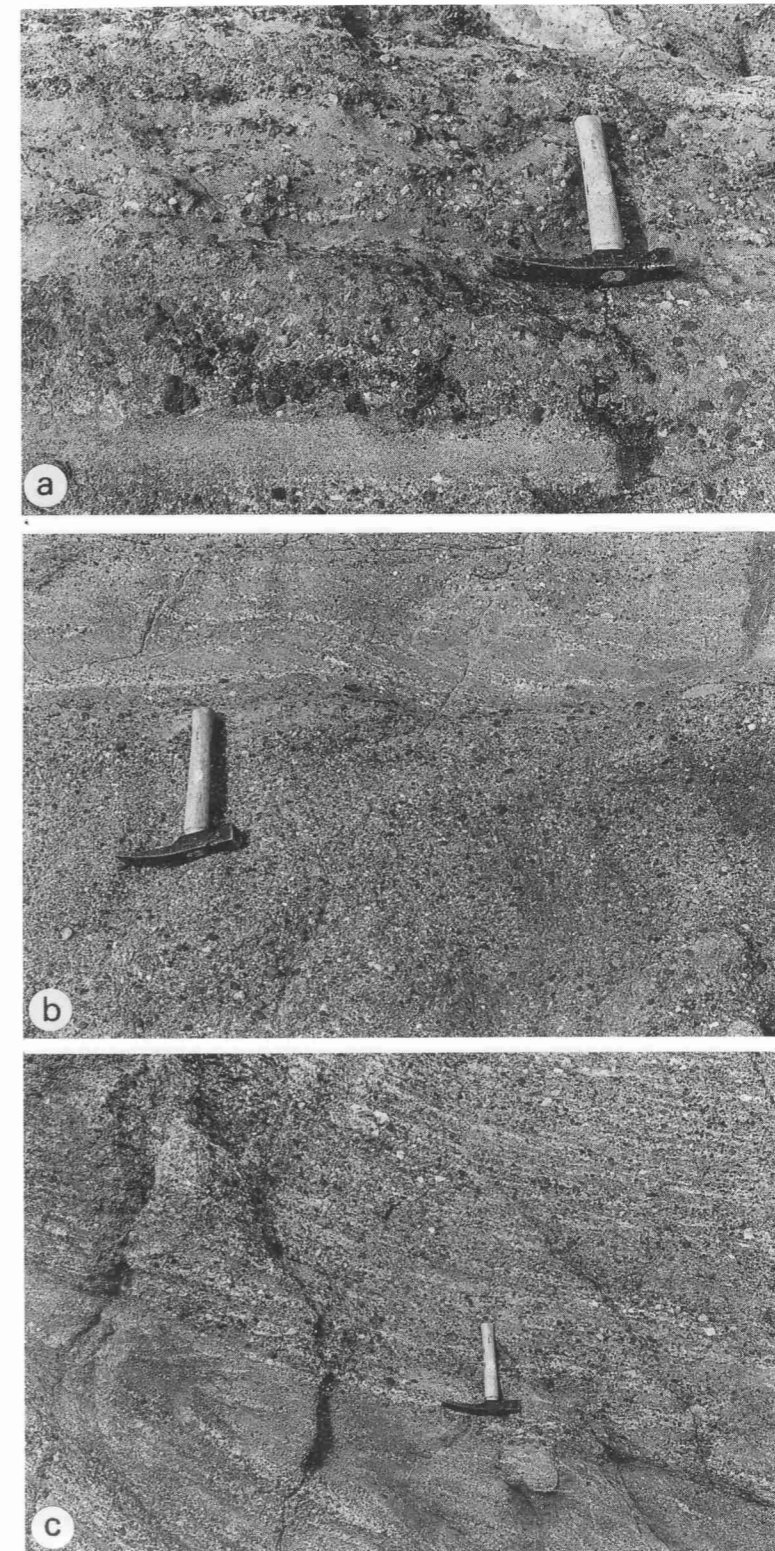
Three facies are distinguished in this group (Fig. 10). Facies G1 comprises very coarse-grained and poorly sorted conglomerates occurring in thick to very thick structureless beds. Angular to sub-rounded boulders up to 30 cm in diameter are common. Equally thick-bedded and typically structureless or crudely stratified beds of pebbly sandstones/sandy conglomerates are a still more common facies (Facies G2). The clasts size is typically 1 to

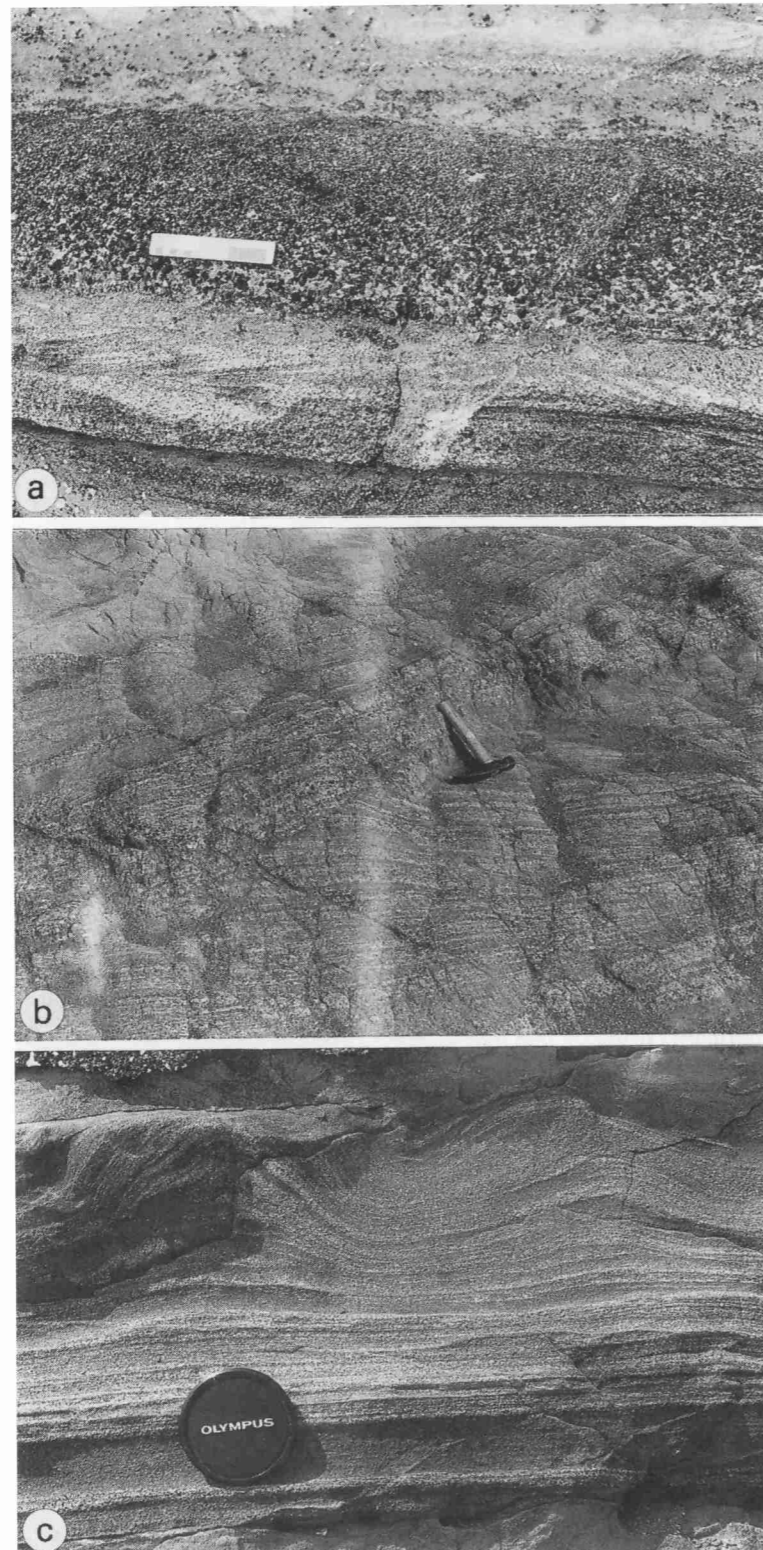
3 cm in diameter although rare isolated clasts of intraformational sandstone may reach 1.5 m in size. The beds of Facies G3 are a slightly finer-grained pebbly sandstone, also thick- and very thick-bedded and either parallel or cross-stratified, with individual sets typically 15–40 cm but ranging up to 1 m or more. Both trough cross-sets and planar tabular sets are present.

