Neogene contourites, Miura–Boso forearc basin, SE Japan

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Abstract: The mid to late Miocene Misaki Formation sediments of the Miura and Boso peninsulas, south central Japan, were deposited in the Pacific-facing forearc region of the proto Izu-Bonin arc at bathyal depths. The hemipelagic background facies, composed mainly of calcareous biogenic and pumiceous voicaniclastic material, are interbedded with thin to thick scoriaceous beds of turbiditic and pyroclastic fall origin. Careful study in the field and in the laboratory of these fine-grained background sediments has revealed the marked influence of bottom currents at certain horizons in producing intervals with distinct muddy contourite characteristics. These include: a general absence of primary structures due to intense bioturbation, some diffuse layering, irregular concentrations of coarser-grained material, sharp and erosive top and bottom lamina contacts, rare micro-cross-lamination disrupted by bioturbation that was continuous with deposition, and a mixed pelagic biogenic (commonly fragmented), volcaniclastic and terrigenous composition. Small-scale cyclicity of variations in grain-size and structural features can be related in part to episodic volcaniclastic input and in part to fluctuation in bottom current strength. Evidence for bottom current reworking of the tops of thin-bedded sandy turbidites is equivocal, and further work is required to resolve this debate. The recognition of Miocene-age contourites from the NW Pacific provides further evidence for the existence of active deep-ocean circulation in the Pacific at this time. However, it is not possible to determine which current system, Antarctic Bottom Water or deep Kuroshio Current, was responsible for these outcrop examples of fossil contourites.

In the search for reliable outcrop analogues of contourites, the Mio-Pliocene Miura Group of SE Japan provides a good example of fine-grained calcareous volcaniclastic hemipelagites that have, in part, been influenced by bottom currents. These were initially recognized as probable contourites during a joint British–Japanese research programme in the 1980s, and first described at the 13th International Geological Congress in Nottingham, UK (Stow & Faugères 1990). They have been referred to in subsequent publications on the area (Lee & Ogawa 1998; Stow *et al.* 1998*a*), as well as in a general review of fossil contourites (Stow *et al.* 1998*b*).

However, the original muddy-silty contourites have not yet been fully described and illustrated, whereas the sandy, cross-laminated facies documented by Lee & Ogawa (1998) are considered by the senior author (Stow *et al.* 1998*a*, *b*) to be thin-bedded turbidites. The aim of this joint paper, therefore, is to present the data pertaining to a muddy contourite interpretation, to propose the section as a type example of fossil contourites that are closely interbedded with other deep-water volcaniclastic facies, and to further discuss the possibility of bottom current reworked sandy turbidites.

More recently, Ito (1996, 1997, 2002) has interpreted parts of the overlying succession in the Boso peninsula, the Plio-Pleistocene Kasuza Group, as the result of bottom current reworking and winnowing of turbidite tops. This interpretation is also questioned by the present senior author and joint work is currently in progress to attempt to resolve this issue.

A wealth of stratigraphic and structural data already exists from previous work in the region. This has been used to support detailed fieldwork on the well-exposed sedimentary succession of the Miura Group throughout the Miura and Boso peninsulas.

Geological and oceanographic setting

Geological setting

The Miura and Boso peninsulas are located just south of Tokyo, flanking the entrance to Tokyo Bay from Okinoyama Bank (Figs 1 and 2). They lie on the NE side of the Izu collision zone between the Izu-Bonin and Honshu island arc systems, and adjacent to Sagami Trough (a short segment of oceanic trench) immediately north from the Boso trench–trench–trench triple junction (Ogawa & Taniguchi 1988, 1989). The Neogene age Miura Group is one of the chief components of the onland geology in this area. It has

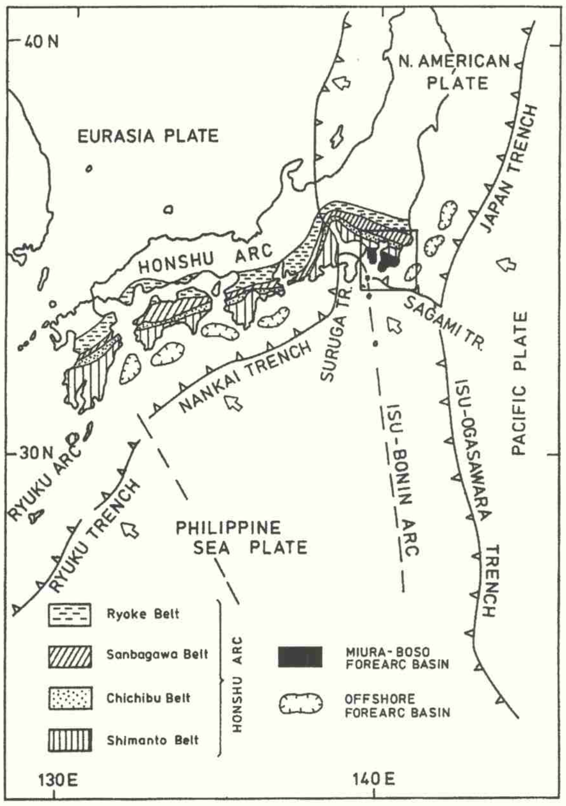

Fig. 1. Regional plate tectonic setting of the Miura-Boso basin. Study area (boxed) is shown in Figure 2 (From Stow *et al.* 1998*a*).

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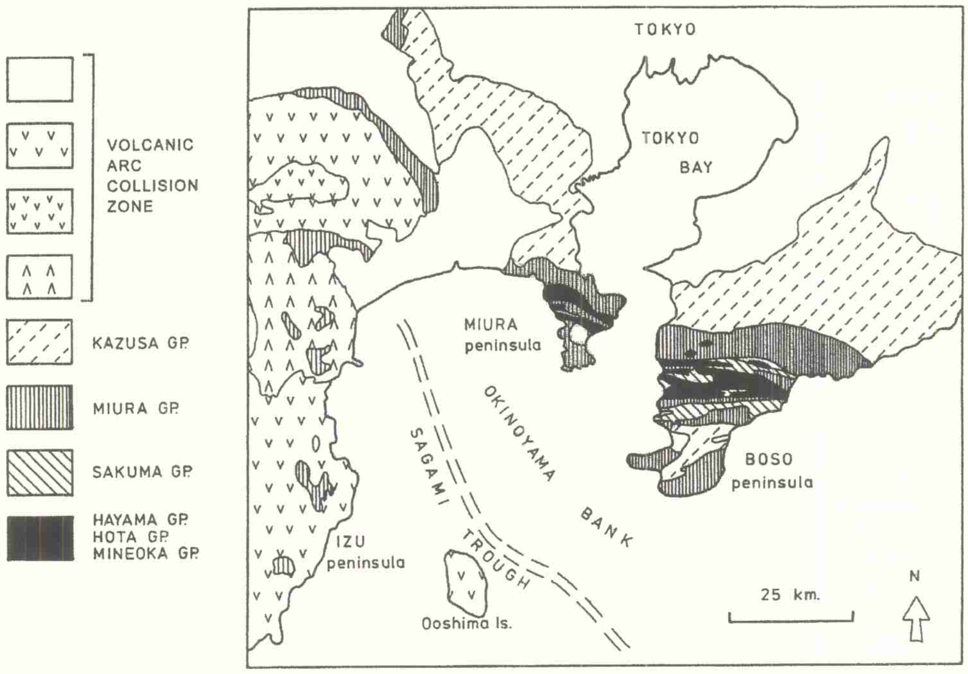

Fig. 2. Simplified geological map of the Miura-Boso peninsulas and adjacent areas. (From Stow *et al.* 1998*a*).

been interpreted as a shallowing-upward succession that accumulated over a 10.5 Ma period from about 13 Ma to 2.5 Ma in a forearc slope-basin setting, as the Philippine Sea plate moved northwards at a rate of 2.5 cm a^{-1} (Soh *et al.* 1991; Taira & Ogawa 1991). Continued collision between the two arc systems resulted in the accretion of the Miura Group from the Philippine forearc region onto the Honshu arc at around 2 Ma.

