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Shearing of partially consolidated sediments in a lower trench slope setting, Shimanto Belt, SW Japan

SUSAN M. AGAR*

Geology Department, Imperial College, London SW7 2BP, U.K.

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Abstract—Detailed mapping of a coastal platform in Shikoku, SW Japan, provides evidence for progressive deformation in partially lithified sediments. The Eocene sediments involved are interpreted as lower slope basin deposits. An assemblage of listric normal faults, sheath folds, broken formations and late-stage faulting has developed during the sediments' burial and uplift history. These structures are typical of many other areas in the Shimanto Belt of Shikoku. Despite the 'soft' sediment style of deformation, the consistency of the fold orientations relative to the regional foliation suggests that they are valid kinematic indicators. A sequence of extensional faulting overprinted by synchronous folding and shearing is recognized. This is interpreted as the response of the sediments to shape changes in the accretionary basement induced by shortening. A general model has been constructed for the evolution of the structures: it is proposed that early listric normal faults are subsequently deformed either by shearing along planar surfaces or by motion over frontal and lateral ramps. Back-rotation of sediments during progressive shortening near the front of the prism tightens the fold hinges and rotates the fold axes towards the local shear direction. Alternative sequences which could account for the observed geometries are also discussed.

INTRODUCTION

RECENT offshore studies around modern convergent margins have helped to characterize early deformational processes associated with subduction. Seismic imaging of the Japan margin (Aoki *et al.* 1982), Barbados (Westbrook & Smith 1983), South America (Shipley & Moore 1986) and the Hikurangi Margin (Davey *et al.* 1986) provide evidence for actively deforming sediments in the toe regions of oceanward propagating thrust systems. This is supported by the three-dimensional sonar data obtained by GLORIA and SEABEAM surveys (Laughton 1981, Ogawa 1985). Shallow boreholes and dredges have also shown how widely the rheological properties of sediments in this setting can vary (Carson *et al.* 1982, Shephard & Bryant 1983, Bray & Karig 1985, Lundberg & Moore 1985).

The sediments around subduction zones are subjected to tectonic stresses early in their burial history (Helwig 1970, Scholl *et al.* 1977, Seely 1977). This is likely to cause rapid changes in their material properties with an equally rapid re-organization of the primary depositional fabric. The shear strength of most horizons will tend to increase with burial (Bray & Karig 1985), although several parameters may modify this trend. Variation in rates of dewatering and compaction in layered sediments can cause extreme variations in pore-fluid pressures (von Huene 1984). This anisotropy can be further enhanced by variation in the composition and rate of development of cement phases (Carson *et al.* 1982). On reaching a critical value of shear strength, the ductile deformation and pervasive intergranular shearing in partially lithified sediments will be replaced by movement on more discrete planes of weakness which favour slip.

If these processes are preserved in the onshore geological record, evidence for stratal disruption over a broad range of lithification states will be displayed. The structures observed result from both burial and tectonic stresses and may be valid kinematic indicators of processes occurring during subduction. Structures generated by surficial slumping may appear to be identical and in some cases it may be impossible to decide whether the structures are directly related to accretion or are produced by gravitational instabilities (Knipe & Needham 1985). Both types of structure, however, are significant in interpreting the dynamic processes in an accretionary complex.

An example of this structural style has been recognized in the Shimanto terrane of Shikoku, SW Japan. This paper presents a description and interpretation of the structures exposed in a small coastal area of the Hata Peninsula, SW Shikoku (Fig. 1). The structures mapped typify several other exposures on the Hata Peninsula.