4.1.2. Facies H. Mixed-composition sandstones

The sandstones of the Hasse Formation are brownish and greenish coloured, fine to coarse grade and for the most part with distinct current-induced structures (Fig. 11). There are relatively few completely structureless beds (Facies H1) and a dominance of medium- to thick-bedded parallel and cross-laminated beds (Facies H2). The thickness of individual sets varies up to about 50 cm. In the thinner-bedded laminated facies (Facies H3), the cross-lamination is on a ripple scale. In both facies H2 and H3 the cross beds tend to show unidirectional current modes although, more rarely, distinct

Fig. 10. Photographs of Facies Group G: mixed-composition conglomerates and pebbly sandstones. (A) Structureless conglomerate/pebbly sandstone (Facies G1/G2). (B) Cross-stratified pebbly sandstone (Facies G3) over structureless conglomerate/pebbly sandstone (Facies G1). (C) Large-scale cross-stratified pebbly sandstone (Facies G2) over slump unit (Facies K1).





bimodal sets occur within the same bed. In many instances also, there has been some convolution of the cross-laminae.

4.1.3. Facies I–K. Other facies classes

Sediments other than the coarser-grained facies described above are not well represented. Mudstones (Facies I1) occur mostly as very thin partings between the sandstones and conglomerates and tend to be very silty but otherwise structureless, even without any bioturbation (Fig. 12). Gradational from the mudstones to the thinner-bedded sandstones are parallel-laminated siltstones (Facies I2). Various acidic tuff horizons are also present (Facies J1), being thin to medium-bedded and laminated.

The two main facies of the 'disturbed and chaotic' facies class are small- to medium-scale slump units (Facies K1) with distinctive, often local, soft-sediment bedding contortion clearly contained within undisturbed strata, and thicker zones of more chaotically disturbed strata (Facies K2), with intraformational blocks and rafts and significant faulting in addition to slump-like folds.

5. Depositional processes

A wide range of depositional processes was involved in the sedimentation of the Miura Group, representing the often complex interaction of active arc volcanism, normal-marine processes and a shallowing-upward trend, presumably related to accretion and uplift. Whereas some of the facies are relatively straightforward to interpret, others are much more equivocal.

5.1. Hemipelagic and bottom current processes

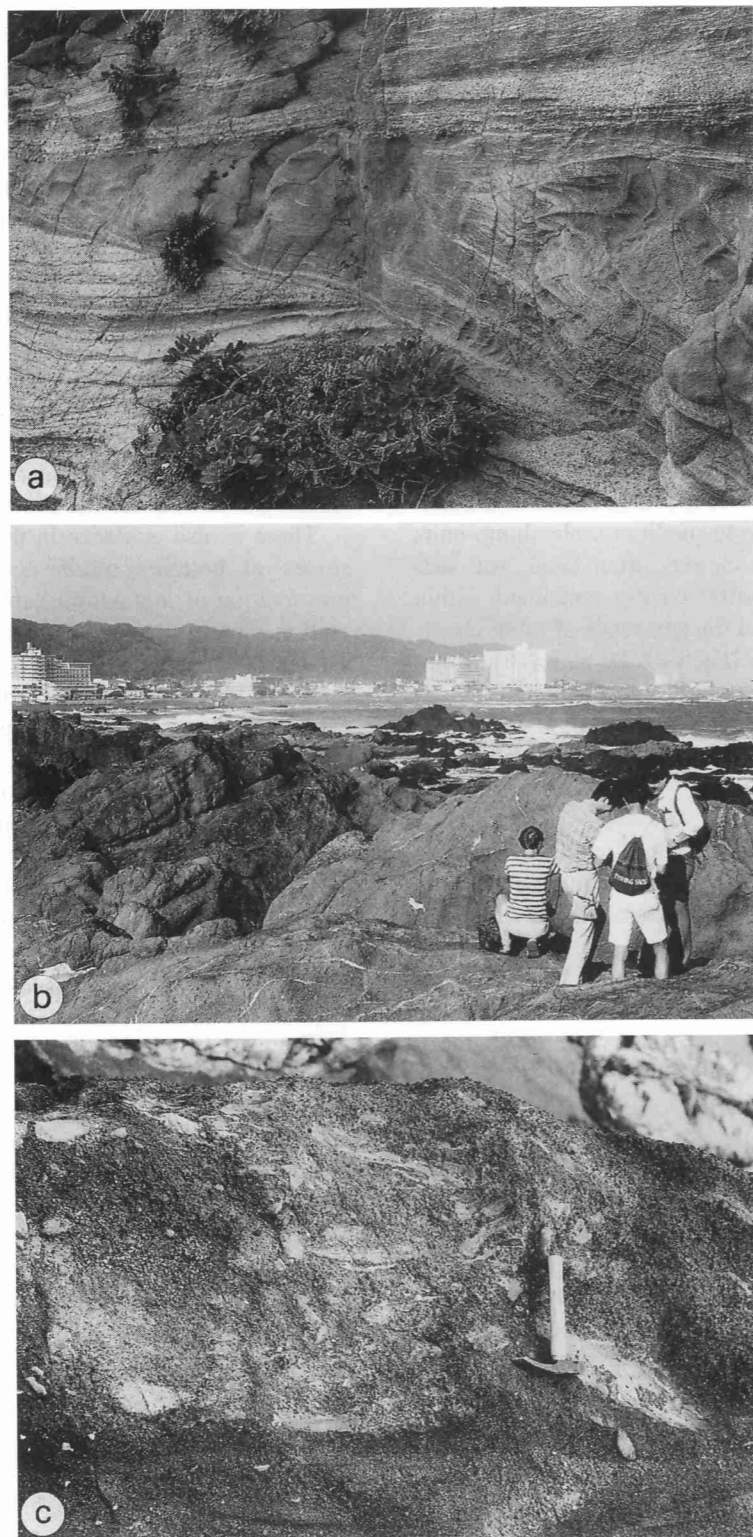
The dominant facies of the Miura Group Misaki Formation is the pumiceous mudstone facies (D1 and D2) which is interpreted as mainly hemipelagic in nature. It is a silty (sometimes sandy) mudstone, with a mixed pelagic biogenic and volcanogenic/terrigenous composition and extensive bioturbation, resulting

from the slow vertical settling of different materials through the water column leaving ample time for the thorough reworking of sediment on the seafloor by burrowing organisms. The high proportion of pumiceous volcanic glass was probably derived from explosive eruptions along the Izu–Bonin Arc to the west rather than from the Honshu Arc. The intermediate- to high-acidic composition of the glasses would argue for mixed sources extending still further to the west. Material was brought to the Miura Basin depositional area in current-driven surface and subsurface plumes as well as in the prevailing winds. More local eruption of basaltic volcanoes contributed the scattered scoriaceous debris, whereas a small proportion of the clays may have been derived either from mainland Japan or from further south.