This accretion involved considerable dextral oblique-slip motion and associated structural deformation (Taira *et al.* 1982; Pickering *et al.* 1990). The latter resulted in a complex series of folds and minor faults, wet-sediment deformation, injection and veining, and bedding-parallel to sub-parallel thrusts. Nonetheless, apart from significant section duplication, the sedimentary succession shows very good preservation and is well exposed, especially in coastal exposures around both peninsulas (Soh *et al.* 1989; Stow *et al.* 1998*a*).

Oceanographic setting

The present day pattern of bottom currents in the NW Pacific has been summarized by Lee & Ogawa (1998) from various sources (Fig. 3, Table 1). It is dominated by south and SW-directed North Pacific Deep Water (NPDW) and generally north-flowing Antarctic Bottom Water (AABW). NPDW lies at depths in excess of 2000 m and down to at least 5800 m in the Japan Trench, where long-term current measurements have recorded steady SW-flow over a period of one year with a maximum velocity of 15–30 cm s^{-1}. AABW, having found its way along the Mariana and Izu-Bonin trenches or through the Yap gateway and north across the Philippine Sea, is then forced to turn either back towards the south or to continue northeast around the Pacific rim. Long-term bottom current measurements on the Pacific flank of the Izu-Bonin Arc show two directions. Deeper than 4000 m, there is a southerly-directed current interpreted as the NPDW, whereas above 2000 m AABW flow is steadily towards the north. In both cases maximum velocities of around 15–20 cm s^{-1} have been recorded.

Of the surficial currents around the Japanese mainland, only the warm-water Kuroshio current is of sufficient magnitude to have any influence at depth. Whereas surface velocities can be in excess of 180 cm s^{-1}, speeds as high as 40 cm s^{-1} have been measured at 2000 m water depth (Taft 1978; Fukazawa *et al.* 1985). Regular periodicity in both deep and shallow currents typically show a tidal, seasonal and/or longer term component. Measurements of internal tides with velocities in excess of 50 cm s^{-1} have been recorded from 2000 m water depth in both the Suruga and Sagami Troughs (Okada & Ohta 1993).

It seems most likely that a very close precursor of the present day circulation system in this part of the NW Pacific Ocean would have been in existence from at least early to mid-Miocene time. Development or intensification of AABW and its penetration into the North Pacific occurred in response to Antarctic cooling in the mid-Miocene (Wright & Miller 1993) and the development of the NPDW would have occurred at a similar time. Both the warm-water Kuroshio and cold-water Oyashio currents were in existence at around 17–16 Ma (Tsuchi & Ingle 1992). Although Stow & Faugères (1991) propose an AABW influence on the Miura Group, and Ito (1997, 2002) suggests a deep Kuroshio current influence for the Kazusa Group, we cannot be certain which deep water system was present during the time period considered here.

Palaeobathymetry

The overall sediment facies and ichnofacies characteristics of the Miura Group clearly show a shallowing upward succession from deep water (undisturbed turbidites and bioturbated hemipelagites of the Misaki Formation) to shallow water (high-energy sandy tidal and channel-fill facies of the Hasse Formation) (Soh *et al.* 1989, 1991; Stow *et al.* 1998*a*). There is also a trend towards a deeper eastern part of the inferred forearc basin, now represented by Boso peninsula sediments. For the older parts of the Misaki Formation, i.e. mid-Miocene time period, palaeodepth estimates based on benthic foraminiferal assemblages range from 2000 to 3000 m for the Miura peninsula to over 4000 m for the Boso peninsula (Ando *et al.* 1989; Akimoto *et al.* 1991). Rapid shallowing then took place through the mid to late Miocene, with eventual uplift and accretion during the Pliocene. Palaeodepth estimates from part of the Hasse Formation are around 100–200 m.

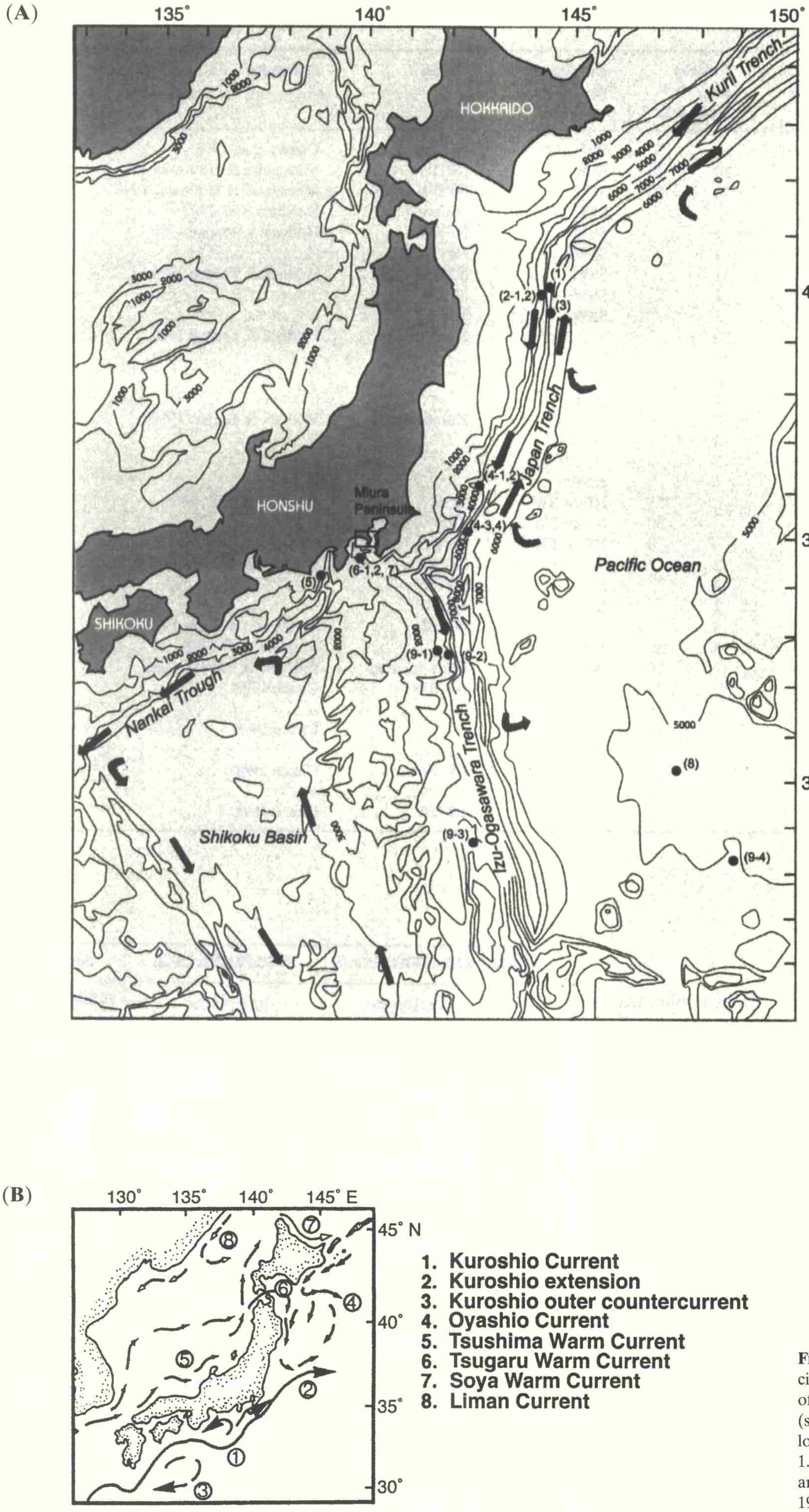

Fig. 3. (**A**) Present-day deep-water circulation in the NW Pacific region south of Japan, summarized from various sources (see Lee & Ogawa 1998). Numbers refer to location of current measurements in Table 1. (**B**) Present-day surface circulation around the Japanese islands. (From Ito 1997).