The Shimanto belt is interpreted as an accretionary complex initiated in the Neocomian (Lower Cretaceous) and developed in a series of subduction pulses throughout the Cretaceous and Palaeogene to the present (Taira *et al.* 1982). Studies of the regional tectonics of SW Japan suggest there was a major change in shear sense along the plate margin during the early Eocene. The sinistral motion persistent throughout the Cretaceous changed to convergent motion in the Eocene (Taira *et al.* 1983). The most recent movements along the Nankai Trough are thought to be dextral (Taira 1981). The Shimanto belt is bounded to the south by the Nankai Trough, which forms the present tectonic boundary of the Eurasian plate and the Philippine Sea plate. To the north the Butsuzo Tectonic Line, a major reverse fault (Hada &

* Present address: Earth Sciences Department, Leeds University, Leeds LS2 9JT, U.K.

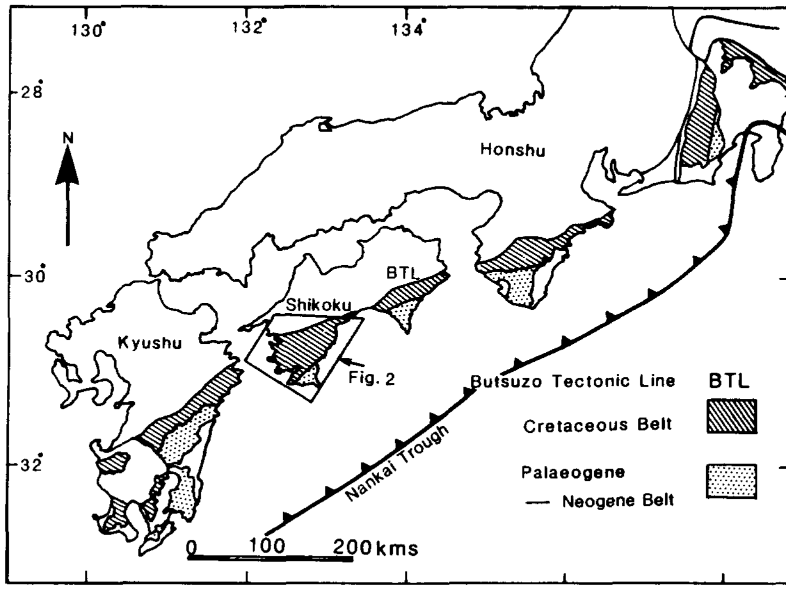

Fig. 1. The general distribution of the Shimanto Belt in SW Japan. The study area lies close to the Cretaceous–Palaeogene boundary in W Shikoku. More detail of this area is shown in Fig. 2.

Suzuki 1983), juxtaposes the Shimanto and the Jurassic Sambosan belts. The Shimanto belt comprises imbricate thrust packages of flysch with minor limestone, chert, tuff and blocks of basalt. The imbricates are unconformably overlain by weakly deformed Cretaceous–Miocene slope basin deposits (Taira 1981), which probably accumulated in fault controlled depressions in the accretionary basement.

Progressive deformation in this part of the Shimanto terrane has disrupted sediments in varying states of consolidation, causing a wide variety of deformational styles to occur in short sequences of strata. On the Hata Peninsula approximately 70% of the belt is represented by broken formations or mélange. The term 'mélange' in this paper refers to internally fragmented and mixed rock bodies comprising blocks of predominantly oceanic lithologies in a sheared argillite matrix. This definition stems from Japanese nomenclature adopted for research in the Shimanto Belt (Suzuki & Hada 1983) and is not intended as a general definition. The term 'broken formation' is used in the sense of Hsü (1968): "A body of broken strata without exotic blocks" and which "regardless of its broken state functions as a rock stratigraphic unit". Areas where the strata have remained coherent and the stratigraphy is preserved, yield more information concerning the early stages of deformation than the broken formations, where recognition of strata and younging directions is often impossible. This paper highlights just one aspect of this deformation: a sequence of fault and fold structures in a coherent block.