There is also evidence in these pumiceous mudstones of bottom current activity, with the rare preservation of lamination, lenticular irregular lamination, sharp silt–mud contacts and so on (parts of Facies D1 and D2). These features indicate the presence of weak bottom currents affecting the essentially hemipelagic settling process (Stow and Faugères, 1990). Such bottom currents would also help in the transport and mixing of various glass types from the west and clay material from the south. It is possible that the enigmatic laminated to weakly bioturbated pumiceous mudstones (Facies D3) represent the deposits of higher-energy bottom currents or laminated contourites (cf. Bein and Weiler, 1976; Duan et al., 1993) but this requires further work for verification.

There are two scales of grain-size variation within the mudstone probably caused by different mechanisms. The first is the increased siltiness and sandiness of the mudstone over several tens of metres that is observed towards the top of the Misaki Formation. This is interpreted as the result of a basin-shallowing trend associated with greater proximity to the shoreline and with stronger shallow-water currents. The second is a smaller-scale variation of more and less silty mudstones over intervals of about 10 cm to 100 cm. In part this is probably best attributed to varia-

Fig. 11. Photographs of Facies Group H: mixed-composition sandstones. (A) Structureless/graded bed (Facies H1) over bi-directional cross-stratified bed (Facies H2). (B) Parallel and cross-stratified sandstones (Facies H2) possibly with erosive/slump unit (Facies K1). (C) Parallel and wavy laminated sandstones (Facies H2).



tions in volcanic activity and hence sediment input and in part might also be due to fluctuation in the strength of the bottom current activity (cf. Gonthier et al., 1984; Stow et al., 1986)

One important aspect of these hemipelagic sediments is the complete absence of any strong wave, tidal or other normal current activity, besides the very weak effects of bottom currents noted above.

5.2. Pyroclastic processes

Some of the dark-coloured scoriaceous beds, particularly in the Misaki Formation are interpreted as the result of direct pyroclastic fall processes, probably involving fall both through the air and then water column. These beds range from variably thin and dispersed within the pumiceous mudstones (Facies A5, B3) to thicker normally graded layers (some of Facies A1, B1). The bases of beds are not sharp and individual clasts may have sunk several centimetres into the underlying sediment after reaching the seafloor. Reverse grading occurs near the base of some beds and even thin layers can have extremely coarse (up to 5 cm) clasts. These features all seem best interpreted as the result of pyroclastic fall (e.g. Fisher and Schmincke, 1984; Cas and Wright, 1987).

Only a few of the light-coloured acidic tuffs show no structures other than normal grading and these may therefore be interpreted as pyroclastic air/water fall tuffs (Facies E1). However, as these are similar to the very fine-grained silt–mud-grade white tuffs that also occur at the tops of thicker tuff beds showing clear turbidite structures (Facies E2, E3), a dilute turbidity current origin is inferred in most cases. In addition, their fine grain size would favour a diffuse hemipelagic dispersion through the water column if they arrived at the sea-surface by air-fall so that they would not then be preserved as distinct thin, non-bioturbated beds.

5.3. Turbidity current processes

There are many clear examples of turbiditic structures in both thick- and thin-bedded scoriaceous

layers of the Misaki Formation (most facies groups). Partial and complete Bouma (1962) structural sequences are common, occurring in graded beds having sharp, loaded bases and more gradational bioturbated tops (Facies C1). A number of these turbidites, including nearly all of those on the Boso Peninsula, have a distinctly mixed composition including both scoriaceous and pumiceous material. In these cases, there is little doubt about their turbidity current origin. In addition, a greater proportion of pumiceous material is probably indicative of a more distal location or aspect.

As with all turbidite sequences, the thick-bedded, structureless or parallel-laminated and less-clearly graded layers are less readily understood (Facies A1, A2, B1, B2). They can be interpreted as division-A and division-B-turbidites or, where water-escape structures are common, related to Lowe's model for coarse-grained turbidites (Lowe, 1982). Structureless beds or units of coarse scoriaceous material over 5 m in thickness (Facies A1, B1) are found on both the Miura and Boso peninsulas. These may have resulted from particularly large sandy debris flow or high-concentration turbidity current events (Stow et al., 1996). Alternatively, they may have formed by very rapid deposition either from vertical density currents following simultaneous air-fall of large amounts of material onto the water surface, or from normal turbidity currents that may have developed by water mixing with subaqueous base-surge pyroclastic flows (e.g. Fisher, 1984).

Very thick isolated beds displaying large-scale cross-stratification (Facies A2, B2) result from large-scale tractional flow process at the base of a turbidity current. Such tractional current structures are by no means uncommon in turbidite sequences around the world (Stow et al., 1996).

Three different mechanisms of turbidity current generation appear probable. One involves the slumping of unstable volcanoclastic debris from the flanks of volcanic seamounts and slope areas surrounding the Miura Basin. The trigger would most likely be a volcanic seismic one and the deposits include a mix of any material that has ac-

Fig. 12. Photographs of Facies Group K. (A) Contorted slump folded unit (Facies K1) within stratified sandstones (Facies H2). (B) Large-scale chaotic horizon (Facies K2). (C) Detail of chaotic horizon (Facies K2).

accumulated in the transitional source area (e.g. the mixed pumiceous/scoriaceous turbidites). The second mechanism would involve the direct transition of high-concentration subaqueous pyroclastic flows into turbidity currents. The deposits would therefore be of more monomict composition and be less readily distinguished from pyroclastic deposits (e.g. coarse scoriaceous turbidites). The third would be the transition of vertical density flows into downslope turbidity currents, also resulting in a monomict composition.

Many of the acidic tuffaceous beds (Facies Group E) also display fine-grained turbidite structural sequences and are best interpreted as such (Stow and Piper, 1984).

5.4. Shallow-marine current processes

Especially in the upper parts of the Misaki and throughout the Hasse Formation, there are scoriaceous and mixed scoriaceous/pumiceous beds with medium- and large-scale planar and trough cross-stratification. The interbedded mudstones are thin and/or silty and bioturbation becomes more evident, more varied and affects even the coarse scoria beds than in the lower parts of the formation. Locally (e.g. Tateyama, Boso Peninsula), such beds also include shallow-water shell debris. Although the current directions measured from cross-stratification are mainly unidirectional, there are also instances of reverse polarity currents and more equivocally, of hummocky cross-stratification and wave ripple lamination.

These various features are interpreted as the result of a basin-shallowing trend leading to the greater influence of shallow-marine processes including waves, tidal and shelf currents. Such features also occur much less commonly in the lower parts of the Misaki Formation on Miura Peninsula, either as isolated beds or apparently modifying the tops of turbidites and pyroclastic fall deposits, perhaps indicating periodic influence of major storms near the bottom of a relatively shallow-slope basin.

5.5. Fan-delta processes

The large-scale cross-lamination and the thick-bedded parallel-laminated layers of the Hasse For-

mation occur in places in association with thick- and very thick-bedded structureless pebbly sandstones, conglomerates and chaotic beds with boulder-sized clasts. There is an absence of interbedded hemipelagic mudstone and an absence of bioturbation. The clasts are mostly poorly and very poorly sorted and show a much more varied range of composition than those of the underlying formations. This association is particularly well exposed near Nojimasaki on the southern tip of the Boso Peninsula, where the sediments have a distinctly brownish colour and contain a relatively large number of oxidised red scoriaceous clasts, red siliceous clasts and granitoid pebbles. This material represents the first distinctive occurrence of Honshu-Arc-derived detritus in the Miura Basin (Soh et al., 1990).

These features, together with the fact that the formations sit at the top of a shallowing-upward trend and possibly over an unconformity, suggest that these facies might be collectively interpreted as resulting from subaerial to subaqueous fan-delta processes. Clearly, there has been a major influx of sediment into the system that might best be explained by the various mass flow and debris flow processes typical of a fan or fan-delta setting.