Table 1. *Summary data on present-day bottom currents from the NW Pacific region, south and east of Japan. Mostly based on long-term current-metre moorings as well as some direct seafloor observations*

Location	Depth (m)	Depth of current metre	Velocity (cm s^{-1}) mean-max		Dominant direction	Origin	Reference	Map key
Japan Trench	6400			30	SW	NPDW	Ogawa *et al.* 1996	1
Japan Trench	5805	5755	10	20	SSW	NPDW (+tide)	Mitsuzawa & Holloway 1998	2–1
Japan Trench	4220	4185	10	20	SSW	NPDW (+tide)	Mitsuzawa & Holloway 1998	2–2
Japan Trench	5000–6000				SSW to NNE	(video)	Horiuchi *et al.* 1993	3
Japan Trench	3100	2043	1		SSW	NPDW	Hollock & Teague 1996	4–1
		3043	1		SSW	NPDW		
Japan Trench	4400	2160	1		SSW	NPDW	Hollock & Teague 1996	4–2
		3145	2		SSW	NPDW		
		4169	2		SSW	NPDW		
Japan Trench	6500	409	30			Kuroshio	Hollock & Teague 1996	4–3
		1909	10					
		2824	5					
		4824	2		NNE			
Japan Trench	5400	517	15			Kuroshio	Hollock & Teague 1996	4–4
		1984	4					
		2984	3					
		4984	4		NNE			
Suruga Bay	1980	850		25	NE or SW	Tidal	Mitsuzawa *et al.* 1991	5
		1160		30	NE or SW	Tidal		
		1970		70	NE or SW	Tidal		
Sagami Trough	Approx 2000	2063	2		S	NPDW	Terramoto & Taira 1985	6–1
		2042	4		S	NPDW		
		1979	2		S	NPDW		
Sagami Trough	1597	1590	4		S	NPDW	Terramoto & Taira 1985	6–2
Sagami Trough	1174	1173	5	20	SW		Momma *et al.* 1998	7
Western Pacific	6200	5000		10	All directions	Eddy currents	Imawaki & Takano 1982	8
Izu-Bonin Ridge	3220	1820		20	NE	AABW	Chaen 1998	9–1
		2820		15	N or S			
Izu-Bonin Ridge	5260	3860		15	N or S		Chaen 1998	9–2
		4860		15	SE			
Izu-Bonin Ridge	4300	3900		20	SE	NPDW	Chaen 1998	9–3
				10	NW or N			
Izu-Bonin Ridge	5550	4100		15	SE	NPDW	Chaen 1998	9–4

Stratigraphic context

The general age and stratigraphy of the Miura Group are well known from palaeontological and palaeomagnetic studies. These data have been summarised in several recent papers (e.g. Kanie *et al.* 1991; Soh *et al.* 1991; Lee & Ogawa 1998; Stow *et al.* 1998*a*) and are illustrated in Figure 4. The basic subdivision is into the lower Misaki Formation, which is conformably to unconformably overlain by the upper Hasse Formation (also known as Hatsuse). However, the base of the Misaki formation is either unconformable or poorly exposed and the top is marked by a significant unconformity, so that a precise age range is less easily established. Estimates of the basal age range from 13 Ma to 10 Ma, while the top is generally taken as 2.5 Ma. Transition from the Misaki to Hasse formations appears to be diachronous from late Miocene in the Boso peninsula to early Pliocene in the Miura peninsula.

Recently much effort has been made to refine dating and attempt basinwide correlation using ash marker beds with some degree of success, particularly for the Miura Peninsula (Fig. 5) (Horiuchi & Taniguchi 1985; Kanie & Hattori 1991; Lee & Ogawa 1998).

Estimates of the total thickness of each formation and of the Miura Group as a whole are also subject to some uncertainty as a result of section duplication and thickening along bedding-parallel thrust faults. The figures given in Figure 4, from over 900 m to over 2000 m for the Misaki Formation are now considered to be

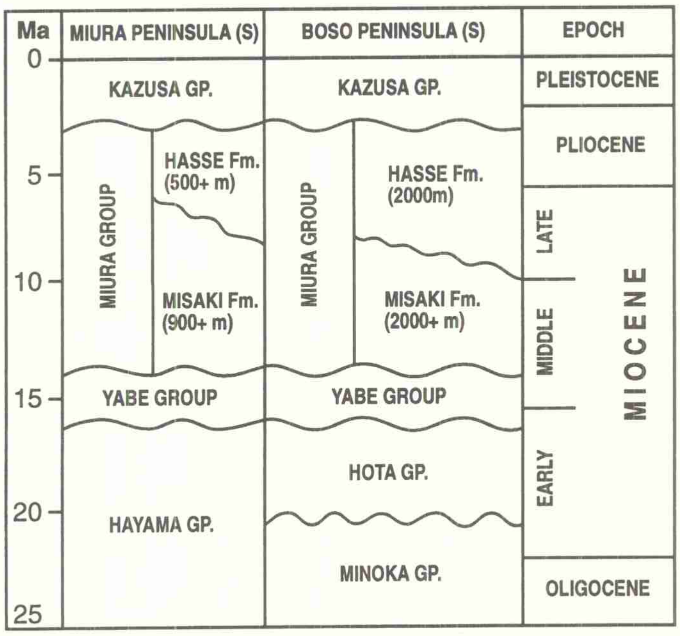

Fig. 4. Summary stratigraphy for the Miura–Boso area. (From Stow *et al.* 1998*a*). There is still uncertainty regarding the basal age of the Miura Group.