The example comes from a coastal platform close to the Inomisaki Peninsula on the east coast of the Hata Peninsula (Fig. 2). The platform lies close to the Eocene–Cretaceous boundary of the Nakamura Forma-

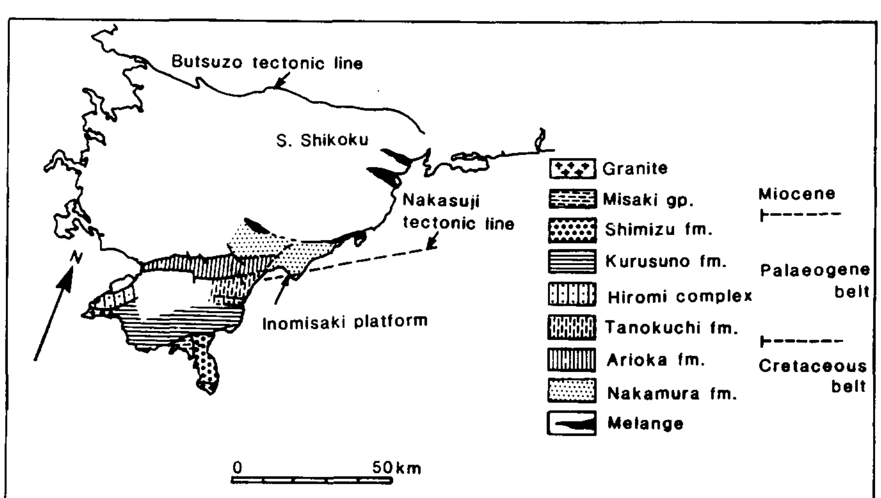

Fig. 2. The geology of the Shimanto Belt on the Hata Peninsula, showing the location of the Inomisaki Platform. Descriptions of the lithologies on the Platform and those of the Tanokuchi, Arioka and Nakamura Formations are given in the text. The Nakasuji Tectonic Line represents a major accretionary fault juxtaposing Cretaceous and Palaeogene sediments.

tion, a sequence of trench-fill turbidites lying to the north (Taira 1981). There are several steeply dipping reverse shear zones in a section extending 5 km to the north of the platform; their detailed movement directions are not known. Inland to the southwest of the area, shallow water deposits of the Campanian–Maastrichtian Arioka Formation are faulted against the Eocene sediments of the Tanokuchi Formation, which have been interpreted as lower slope basin deposits, including submarine channels with overbank deposits (Taira 1981). The Tanokuchi Formation lies along strike from the sediments described here and may be contemporaneous.

The Inomisaki Platform sediments are thin to medium bedded distal turbidites of Eocene age (Taira personal communication). They comprise well-sorted, quartz-rich, sandstone with laminated siltstone and mudstone. There are only minor zones of broken formation, most of the strata having behaved coherently, so that original stratigraphy is preserved between faults. Distinctive fining-upward sequences and sedimentary structures such as flaser bedding and ripple cross-lamination clearly indicate the younging direction, enabling detailed structural analysis. Studies of the Hikurangi Margin have shown distal-type turbidites to be confined to lower slope basins and it seems likely, because of the along strike correlation with the Tanokuchi Formation, that the Inomisaki Platform sediments are from a similar environment. However, investigations of recent slope and trench sediments have shown that very few sedimentary facies encountered are wholly diagnostic of their settings (Underwood & Bachman 1982, von Huene 1984).

THE STRUCTURE OF THE INOMISAKI PLATFORM

Figure 3 shows maps of the lithologies and structural features of the Inomisaki Platform. A consistent sequence of structures can be recognized in this steeply dipping sequence. The earliest major structures are a series of nested listric normal faults. These fault planes are emphasized by dark seams of residual material, which penetrate and anastomose through a few centimetres of the adjacent rock. Minor brecciation with carbonate cement is localized along faults. No pervasive intragranular deformation is evident, but thin-section studies of the fault rock and localized areas within folded sediments reveal that early cataclasis is overprinted by pressure solution (Fig. 4). The original configuration of listric normal faults is obscured by later deformation, but most appear to be part of a set of synthetic and antithetic faults with a major detachment. These faults are generally oriented at about 45° to the bedding, becoming parallel to bedding at the detachment plane. Minor dip-slip displacements of 1–50 cm are apparent, but may have been reactivated during later deformation and do not necessarily represent the original normal displacements. The component of strike-slip motion on these faults is not known.