5.6. Wet-sediment deformation

The disturbed and chaotic strata (Facies F1 to F5) have clearly resulted from some processes of wet-sediment deformation. Normal downslope gravity slide and slump processes are assumed to have been responsible for the contorted layers of Facies F1 and in some cases for the thicker chaotic units of Facies F. This interpretation supports the presence of reasonable submarine slopes and triggering mechanisms, most likely seismic. The analogous facies (Facies K1 and K2) in the Hasse Formation are interpreted as the result of similar gravity sliding in shallow-water fan-delta and, in some instances, possibly subaerial settings.

The other chaotic layers, described as Facies F3 to F5, are interpreted as the result of wet-sediment injection processes both parallel and perpendicular to bedding that probably took place during accretion and eduction of the Miura block (Pickering et al., 1990). Exotic clasts were derived from deep within the accretionary complex and forced upwards by

intense overpressuring in a mud diapiric melange. Intraformational clasts were incorporated as the diapiric intrusion neared the surface. Injection as thin clastic sills and dykes occurred, further ripping off material from the adjacent strata and mixing this with the intruding sediment. In places, the mud diapirs may have broken the surface forming large subaqueous mud volcanoes.

5.7. Interaction of processes

Two very interesting aspects of the Miura Basin sediments studied are, firstly the range of processes involved in their deposition and, secondly, the interaction of certain very different processes in the shaping of individual composite beds.

(1) *Hemipelagic sediments* have by definition been formed by the interaction of various poorly understood processes that result in the accumulation by slow lateral advection and ultimately by vertical settling, of silty fine-grained sediments typically in outer shelf and slope settings (e.g. Stow, 1985b, 1986; Stow and Tabrez, 1997). In the case of the Miura Group, the background hemipelagites were derived from the finest pyroclastic fall material, pyroclastic flows that evolved into surficial and mid-water-column plumes, re-suspension of arc flank sediments and from direct primary biogenic productivity in surface waters. Various more or less distal sources were most likely involved including both the Izu–Bonin and Honshu arcs. In some parts, final deposition of the hemipelagic material was influenced by thermohaline bottom currents that may also have introduced material from further afield (Fig. 13).

(2) The origin of the *tripartite composite scoria beds* (Facies C2) has been interpreted by Soh et al. (1989) as follows. Element I, is either the result of a submarine base-surge that developed into a turbidity current flowing down the flank of an evolving volcano, or as the deposits of early, multiple, submarine eruptions as the volcano was constructed. Element II, is interpreted as the subaqueously emplaced deposits of subaerial eruptions that occurred after the volcano had grown above sea-level. The three parts (IIa, IIb and IIc) show a change from dominant vertical settling through the water column of air-fall ejecta, partly as individual clasts and partly as a vertical

density flow, to settling combined with dominant lateral motion, in some cases by turbidity currents in other cases due to storm-current reworking. Element III represents the final fall-out from suspension of volcanic glass shards and ash. Because of the probable water depth (>1 km) and distance from volcanic source, we would now prefer to emphasise the role of the debris flow–turbidity current processes in the deposition of these units, but still recognising their close association with and probable derivation from primary pyroclastic processes (Fig. 14).

(3) The still more *complex scoria units* (Facies C3), that show repeated reverse and normal grading and that have concentrations of fine to coarse pumice clasts intermixed with the dominant scoria, attest even more clearly to the close interaction of successive explosive eruptions, leading to subaqueous pyroclastic flows and subaerial to subaqueous ash fall, with various mass flow processes including debris flows and turbidity currents. These latter have been triggered by different mechanisms, including the mixing of seawater with base-surge flows, the evolution of seismic-induced slides and slumps and the transition from vertical to lateral motion of vertical density currents (Fig. 14). Reworking by normal marine (storm) currents and by bioturbation is also noted in some instances.

(4) The interaction of both storm currents and shallow-marine currents with beds deposited by turbidity currents and by pyroclastic fall is particularly evident in the shallow-water and proximal fan-delta setting represented by the Hasse Formation.

6. Facies distribution

Whereas the coastal outcrops around the Miura and Boso peninsulas are good and relatively continuous, the inland outcrops particularly in Miura are poor and discontinuous. The sections measured in detail, therefore, are all coastal. Although the distances between sections range from 0.3 km to 4 km, precise correlation between sections is still uncertain and is currently being reassessed. With these limitations in mind we consider first the generalised regional distribution of facies and of specific facies characteristics, including grain size, bed thickness, composition and palaeocurrents.

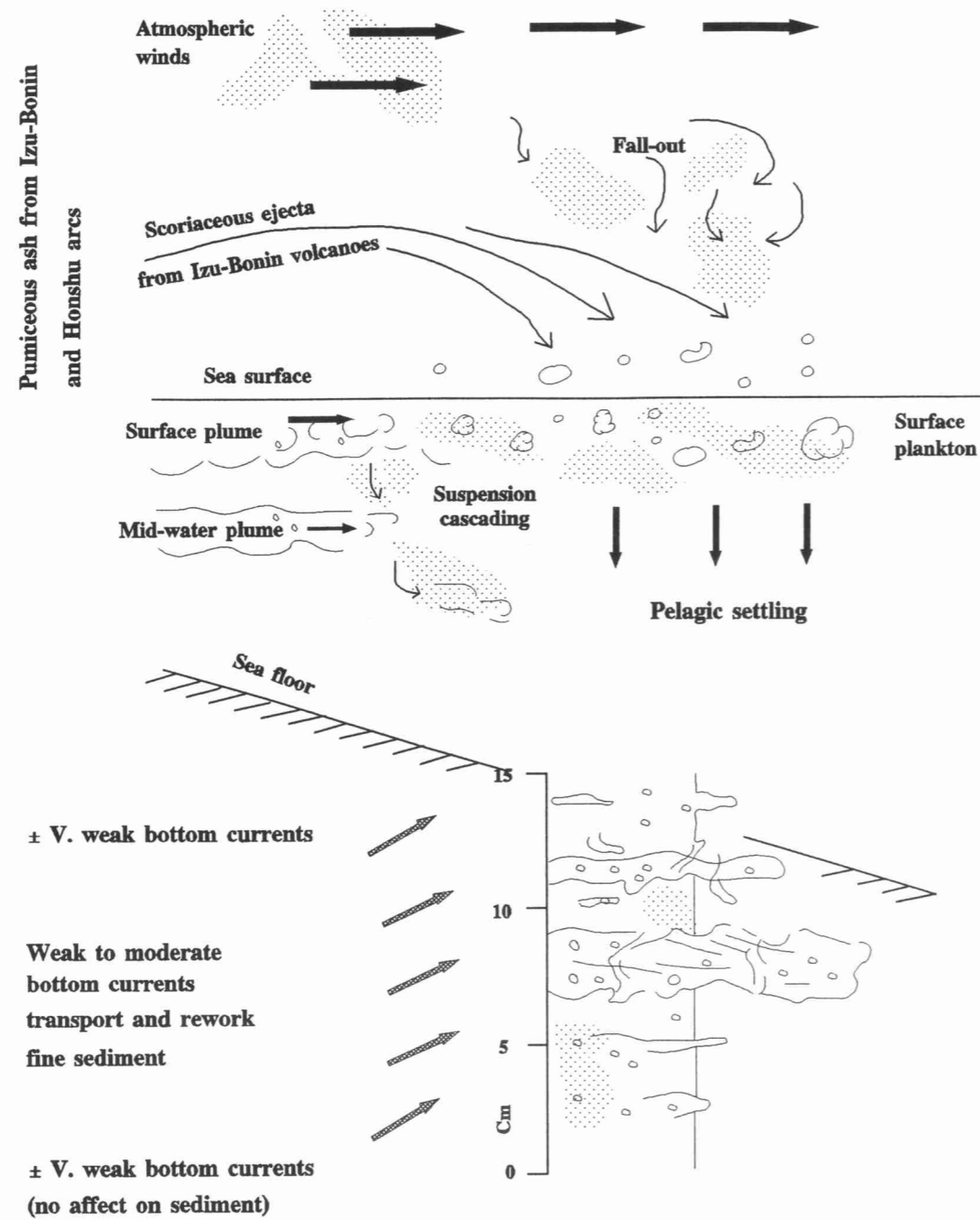


Fig. 13. Hemipelagic and bottom current processes in the deposition of Miura Group sediments.