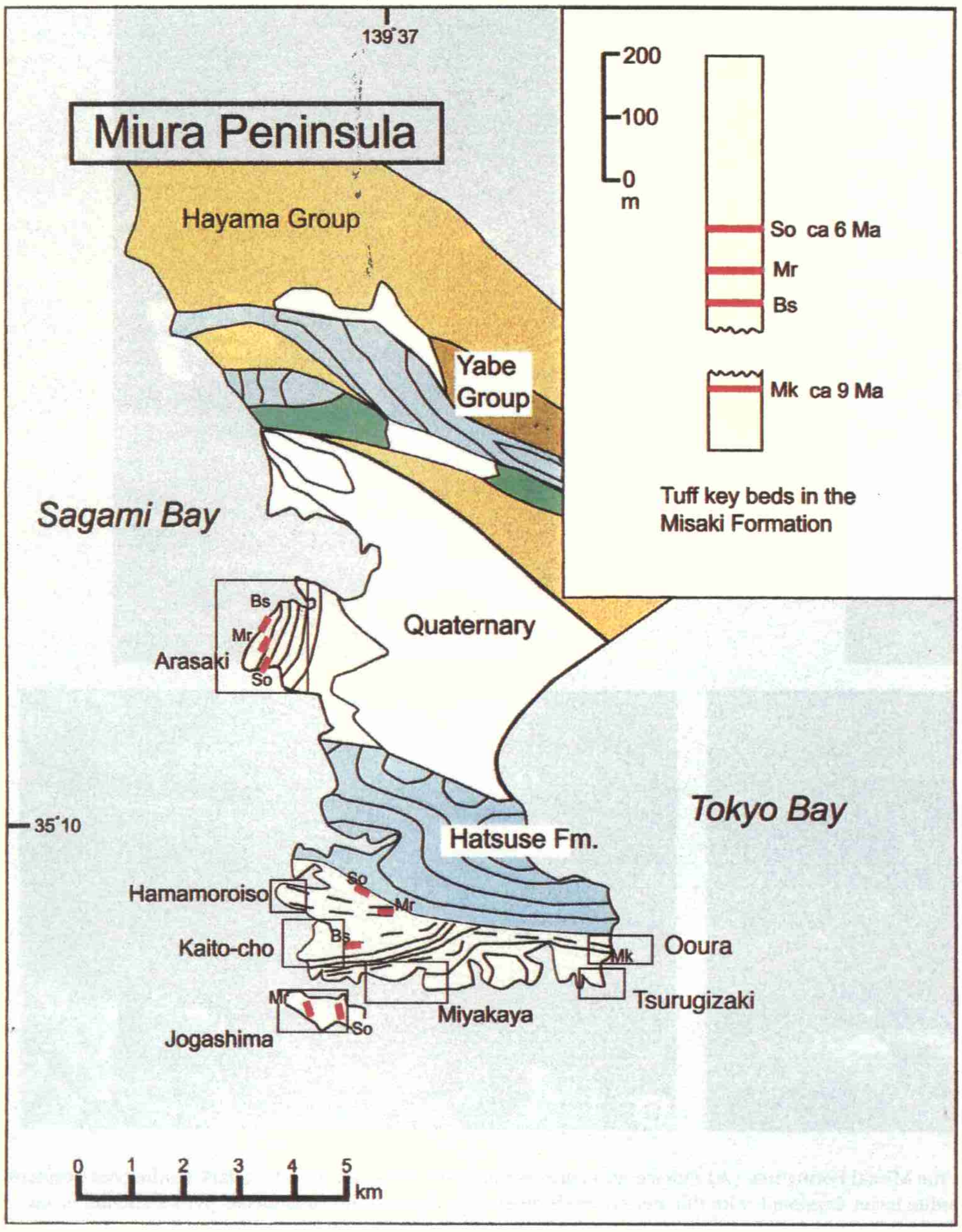

Fig. 5. Schematic geological map of the Miura Peninsula showing distribution of the Misaki Formation, representative key tuff horizons (with radiometric ages), and principal localities referred to in text. (Modified from Lee & Ogawa 1998).

overestimates, perhaps by about 50%. If we take a thickness range of 700–1400 m for the Misaki Formation deposited in a time period of 7 Ma, then we obtain an average sedimentation rate of 100–200 m Ma^{-1} (10–20 cm ka^{-1}). The Hasse Formation probably accumulated more rapidly than this. Note that these figures are for compacted, lithified sediment and include both rapidly deposited event beds as well as more slowly deposited background hemipelagites and contourites.

Sediment facies

Misaki formation facies

Based on previous detailed description and interpretation of the Misaki formation (Stow *et al.* 1998*a*), we recognize six separate facies groups comprising 22 individual facies (Fig. 6). These include coarse-grained scoriaceous beds (Facies Groups A, B and C), fine-grained pumiceous beds (Facies Group D), tuffaceous beds (Facies Group E) and disturbed or chaotic strata (Facies Group F).

The scoriaceous beds are distinctive dark-coloured layers making up 5–45% (average 10–20%) of the succession. They are composed mainly of basic to intermediate composition lava clasts and grains, with rare pumice fragments, set in a matrix of altered glass and vitric ash. The scoria are typically low-alkali tholeiite series basaltic andesite, similar in composition to the present day Izu-Oshima Island volcanics. They are event beds, mainly deposited by turbidity currents, debris flows and direct pyroclastic fall processes.

The dominant (background) facies making up 55–95% of the Misaki formation are the light-coloured, fine-grained (mud-silt grade), pumiceous sediments. They are composed of variable admixtures of pumice, clays, biogenic material and scattered scoriaceous debris. Bioturbation is dominant throughout. These are interpreted as slowly deposited hemipelagites and contourites.

At certain horizons through the succession are distinctive, light-coloured, thin-bedded, acidic composition tuffaceous beds. These are the ash layers that can be correlated across the basin on the basis of their characteristic geochemical signatures, and some of which have been radiometrically dated. Their sedimentary structures indicate that most have been deposited by low-concentration turbidity currents.

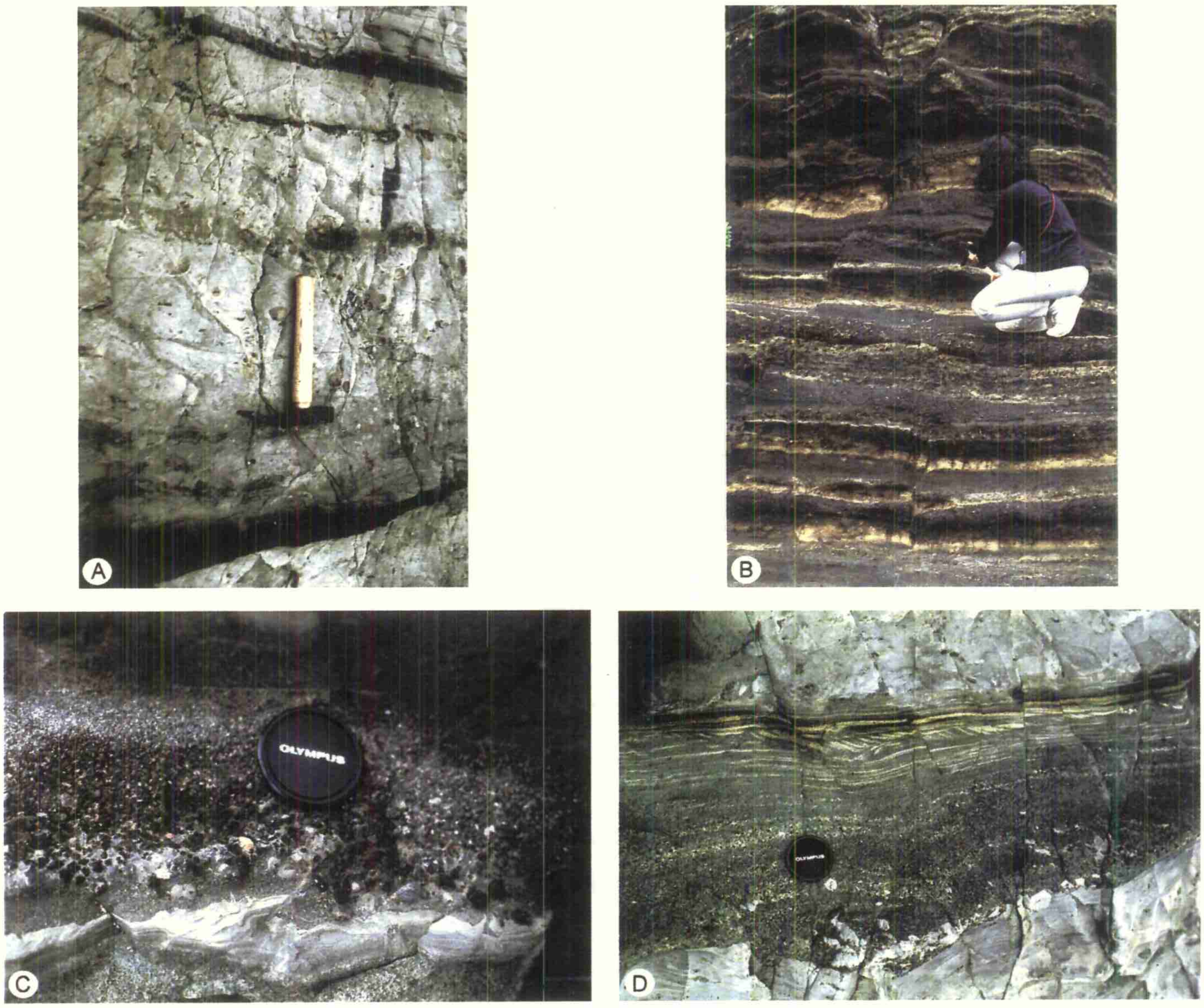

Fig. 6. Photographs of representative facies from the Misaki Formation. (**A**) Pumiceous hemipelagite facies dominant, with thin dark scoriaceous horizons and brown sideritic nodules. (**B**) Scoriaceous turbidite facies dominant, with thin pumiceous horizons. (**C**) Scoriaceous subaqueous pyroclastic-fall facies. (**D**) Mixed composition volcaniclastic turbidite, showing Bouma A–E divisions, sharp erosive base and large pumiceous clasts.