The faults have been deformed by two pairs of sideways downward-facing folds, which are isoclinal with steeply dipping axial surfaces. Figure 5(a) shows two of the faults folded around the hinge of the syncline in the centre of the map in Fig. 3. The presence of a continuous detachment along the base of the thickened sandstone bed is shown by truncated silt and shale horizons. Figure 5(b) shows the tapered ends of beds detached along listric normal faults, now folded in the core of a downwards-facing anticline. There is little evidence for interlayer slip during folding. A few lineations are present on bedding surfaces, but not enough to constrain kinematics. A weak axial-planar crenulation cleavage is developed only in the hinge regions of the tightest folds where detrital micas are aligned on the limbs of the microfolds but are apparently undeformed. A very weak pressure-solution cleavage, parallel to the lithological layering, is developed in the mudstones away from the fold hinges. No ponded sediment or erosion surfaces are associated with these folds and no burrows were found to cross fold hinges.

In places the folds detach along 1–2 m thick broken formations. The shales in the broken zones have a weak layer-parallel pressure-solution cleavage. The mudstone acts as a matrix for attenuated sandstone lenses, which have been flattened and slightly sheared along narrow (<1 mm) cataclastic zones, similar to the web structures described by Cowan (1982). Carbonate nodules are also found in these horizons. The orientation of fracture sets associated with broken zones strongly resembles those observed in fault gouges (Logan *et al.* 1978, Hall & Rutter 1984) and may be useful as shear sense indicators.

The latest structures to develop are a minor set of faults with between 1 and 10 m dextral offset. The vertical displacements on these faults are not known.

Three-dimensional control

A vertical road section (Fig. 6), 0.5 km to the east of the mapped platform, gives good three-dimensional control on the structures described. The section lies directly behind the eastward extension of the platform in Fig. 3 where the same structural relationships are exposed. Small isoclinal folds in the road section have subhorizontal fold hinges and detach on layer-parallel zones of broken formation which dip steeply to the northwest and southeast, occurring every 5–10 m across strike. These are post-dated by sets of more shallowly dipping thrust faults. Early listric faults are back-rotated to a subvertical orientation and, where cross-cutting relationships are absent, are hard to distinguish from the later thrusts, although thrust faults generally develop broad gouge zones with slickensides, whilst early normal faults have discrete planes with pressure-solution seams. The combination of horizontal and vertical profiles of fold structures suggests that their three-dimensional geometry is similar to that of sheath folds described in shear zones formed at depths much greater than these sediments (Quinquis *et al.* 1978, Watts & Williams 1979).