6.1. Regional pattern

Generalised sections each covering a few hundred metres of succession are shown in Fig. 15

for the Miura Peninsula and in Fig. 16 for Boso Peninsula. Seven main facies associations are identified on these sections: (1) pumiceous mudstones dominant, with thin and very thin scoriaceous

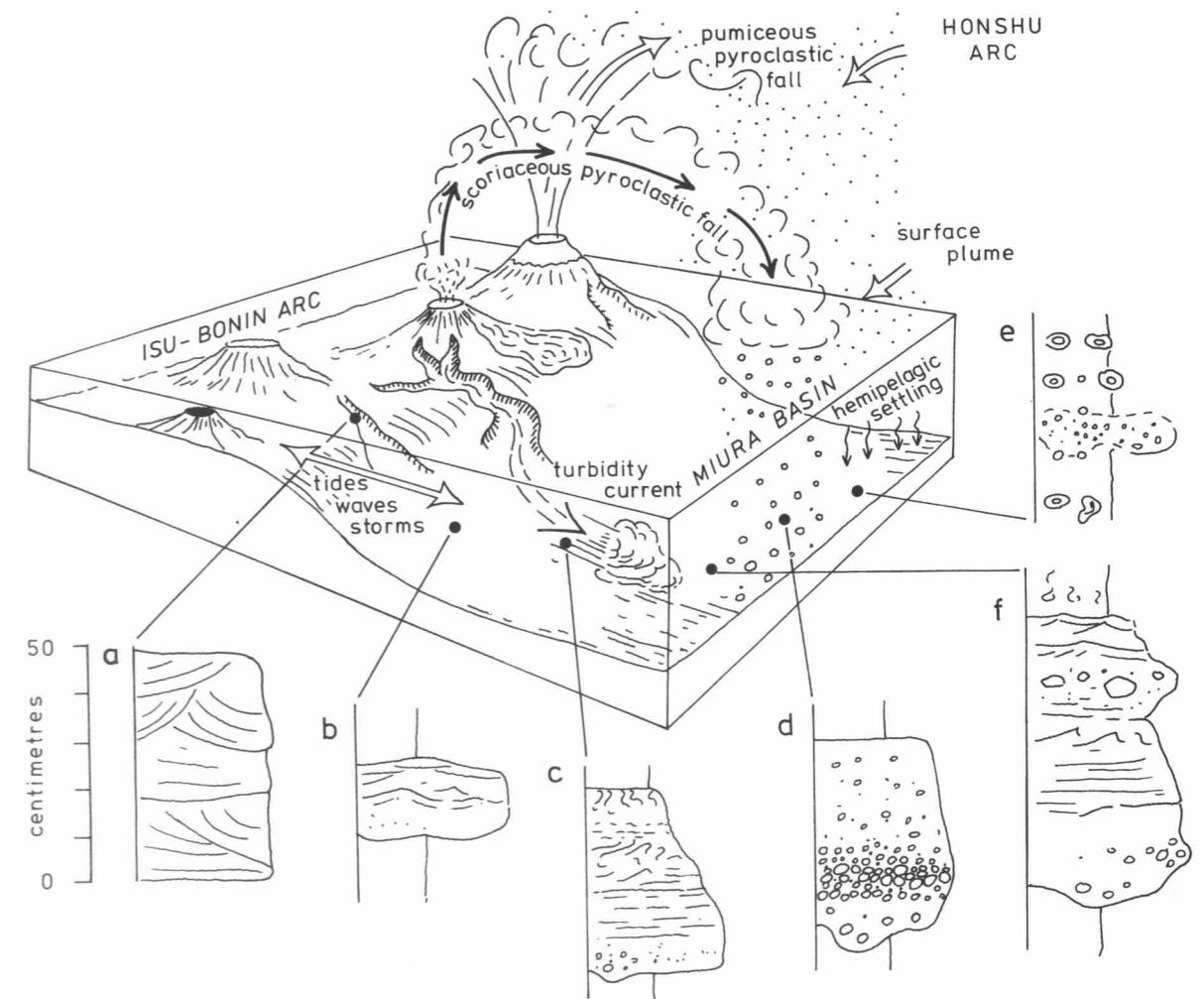


Fig. 14. Interaction of pyroclastic and turbidity current processes in the deposition of composite scoriaceous beds.

layers forming a small part of the section; (2) pumiceous mudstones interbedded with thin to thick dark scoriaceous layers; (3) pumiceous mudstones interbedded with thin to thick mixed scoriaceous/pumiceous layers; (4) sections dominated by disturbed and chaotic strata; (5) mixed-composition, grey-coloured, scoriaceous/pumiceous beds dominant, interbedded with pumiceous mudstones; (6) mixed-composition, brown- and green-coloured, scoriaceous/pumiceous beds of coarse- to fine-grained sand grade without interbedded pumiceous mudstones; and (7) mixed-composition, brown- and green-coloured, scoriaceous/pumiceous beds of pebbly-sandstones and conglomerates without interbed-

ded pumiceous siltstones. Facies Associations (1), (2) and (3) are dominant in the Misaki Formation, with (1) and (2) on Miura Peninsula and (3) on Boso. Facies Association (5) is transitional between the Misaki and Hasse formations, whereas (6) and (7) are dominant in the Hasse Formation. The chaotic units (4) and also interbedded tuffaceous layers can occur throughout the area and formations considered.

On the Miura Peninsula the vertical succession typically passes from basal mudstones with common to abundant scoriaceous beds (Facies Association 2), several hundreds of metres thick, upwards through a mudstone-dominated section (Facies Association 1), also several hundreds of metres thick and to a