A variety of disturbed and chaotic strata are recognized including clear slump and debris flow units on the one hand, and sediment injection bodies on the other. The latter are most likely related to the period of post-depositional disturbance caused by compression, eduction and accretion of the Miura forearc basin succession.

Contourite characteristics

Within the background hemipelagic facies, there are certain intervals that show a greater influence of bottom current activity during sediment accumulation (Fig. 7). The evidence for this includes:

- A general absence of primary sedimentary structures through much of the facies, but intervals with clear but diffuse layering (indistinct parallel lamination).
- Intervals with remnant parallel and rare cross-lamination of dark scoriaceous material within the light-coloured pumiceous mudstone.
- Irregular concentrations and elongate lenses of coarse scoriaceous and bioclastic material.
- Sharp and/or erosive contacts associated with zones of diffuse lamination and slightly coarser grain sizes.
- An ichnofacies assemblage dominated by *Chondrites*, *Helminthoides*, *Planolites* and *Zoophycos* together with intense bioturbation throughout, but an apparent absence of *Zoophycos* and larger trace fossils in the more laminated zones.
- These diffusely laminated intervals show bioturbation continuous with deposition, together with localised sharp horizons of non-deposition or minor erosion below which a slightly different ichnofacies is apparent, including short vertical burrow systems.
- A grain size that is typically poorly-sorted mudstone, but varies from sand-rich muddy silt to silty clay, and includes localised lenses or layers of slightly better sorted coarse silt and sand-size material.
- Cyclic grain size variation between more and less silty (sandy) mudstones over intervals of about 10 cm to 100 cm, in some cases probably due to increased volcanic input of sandy scoriaceous material, but in other cases varying in phase with the diffusely laminated intervals and so interpreted as fluctuation in the strength of bottom current activity.
- A mixed pelagic/biogenic and volcanogenic/terrigenous

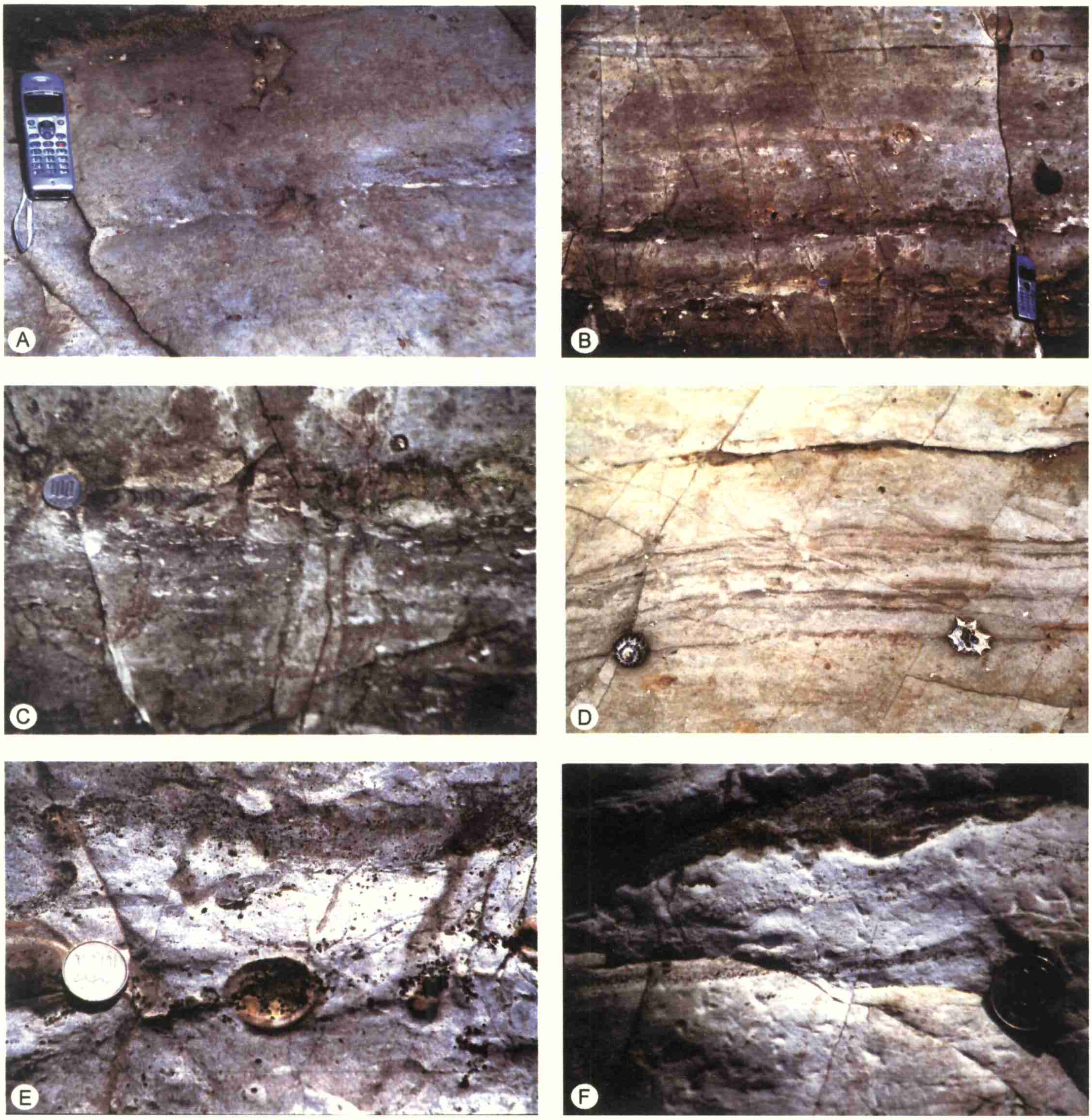

Fig. 7. Selected photographs of contourite facies from the Misaki Formation. (**A**) Uniform silty mud with indistinct parallel lamination, vague bioturbational mottling and rare burrows. Ooura, Miura Peninsula – width of view approx. 15 cm. (**B**) Uniform muddy silt with indistinct parallel lamination, intense bioturbational mottling, common burrows. Note minor erosive/non-deposition horizons (or omission surfaces) with more vertical burrows evident. Pale buff-coloured silty-sandy layer near base. Ooura, Miura Peninsula – width of view approx. 15 cm. (**C**) As for **B**, with buff-coloured sandy contourite towards top. Ooura, Miura Peninsula – width of view approx. 15 cm. (**D**) Typical pumiceous silty mud contourite facies from near Mera on Boso Peninsula. Note silty lamination, somewhat diffuse in parts and disturbed by burrowing. Width of view approx. 15 cm. (**E**)Muddy to silty hemipelagite-contourite facies with bioturbation, burrows, scattered nodules and dispersed scoriaceous grains. Tsurugusaki, Miura Peninsula – width of view approx. 15 cm. (**F**) As for **E**, with clearer but still diffuse layering of silty material within muddy background. Tsurugusaki, Miura Peninsula – width of view approx. 15 cm.

composition, including foraminifers, nannofossils, diatoms and radiolarians, dominant pumiceous glass with intermediate to high acidic composition and minor basaltic scoriaceous grains, and clays from both detrital and volcanic alteration sources.