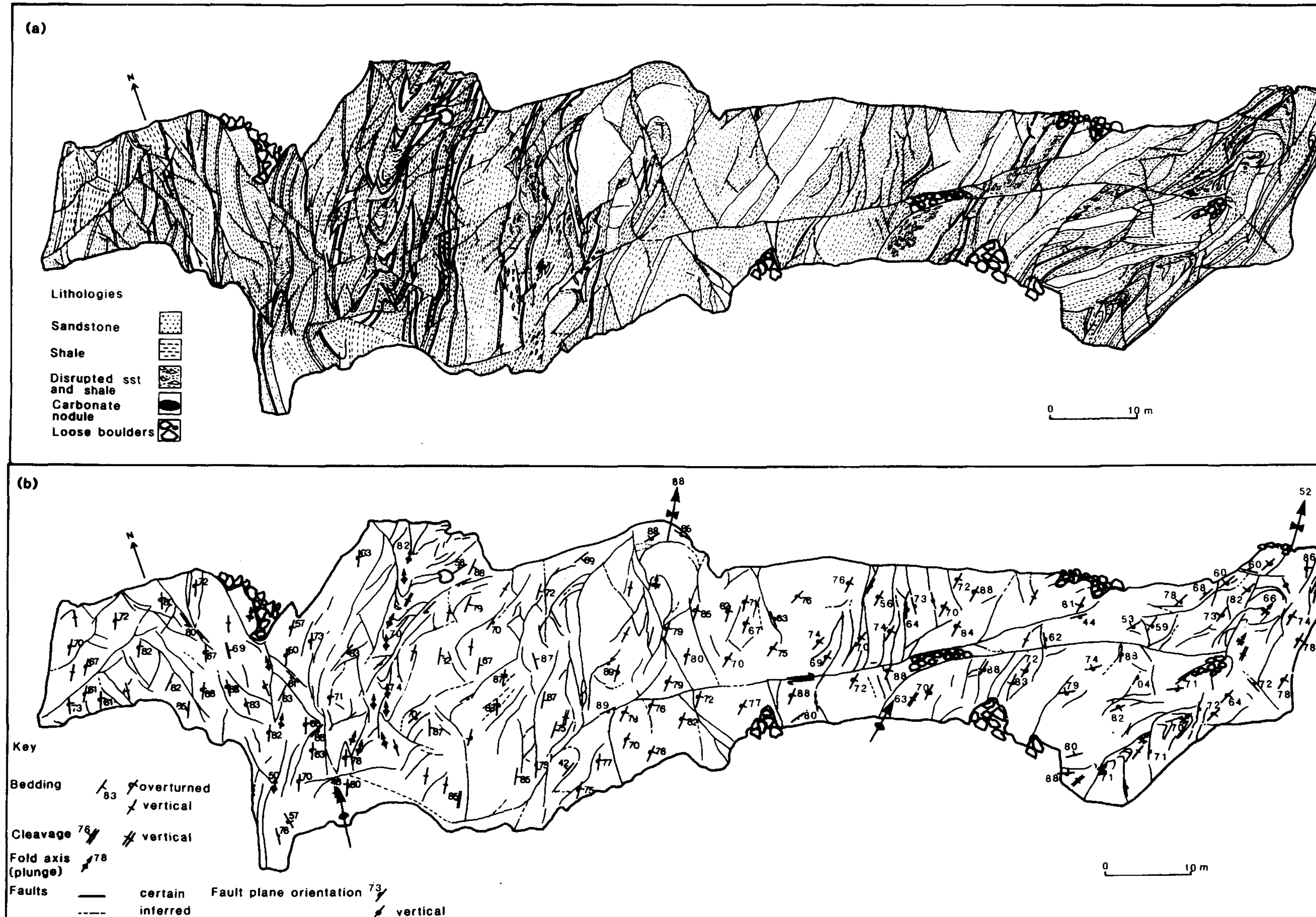

Fig. 3. (a) A lithological map of the Inomisaki Platform showing thin to medium flysch deposits which are thought to be Eocene. Minor disrupted zones with rare carbonate nodules occur at the detachment surfaces of the isoclinal folds. Note the extreme thickening of the sandstone bed in the hinge region at the centre of the map. (b) A structural map of the Inomisaki Platform. The area contains two isoclinal anticline–syncline pairs which fold early listric normal faults (solid lines). The folds are sideways or downwards-facing. The E–W-trending faults have minor dextral offsets but their absolute displacement is unknown. They post-date all the structures on the platform and are thought to be unrelated to early phases of deformation which generated the listric normal faults and subsequent folding.