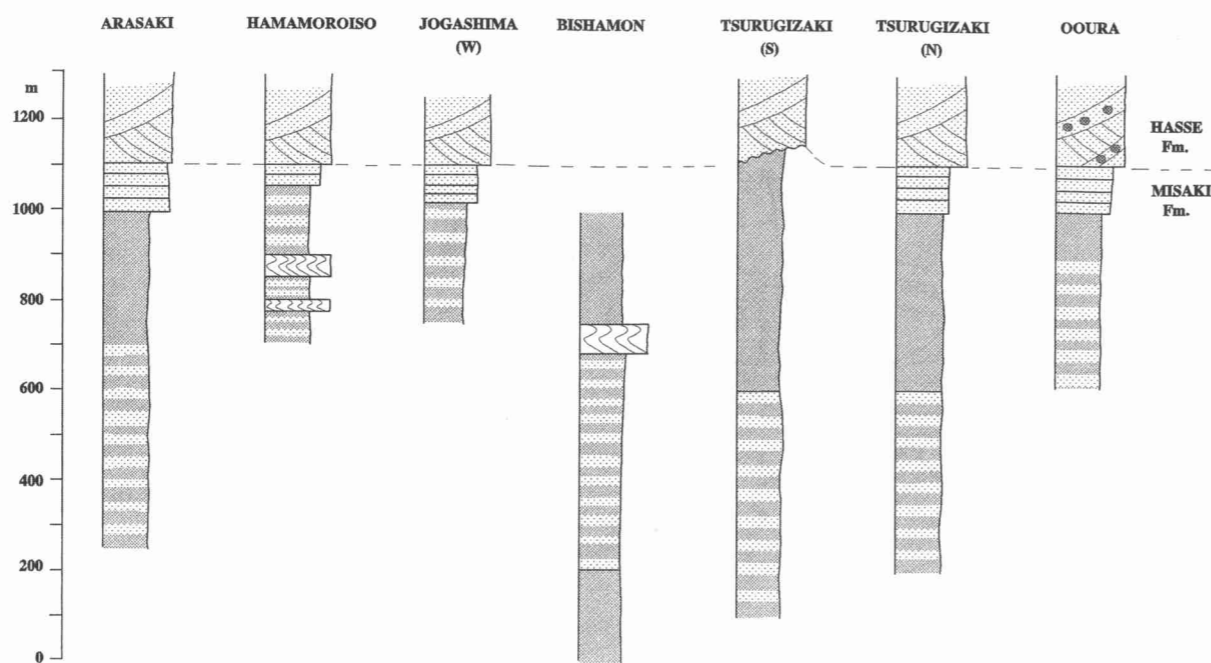


Fig. 15. Facies associations and their distribution within the Miura Group, Miura Peninsula.

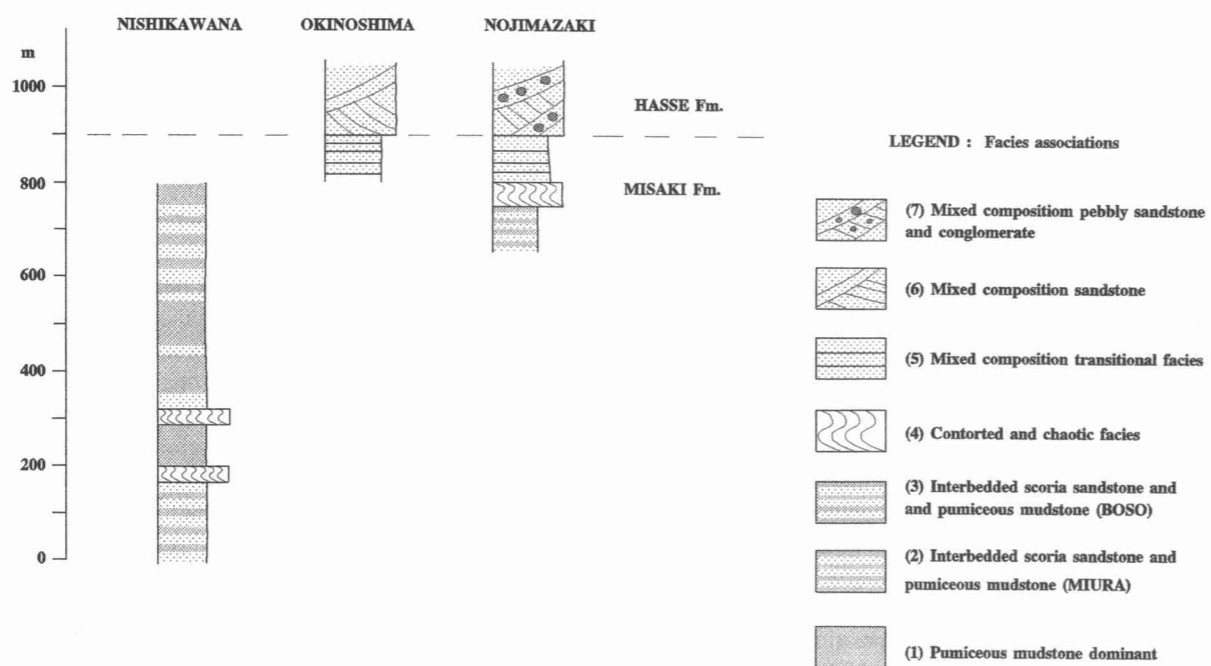


Fig. 16. Facies associations and their distributions within the Miura Group, Boso Peninsula.

transition zone a few tens of metres thick (Facies Association 5) at the top of the Misaki Formation. The overlying Hasse Formation is made up mainly of trough cross-stratified sandstones and pebbly sandstones (Facies Association 6) together with some coarser-grained material (Facies Association 7). A more chaotic zone (Facies Association 4) is present in some but not all of the measured sections. There are also zones within the Misaki Formation with more abundant tuffaceous layers interbedded with the other facies. The sections exposed along the Hamamoroiso and Jogashima shorelines are rather thinner than the other measured sections and do not have a thick development of the mudstone-dominated Facies Association (1) immediately below the transition into the Hasse Formation.

The nature and abundance of the scoriaceous beds within the Misaki Formation shows some constant variation across the peninsula (Figs. 15 and 16). At Jogashima, scoria beds form an average 38% of the measured section (Facies Association 1) and 52% of the transitional zone. The thickest beds are in excess of 3 m whereas, more typically, the thicker scoria beds range from 25 cm to 75 cm in thickness. Individual scoria clasts reach a maximum of 15 mm to 20 mm (very rarely up to 35 mm) in the main Misaki Formation, with the incoming of larger, more varied composition clasts (e.g. pumiceous mudstones) in the transition zone facies (maximum 110 mm) and in the Hasse Formation, where clasts are locally up to several tens of centimetres in diameter.

The section at Arasaki has on average a lesser proportion of scoria beds (approximately 16%), although this figure includes an average of 3% in Facies Association (1) and 22% in Facies Association (2). The transition zone has between 25% and 80% scoria beds. The maximum bed thickness, typically 25 cm to 75 cm and rarely up to 3 m and scoria clast sizes, typically up to 25 mm and more rarely 40 mm, are very similar to those found at Jogashima. Some particularly large mudstone clasts (1–2 m diameter) are found in the transition zone, whereas the Hasse Formation itself only has very rare clasts in excess of a few centimetres in diameter.

Sections measured further to the east, at Bishamon, Kenzaki, Tsurugizaki and Ooura, have generally less scoria beds (average 2–3% in Facies Association 1, average 8–12% in Facies Association 2).

The thicker scoria beds range from 10 cm to 30 cm, with very rare examples of 50 cm and 2.6 m maximum and clast sizes typically range up to 10–15 mm, very rarely 25 mm. The transition zone and Hasse Formation are thicker-bedded and coarser-grained, but without the large clasts found at Jogashima.

Although the general aspect of the Miura Group on the Boso Peninsula (Fig. 16) is similar to that on Miura, there are in fact many differences in detail. The main occurrence of the Misaki Formation is along the shore at Nishikawana. The lowermost part of this section (Facies Association 3) comprises an average of 34% mixed scoriaceous/pumiceous beds within the ubiquitous pumiceous mudstones. The maximum bed thickness, typically 0.5 m to 1.5 m and up to 2.8 m and clast sizes, typically several centimetres, maximum 15 cm, are only slightly greater than for the Jogashima Formation. The mixed-composition beds and the dominance of turbidites over pyroclastic fall facies, however, is significantly different. Much of the remaining section is very fine-grained and siltstone-dominated (Facies Association 1) with only localised occurrences of thicker, coarser-grained turbiditic scoria beds.

The transition between the Misaki and Hasse formations is apparently quite abrupt where observed, for example the Miori, Boda and Nojimazaki sections, and without the transitional facies association (5) encountered on the Miura Peninsula. The section measured at Okinoshima appears to be of transitional facies type although its stratigraphic context with respect to the Misaki Formation is unclear. In this area, interbedded pumiceous/tuffaceous sandstones, scoriaceous sandstones and coarse granular pumiceous siltstones pass upwards into large-scale cross-stratified scoriaceous/pumiceous beds rich in shallow-water shell debris and trace fossil assemblages.