- Much of the coarser biogenic material is fragmeneted and, in some cases, iron stained.

Most of these features are consistent with deposition of fine muddy and silty contourites under the influence of weak to moderate, fluctuating bottom currents (Fig. 8). One distinctive facies is a better sorted pumiceous siltstone (to very fine silty sandstone) with plane parallel lamination, without scattered scoria and with minor bioturbation throughout, continuous with

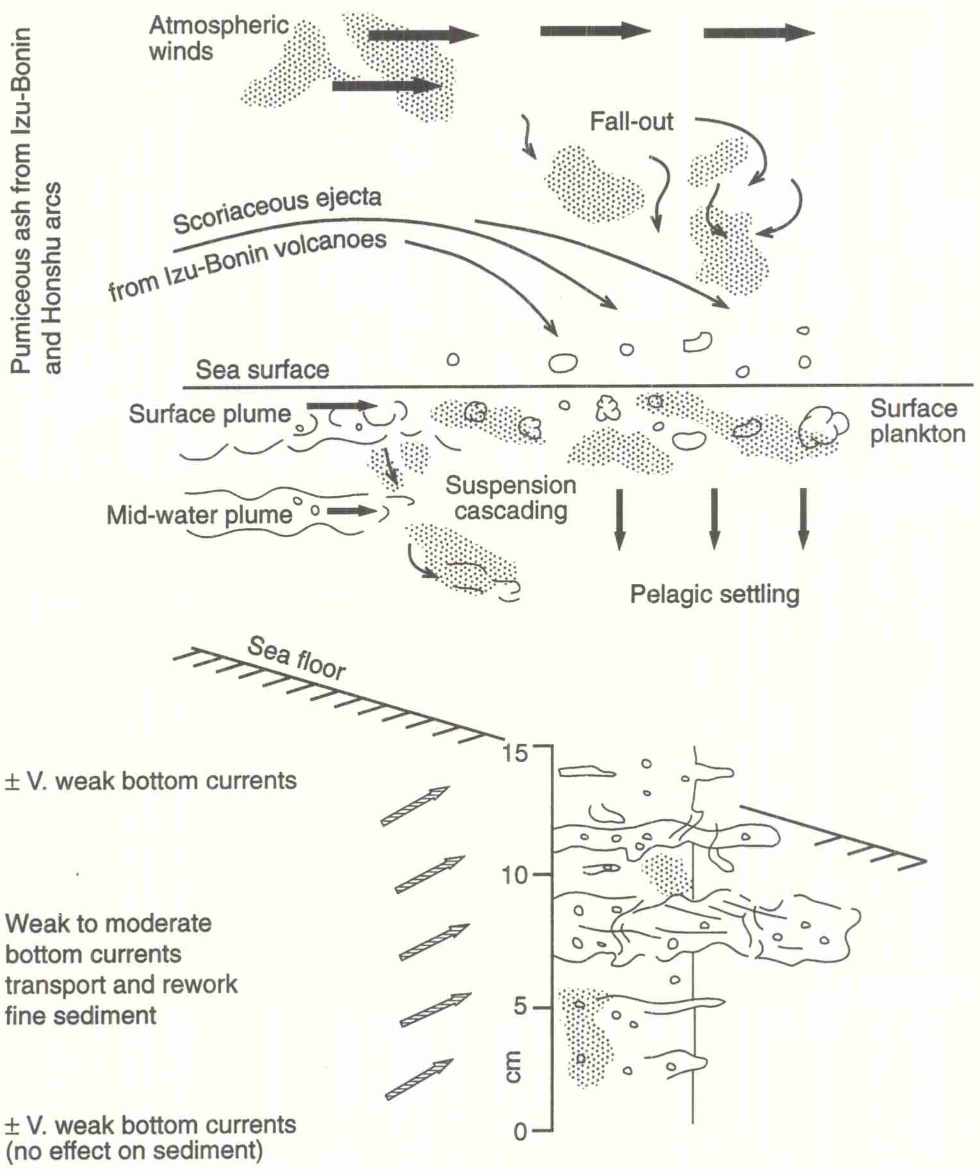

Fig. 8. Combination of hemipelagic and bottom current processes in the deposition of Misaki Formation fine-grained sediments. (From Stow *et al.* 1998*a*).

deposition. This might be interpreted as a higher-energy laminated contourite.

Distribution of fine-grained contourites

Due to the problems of structural complexity and sequence repetition, it has proved difficult to reconstruct the true vertical and lateral facies relationships. It is especially difficult to correlate between the rather different successions on Miura and Boso peninsulas.

A first order distribution of seven principal facies associations was presented by Stow *et al.* (1998*a*), and is reproduced here as Figure 9. This serves to illustrate as much the differences between sections as their correlation. Overall, there is a coarsening-upward trend from the Misaki formation, through a transitional facies to the Hasse formation, coincident with basin shallowing. Work on the geochemical characterisation of specific tuff beds has allowed for some detailed correlation between sections on the Miura peninsula (Fig. 5) (Horiuchi & Taniguchi 1985; Lee & Ogawa 1998).

At present we can only note that features of contourites within the fine-grained pumiceous mudstones are recognized in many parts of Miura peninsula, including Arasaki, Hamamoroiso, Jogashima, Miyakawa, Tsurugisaki and Ooura. We have also noted similar features at Mera on the Boso peninsula. They appear to range in age from near the base of the Misaki formation exposed to near the top. Towards the top, the facies indicate progressively shallower water and hence a greater influence of current activity. These currents, however, are interpreted as more likely of tidal or shelf origin, rather than deeper water bottom currents.

Discussion

Are they contourites?

Knowing how difficult it is to positively identify contourites in ancient successions on land, and being fully aware that the literature abounds with false and misleading identifications (Lovell & Stow 1981; Pickering *et al.* 1989; Stow *et al.* 1998*b*), it is important to critically examine our evidence and claim as presented here. We will attempt to follow the three-stage procedure and criteria laid down by Stow *et al.* (1998*b*), but must note that these are rather different from the criteria recently advocated by Shanmugam (2000).

(a) *Large-scale:* For rocks of Neogene age the palaeoceanographic reconstruction is generally very good, so that we are