The best exposures of the Hasse Formation are along the south coast at Shimazaki, Nojimazaki, Shiowa and Otsukama. Here, the typically brownish-coloured, coarse-grained, varied composition facies occur in thick to very thick or ill-defined beds. Locally these are very poorly sorted with clasts ranging up to several tens of centimetres, maximum 1.5 m. Structureless and crudely stratified beds are more common than the trough cross-stratification so typical of the Hasse Formation on Miura Peninsula.

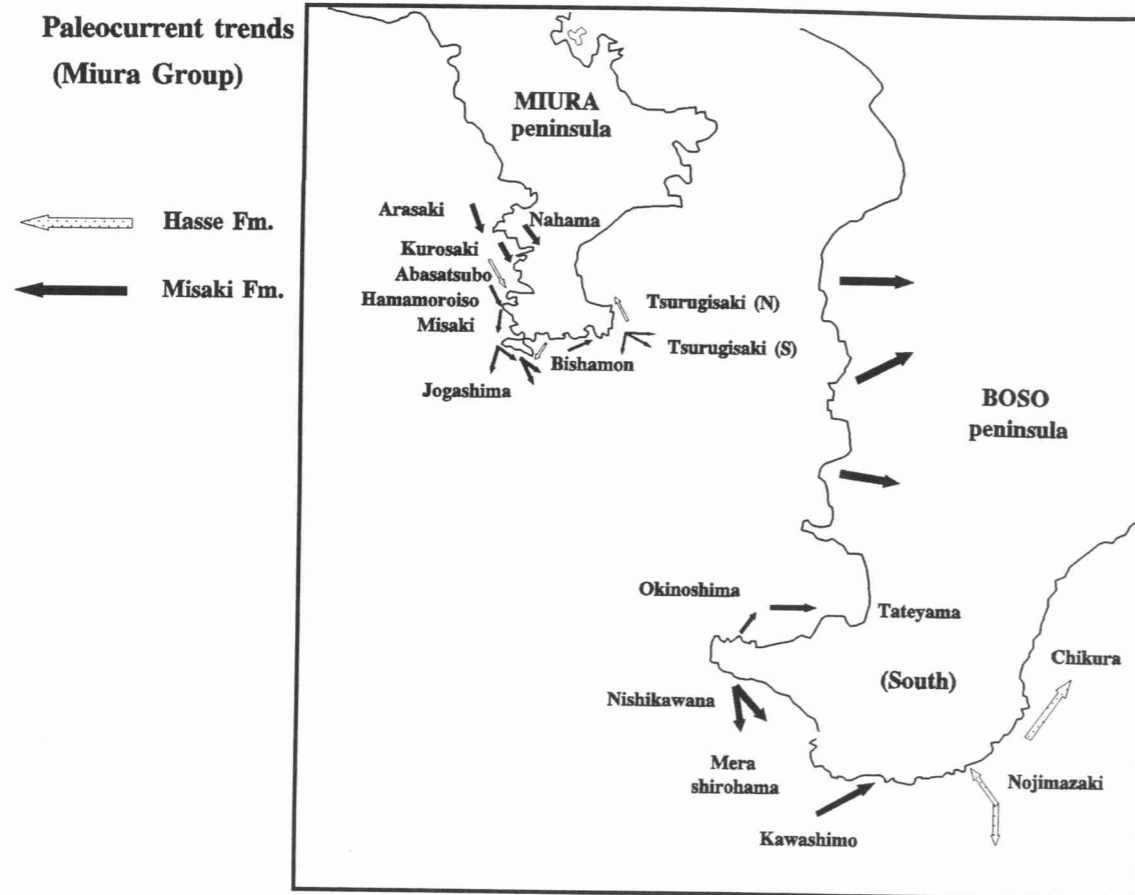


Fig. 17. Palaeocurrent measurements in the Miura Group sediments.

6.2. Palaeocurrent trends

Palaeocurrent measurements have been made on many hundreds of examples of cross-bedding together with more limited data from sole structures, mainly from the scoriaceous and mixed-composition sandy deposits. A summary of the dominant trends within the Miura Group on both the Miura and Boso peninsulas is shown in Fig. 17. In general, palaeocurrents within the Misaki Formation are directed towards the south and southeast on Miura Peninsula and towards the southeast to northeast on Boso Peninsula, with some exceptions and some apparently reverse flow directions in each region. Towards the top of the Misaki Formation, in the transition zone to the Hasse Formation, the flow directions locally become more variable, with indications

of shallow-water bedforms showing oscillation and reverse flows.

Although the Hasse Formation clearly indicates shallow-water conditions of deposition, for the most part the palaeocurrent measurements at any one locality are generally very consistent and unidirectional. On the Miura Peninsula, for example, they flow towards the southeast at Arasaki, towards the east and northeast on eastern Jogashima (Arasaki) and towards the northwest at Tsurugisaki. Palaeocurrent flow to the east, south and north are found in the Hasse Formation on Boso Peninsula.

These palaeocurrent trends for the turbidite-dominated lower part of the Miura Group are consistent with derivation of material from a source to the west if we take into account a probable 30° clockwise rotation of the Miura block since deposition.

This could have been an active part of the Izu–Bonin Arc at that time. The shallower-water transition zone and upper formations, then show evidence for alongshore as well as onshore–offshore sediment movement. However, the processes of accretion, left-lateral oblique motion and consequent deformation suffered by the Miura Group must call into question the precise validity of any palaeocurrent directions now preserved.

6.3. Vertical facies sequences

On a basin-fill scale, we have already noted the superposition of pumiceous mudstones with interbedded scoriaceous sandstones, a transitional coarser-grained zone and overlying mixed-composition sandstones and conglomerates (Figs. 15 and 16). This is believed to result from basin-shallowing related to uplift and accretion. The scoriaceous sandstones are mostly interpreted as resedimented volcanoclastic turbidites interbedded with slope basin hemipelagites, so that we might expect vertical sequences of facies, on a scale of a few metres to a few tens of metres, analogous to those common in other turbidite systems (e.g. Stow, 1985a, 1986; Stow et al., 1996).

However, careful logging of many hundreds of metres of section at various localities on both Miura and Boso peninsulas has revealed no obvious mesoscale sequences that show systematic trends of either grain size or bed thickness. As mentioned previously, the Miura Basin succession does show variations in the relative proportion of coarse-grained scoriaceous and background pumiceous beds both regionally and temporally, but with no clear regularity of change. This type of random pattern or non-sequence would appear to be compatible with deposition in a slope-basin or slope-apron setting, without development of long-term channel-levee or fan systems. The main control on input of volcanoclastic turbidites would have been volcano-tectonic activity on the adjacent Izu–Bonin Arc, as found for the turbidite–debride record recovered from ODP boreholes further south along the Pacific margin of the arc (Hiscott et al., 1992; Forster, 1995).

Within the mudstone-rich facies association, which is the dominant one in most sections, there is no evidence of small-scale sequences. Where there are more scoriaceous turbidites present there are

thinning- and thickening-upwards sequences over a few metres of section interspersed with a more random arrangement of bed thickness. However, there is insufficient evidence at present to interpret these as turbidite compensation cycles (Mutti and Sonnino, 1981) or as due to some other forcing mechanism.

6.4. Miura Basin development

The late Cenozoic collision of the Izu–Bonin Arc with the Honshu Arc in south central Japan is well recognised and has been documented by several authors (e.g. Matsuda, 1978; Niitsuma, 1988). The tectono-sedimentary effects of this arc–arc collision are recorded in the basins that surround the Tanzawa Mountains–Mount Fuji–Izu Peninsula impact zone. This latter is the most recently impacted block that has been accreted to the Honshu Arc from the Izu–Bonin Arc. The sediments preserved in an arcuate zone to the north represent fill and uplift of foredeep basins developed between the two arc systems (Ito and Masuda, 1986; Ito, 1987). The Neogene succession of Kakegawa to the west is interpreted as the fill of a forearc basin in front of the Honshu Arc, whereas that of the Miura–Boso peninsulas to the east represents forearc sediments that accumulated in a slope-apron/slope-basin setting east of the Izu–Bonin Arc (Ogawa, 1982, 1983, 1985).

The present detailed study of sedimentary successions on both the Miura and Boso peninsulas is conformable with their origin in a forearc to trough setting (Soh et al., 1990) and has shown three distinct phases of development for the Miura Basin from the Mid-Miocene to Pliocene (Fig. 17).

6.4.1. Slope-apron/slope-basin (14–7 Ma approx.)

The first phase was one of normal deep-water slope-apron sedimentation on the Pacific flank of a mainly submarine arc. A general lack of terrestrial woody debris or shallow-water fragments attest to the submerged nature of arc volcanoes. A water depth of 1–1.5 km (or more) is inferred for the slope-apron sediments from benthonic foraminiferal assemblages. The succession is dominated by calcareous pumiceous mudstones of hemipelagic origin, that have been influenced in parts by thermohaline bottom currents. The onset of this bottom current activity may have been related to marked

global cooling, the build up of ice in Antarctica and intensification of Antarctic Bottom Water flow (Stow and Faugères, 1990). Alternatively, the incipient Kuroshio (surface) Current may have been sufficiently large and powerful to affect sedimentation at slope depths (1–2 km).

This background sedimentation was punctuated by subaqueous pyroclastic fall events and episodic volcanoclastic turbidites, both introducing dark scoriaceous material from the adjacent Izu–Bonin Arc. Very thick-bedded, coarse-grained turbidites, debrites and syndimentary slides were deposited locally, especially towards the latter part of this period. There is no firm evidence for direct pyroclastic flow deposits, although some of the complex beds may have resulted from mixed pyroclastic/turbiditic processes.

The differences in facies development, composition and palaeocurrent directions suggest that the Miura–Boso sediments were derived from several sources along the Izu–Bonin Arc without the development of well-established channel or fan systems. The Miura and Boso areas may have acted as two or more distinct slope basins during much of this period.

6.4.2. Shallowing phase (7–6 Ma approx.)

The second phase was a relatively rapid and short-duration period of marked regression. The hemipelagic background sediment is much reduced between thicker, coarser-grained and more abundant scoriaceous beds. Most of these probably originated as turbidites, but many now show considerable evidence of reworking by shallow-water processes, including tidal, wave and storm-induced currents. The sediment composition becomes more mixed and varied and in some places, neritic shell debris and intensive bioturbation are present.

We interpret this sudden onset of regression as marking the beginning of accretion and uplift of the Miura–Boso forearc region. Unfortunately, biostratigraphic dating of this event is not yet sufficiently refined to be certain of the precise age of onset and it seems likely that this transitional phase was regionally time transgressive.

6.4.3. Shallow-water/fan-delta (6–3 Ma approx.)

Following the relatively short transition period, the third phase was one of shallow-water condi-

tions throughout the Miura–Boso region. There is a complete dominance of tidal and wave-reworked mixed-composition facies in the Hasse Formation on Miura Peninsula, together with coarse-grained debrites, slumps and associated proximal fan-delta facies on Boso Peninsula. Without any interbedded marine mudstones it is uncertain whether or not some of the Hasse Formation on Boso was deposited on the subaerial position of a fan delta.

Clearly, this phase represents continued significant uplift of the depositional basin and its principal source area, the Izu–Bonin Arc. Input from another source is indicated by the incoming of clasts of Palaeozoic rocks, schists and volcanics derived from the Honshu Arc to the west. Accretion to mainland Japan was therefore well established by this time. The general lack of primary pyroclastic flow and fall deposits further indicates the cessation of active volcanicity in the immediate area. Shortly following accretion of the Miura block onto the Honshu Arc, dextral strike-slip movement had predominated (from about 2 Ma; Seno, 1989) bringing the peninsulas into their present location. Detailed structural studies of the Miura Group (Ogawa, 1978, 1982; Pickering et al., 1990) have demonstrated the chronology of deformation that has occurred; (a) normal faulting prior to accretion, (b) vein injection related to N–S compression, (c) section shortening via bed-parallel thrusts, high-angle reverse faults and limited folding, and (d) oblique-slip faulting and folding related to dextral transtension and transpression after accretion of the Miura block. The widespread wet-sediment injection and brachiation, preferentially along bed-parallel thrusts, that is commonly observed in the Miura Group mainly occurred during (c) above, under conditions of elevated pore-fluid pressure in the deforming sediments (Pickering et al., 1993). These injected sediments may represent the preservation of parts of one or more mud volcanoes that developed along the margin during compression and eduction.

7. Conclusions

Several very interesting and more generally applicable conclusions have emerged from this detailed study of sediment facies and processes in the Miura Basin.

(1) The Miura Basin development outlined in this study has close analogues in other parts of the Izu–Bonin/Honshu arc–arc collision zone in south central Japan. For example, the infill of late Cenozoic basins north of the Izu Peninsula (including Aikawa, Fujikawa and Ashigara basins) comprises a variety of volcanoclastic and siliciclastic facies arranged in thick regressive cycles that represent evolution from deep-sea, through slope-apron/submarine fan to fan-delta depositional settings (Ito, 1985, 1986, 1987; Ito and Masuda, 1986; Soh, 1986). The facies of the seaward slope system (Ito, 1987) may be most directly analogous to those of the Misaki Formation. The present-day Bonin–Mariana forearc region was drilled by DSDP–IPOD Leg 60 (Hussong et al., 1981) and again on ODP Leg 126 (Taylor et al., 1992), whilst the forearc and trench area off the main Honshu Arc was examined during ODP Leg 131 (Hill et al., 1993). Sediments recovered on these Legs show close similarities to the lower part of the Miura Group. Accretion and eduction of the Miura block has led to its distinctive regressive sequence of facies and the complex interaction of depositional processes in its development.

(2) The composite model presented for the depositional setting of the Miura Basin during the Miocene and Early Pliocene is believed to be widely applicable to slope sedimentation off any active volcanic chain or isolated seamount. Numerous examples of sedimentary successions have been documented from forearc basins (e.g. Van Weering et al., 1989; Seyfried et al., 1991), backarc basins (e.g. Pirrie and Riding, 1988; MacDonald et al., 1988) and marginal basins (e.g. Kokelaar and Howells, 1984), in other parts of the world, and many of these show very similar facies and organisation to the Miura Basin.

(3) Of particular significance is the range of processes that have contributed to deposition of Miura Basin sediments. In the shallow-water parts of the basin the direct input of coarse-grained volcanoclastic sediments via pyroclastic processes is very evident, followed by extensive shallow-marine reworking and offslope transfer of material. For the deeper-water parts of the margin, deposition involves hemipelagic, bottom current, turbidity current, debris flow, sliding and pyroclastic fall processes. Equally important is the fact that, in many cases, individual beds

are seen to result from complex process interaction rather than single processes. These have involved: (a) multiple input hemipelagic deposits coupled with extensive bottom current reworking; and (b) multiple explosive eruptions leading to, mainly subaqueous, pyroclastic flows and large-scale ash falls that then evolve into debris flows and turbidity currents.

(4) Although the Miura Basin succession has undergone considerable deformation during accretion as part of a forearc complex and eventual eduction as a result of arc–arc collision, the sedimentary record has been clearly preserved. A variety of disturbed and chaotic units provide evidence of widespread syndimentary injection as thin sediment dykes and sills and larger-scale diapirs. Without careful observation such units can be easily misinterpreted as normal slide or debris flow deposits.

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