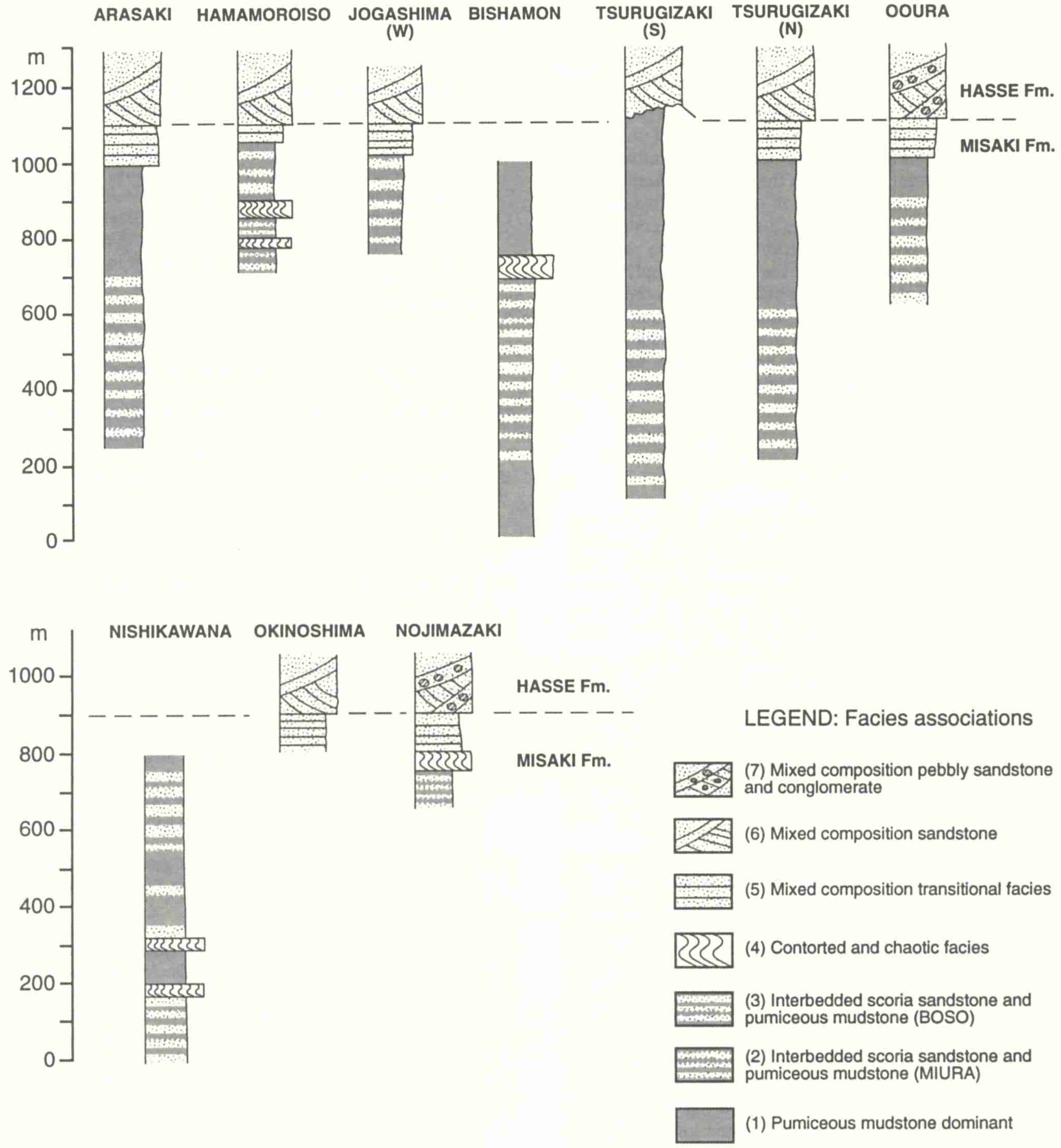

Fig. 9. Facies associations and their distribution within the Miura Group, Miura and Boso Peninsulas. (From Stow *et al.*, 1998*a*).

confident of the original depositional setting in a slope to forearc basin of the Izu-Bonin Arc. The estimates of deep-water palaeobathymetry are also reasonably accurate. From modern oceanographic data, there is clear evidence for the action of two or three geostrophic current systems capable of moving and depositing at least fine-grained sediments in the Izu-Bonin deep water slope region. These current systems were almost certainly present from early to mid-Miocene time. The data therefore support the potential for depositing contourites in rocks of this age and area.

(b) *Medium-scale:* The contourite facies are closely interbedded with turbidites, hemipelagites and other deep-water facies as might be expected in a slope-basin setting. They do not, therefore, exhibit any distinctive drift geometry other than presumed intercalated sheets. Palaeocurrent measurements have mostly been taken from the coarser grained facies, which were originally deposited by turbidity currents or pyroclastic fall. These data are discussed below in terms of the possible reworking by bottom currents. Kanamatsu (1995) has investigated the magnetic fabric (anisotropy of magnetic susceptibility) of both the coarse and fine-grained facies. For the latter, his results show mixed current directions of flow to the SSE, NNW and NE, when corrected for inferred plate rotation during emplacement. These directions are not incompatible with an element of alongslope current influence. Systematic regional trends in mineralogy, geochemistry or textural attributes have not been observed. However, the mixed composition of volcaniclastic ash in the pumiceous facies, together with bioclastic debris and terrigenous clays, would also support the supply of far-travelled material by bottom currents into an otherwise local source. In summary, there is little at this scale of observation to either positively support or refute a contourite interpretation, but several indicators that do favour at least a weak bottom current influence.

(c) *Small-scale:* There is abundant evidence at the scale of the sediment facies – in terms of structures, ichnofacies characteristics, textures and composition – that support the influence of weak to moderate bottom currents on the otherwise hemipelagic background sediment. This evidence is outlined above and we would therefore interpret the system as a contourite-hemipelagite continuum. The cyclic grain-size variation through the section is probably in part due to episodicity in the primary supply of volcaniclastic material. However, close inspection reveals the coincidence of change in other sedimentary features with grain size in some cases – for example, an increase in primary diffuse lamination and bioturbational hiatuses with coarser grain size. This suggests that fluctuation in long-term bottom-current velocity has also played a part.

Reworked turbidites? – re-examining the evidence

Most of the coarse-grained scoriaceous beds as well as the fine-grained tuffaceous layers were clearly deposited by turbidity currents and direct pyroclastic fall. All recent and detailed sedimentological studies in the area support this conclusion (Ogawa & Taniguchi 1988, 1989; Soh *et al.* 1989; Pickering *et al.* 1990; Stow *et al.* 1998*a*). However, if bottom currents were active during deposition of the background hemipelagite-contourite continuum as argued above (see also Stow & Faugères 1991; Lee & Ogawa 1998; Stow *et al.* 1998*a*, *b*), then it is possible that they were sufficiently strong to winnow and rework the tops of some turbidites. Lee & Ogawa (1998) have argued that this is indeed the case, especially for pale-coloured pumiceous beds showing parallel or cross lamination, whereas Stow *et al.* (1998*a*) note nothing unusual about the Misaki formation turbidites that would suggest any bottom current influence.

The evidence presented centres largely on measurements of palaeocurrent indicators, dominantly cross-bedding, but supported also by magnetic fabric data from Kanamatsu (1995). All authors agree that there is a dominant SE (corrected) palaeocurrent trend for Misaki formation facies on the Miura peninsula, which veers to more easterly on Boso. This fully supports mainly turbidity current supply from the Izu-Bonin arc located somewhere west of the slope-forearc basin system. All further note some local variation, with minor ENE and NE directions observed. In general, we do not see this variability as incompatible with a turbidite system; in fact, it is the norm for such deep-water systems. However, Lee & Ogawa (1998) have also documented minor NW directed trends in some localities, which they interpret as indicative of bottom currents generated by internal tides reworking the tops of turbidites. This they note is most common in the middle to upper Misaki formation, but absent from older parts of the succession.

In writing this joint paper, we agree to differ in our interpretation of whether or not bottom currents (internal tides or alongslope currents) have had any significant influence on the tops of turbidites. Further work is clearly required to help resolve this debate, and the apparent reverse-flow units need particular scrutiny.

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References

Akimoto, K., Uchida, E. & Oda, M. 1991. Palaeoenvironmental reconstruction by benthic foraminifers from middle to late Miocene in the Misaki Formation, southern Miura Peninsula. *Chikyu Earth monthly*, **13**, 24–30.

Ando, J., Tanaka, Y. & Hasegawa, S. 1989. Sedimentary environment of the Miura Group in the southern Miura Peninsula. Abstracts Volume, 96th Annual Meeting. *Geological Society of Japan*, 216.

Chaen, M. 1988. Report on study of deep-water circulation processes. *In:* Teramoto, T. (ed.) *Monbusho Grant Report.* Tokyo, 73–84.

Fukazawa, O. et al. 1985. The Kuroshio Current in Shikoku Basin. *In:* Kajiura, K. (ed.) *Oceanic Characteristics and their Changes.* Kouseisha-Kouseikaku, Tokyo, 89–120.

Hanamura, Y. & Ogawa, Y. 1993. Layer-parallel faults, duplexes, imbricate thrusts and vein structures of the Miura Group: keys to understanding the Izu forearc sediment accretion to the Honshu forearc. *The Island Arc*, **3**, 126–41.

Horiuchi, K. & Taniguchi, H. 1985. Study on the correlation of tuff key beds in the Miura Group, Southern Miura Peninsula, Central Japan. *Science Report of Nihon University*, **20**, 11–31.

Horiuchi, K., Momma, H., Mitsuzawa, K. & Fujioka, K. 1993. Holothurians and bottomcurrents on the oceanward slope of the Japan trench. *Proceedings of JAMSTEC Symposium on Deep Sea Research*, 41–48.

Imawaki, S. & Takano, K. 1982. Low-frequency eddy kinetic energy spectrum in the deep Western North Pacific. *Science*, **216**, 1407–1408.

Ito, M. 1996. Sandy contourites of the lower Kazusa Group, a middle Pleistocene forearc basin fill in the Boso Peninsula, Japan. *Sedimentary Geology*, **88**, 219–230.

Ito, M. 1997. Spatial variations in turbidite-to-contourite continuums of the Kiwada and Otadai formations in the Boso Peninsula, Japan: an unstable bottom-current system in a Plio-Pleistocene forearc basin. *Journal of Sedimentary Research*, **67**, 571–582.

Ito, M. 2002. Kurosiho Current-influenced sandy contourites from the Plio-Pleistocene Kazusa forearc basin, Boso Peninsula, Japan. *In:* Stow, D. A. V., Pudsey, C. J., Howe, J. A., Faugères, J.-C. & Viana, A. R. (eds) *Deep-Water Contourite Systems: Modern Drifts and Ancient Series, Seismic and Sedimentary Characteristics.* Geological Society, London, Memoirs, **22**, 421–432.

Kanamatsu, T. 1995. *A study of the magnetic fabric of the sediment in the accretionary complex, Boso and Miura Peninsulas, Central Japan.* PhD Thesis, Tokyo University, Japan.

Kanie, Y. & Hattori, M. 1991. Report of the symposium on *Chronology and palaeoenvironmental aspects of the Miura Group, central Japan* held at the 97th annual meeting of the Geological Society of Japan in 1990. *Journal Geological Society of Japan*, **97**, 849–864.

Kanie, Y., Okada, H., Sasahara, Y. & Tanaka, H. 1991. Calcareous nannoplankton age and correlation of the Neogene Miura Group between the Miura and Boso Peninsulas, Southern-Central Japan. *Journal Geological Society of Japan*, **97**, 135–155.

Kitazato, H. 1997. Palaeogeograpic change in central Honshu, Japan, during the Cenozoic, in relation to the collision of the Izu-Ogasawara Arc with the Honshu Arc. *The Island Arc*, **6**, 144–157.

Kodama, K., Oka, S. & Mitsunhi, T. 1980. *Geology of the Misaki District.* Geological Survey of Japan, Quadrangle Series, Tokyo, **8**.

Kotake, N. 1989. Taphonomy of the trace fossils in bathyal deposits of the Boso Peninsula, Central Japan. *Benthos Society of Japan*, **35**, 53–60.

Mitsuzawa, K. 1992. Measurement of currents and temperature inside the submarine caldera in Kaikata Seamount. *Proceedings JAMSTEC Symposium on Deep Sea Research*, **8**, 163–168.

Mitsuzawa, K., Kumai, R., Nakao, A., Yamaguchi, N. & Fukasawa, M. 1991. *Observation of bottom currents in the Suruga Trough.* JAMSTEC Technical Report, 45–50.

Lee, In Tae & Ogawa, Y. 1998. Bottom-current deposits in the Miocene–Pliocene Misaki Formation, Izu forearc area, Japan. *The Island Arc*, **7**, 315–329.

Lovell, J. P. B. & Stow, D. A. V. 1981. Identification of ancient sandy contourites. *Geology*, **9**, 347–349.

Ogawa, Y. 1985. Variety of subduction and accretion processes in Cretaceous to recent plate boundaries around southeast and central Japan. *Tectonophysics*, **112**, 493–518.

Ogawa, Y. & Taniguchi, H. 1988. Geology and tectonics of the Miura-Boso Peninsulas and the adjacent area. *Modern Geology*, **12**, 147–168.

Ogawa, Y. & Taniguchi, H. 1989. Origin and emplacement process of the basaltic rocks in the accretionary complexes and structural belts in Japan in view of minor element analysis and mode of occurrence. *Journal of Geological Society of Japan*, **98**, 118–132.

Okada, H. & Ohta, S. 1993. Photographic evidence of variable bottom-current activity in the Suruga and Sagami Bays, Central Japan. *Sedimentary Geology*, **82**, 221–237.

Pickering, K. T., Agar, S. M. & Prior, D. J. 1990. Vein structure and the role of pore fluids in early wet-sediment deformation, late Miocene volcaniclastic rocks, Miura group, SE Japan. *In*: Knipe, R. J. & Rutter, E. H. (eds) *Deformation Mechanisms, Rheology and Tectonics*. Geological Society, London Special Publications, **54**, 417–430.

Pickering, K. T., Hiscott, R. N. & Hein, F. J. 1989. *Deep-Marine Environments: Clastic Sedimentation and Tectonics*. Unwin Hyman, London.

Shanmugam, G. 2000. 50 years of the turbidite paradigm (1950s–1990s): deep-water processes and facies models – a critical perspective. *Marine & Petroleum Geology*, **17**, 285–342.

Soh, W., Pickering, K. T., Taira, A., & Tokuyama, H. 1991. Basin evolution in the arc-arc Izu collision zone, Mio-Pliocene Miura Group, central Japan. *Journal of the Geological Society, London*, **148**, 317–330.

Soh, W., Taira, A., Ogawa, Y., Taniguchi, H., Pickering, K. T. & Stow, D. A. V. 1989. Submarine depositional processes for volcaniclastic sediments in the Mio-Pliocene Misaki formation, Miura Group, central Japan. *In*: Taira, A. & Masuda, F. (eds) *Sedimentary Facies in the Active Plate Margin*. Terra Scientific Publications, Tokyo, 619–630.

Stow, D. A. V. & Faugères, J.-C. 1991. *Miocene contourites from the proto Izu-Bonin forearc region, southern Japan*. Abstract Volume, 13th International Sedimentological Congress, Nortingham, UK.

Stow, D. A. V., Faugères, J.-C., Viana, A. & Gonthier, E. 1998*b*. Fossil contourites: a critical review. *Sedimentary Geology*, **115**, 3–32.

Stow, D. A. V., Taira, A., Ogawa, Y., Soh, W., Taniguchi, H. & Pickering, K. T. 1998*a*. Volcaniclastic sediments, process interaction and depositional setting of the Miocene–Pliocene Miura Group, SE Japan. *Sedimentary Geology*, **115**, 351–382.

Taft, B. A. 1978. Structure of the Kuroshio south of Japan. *Journal of Marine Research*, **36**, 77–117.

Taira, A. & Ogawa, Y. 1991. Cretaceous to Holocene forearc evolution in Japan and its implication to crustal dynamics. *Episodes*, **14**, 205–212.

Taira, A., Okada, H., Whitaker, J. H. McD. & Smith, A. J. 1982. *The Shimanto Belt of Japan: Cretaceous–Lower Miocene Active Margin Sedimentation*. Geological Society, London, Special Publications, **10**, 5–26.

Taniguchi, H., Ogawa, Y. & Soh, W. 1991. *Tectonic development of the Izu Arc and Proto-Izu Arc*. Journal of Geography, Tokyo Geographical Society, **100**, 514–29.

Tsuchi, R. & Ingle, J. C., eds. 1992. *Pacific Neogene: Environment, Evolution and Events*. University of Tokyo Press, Tokyo.

Wright, J. D. & Miller, K. G. 1993. Southern Ocean influences on late Eocene to Miocene deep-water circulation. *Antarctic Research Series*, **60**, 1–25.