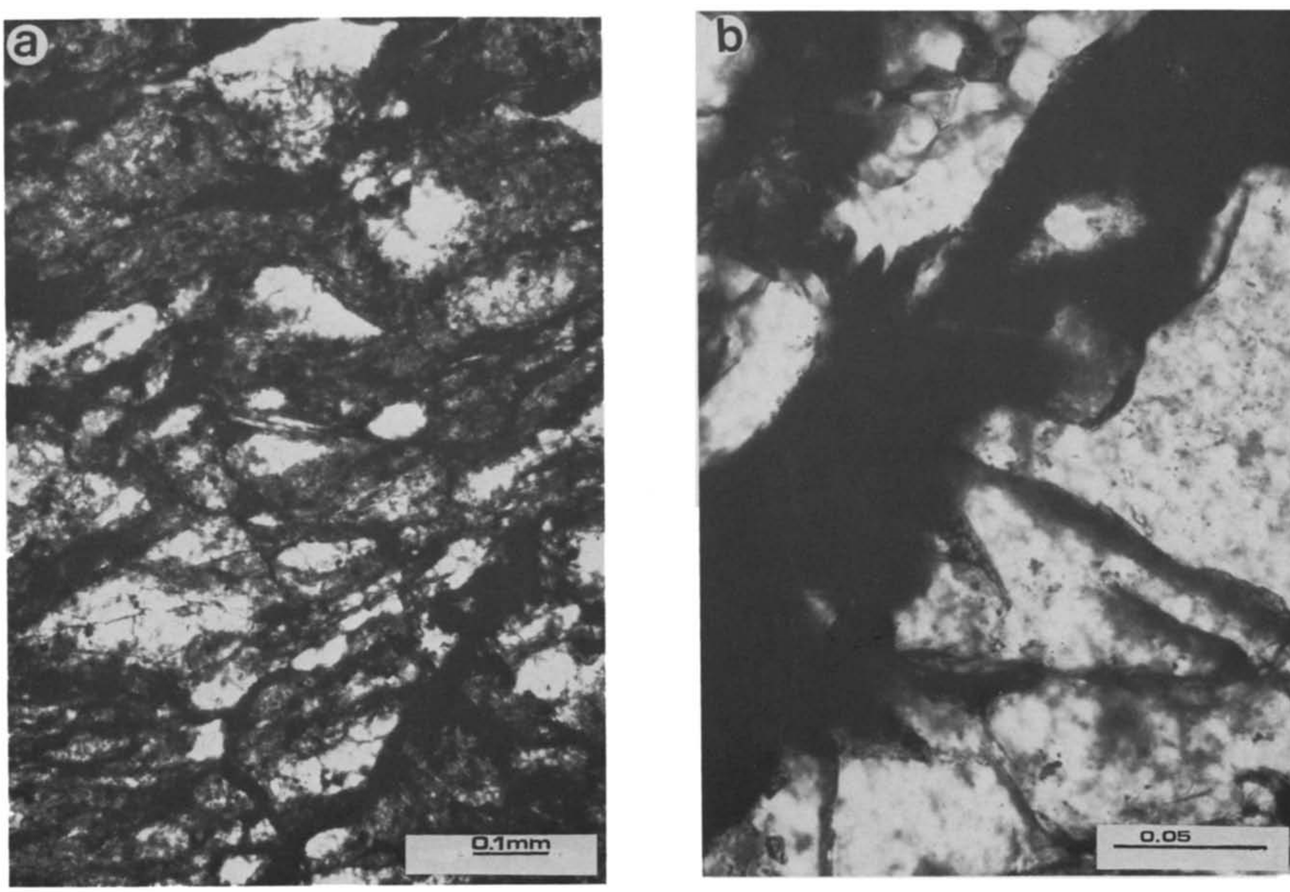

Fig. 4. (a) Photomicrograph of fault rock from the Inomisaki Platform. Many of the quartz grains are fractured with clay alteration at their margins. Pressure-solution seams anastomose around and through fractured grains. (b) A quartz grain divided by a single pressure-solution seam which truncates fractures formed during earlier stages of fault-rock deformation.

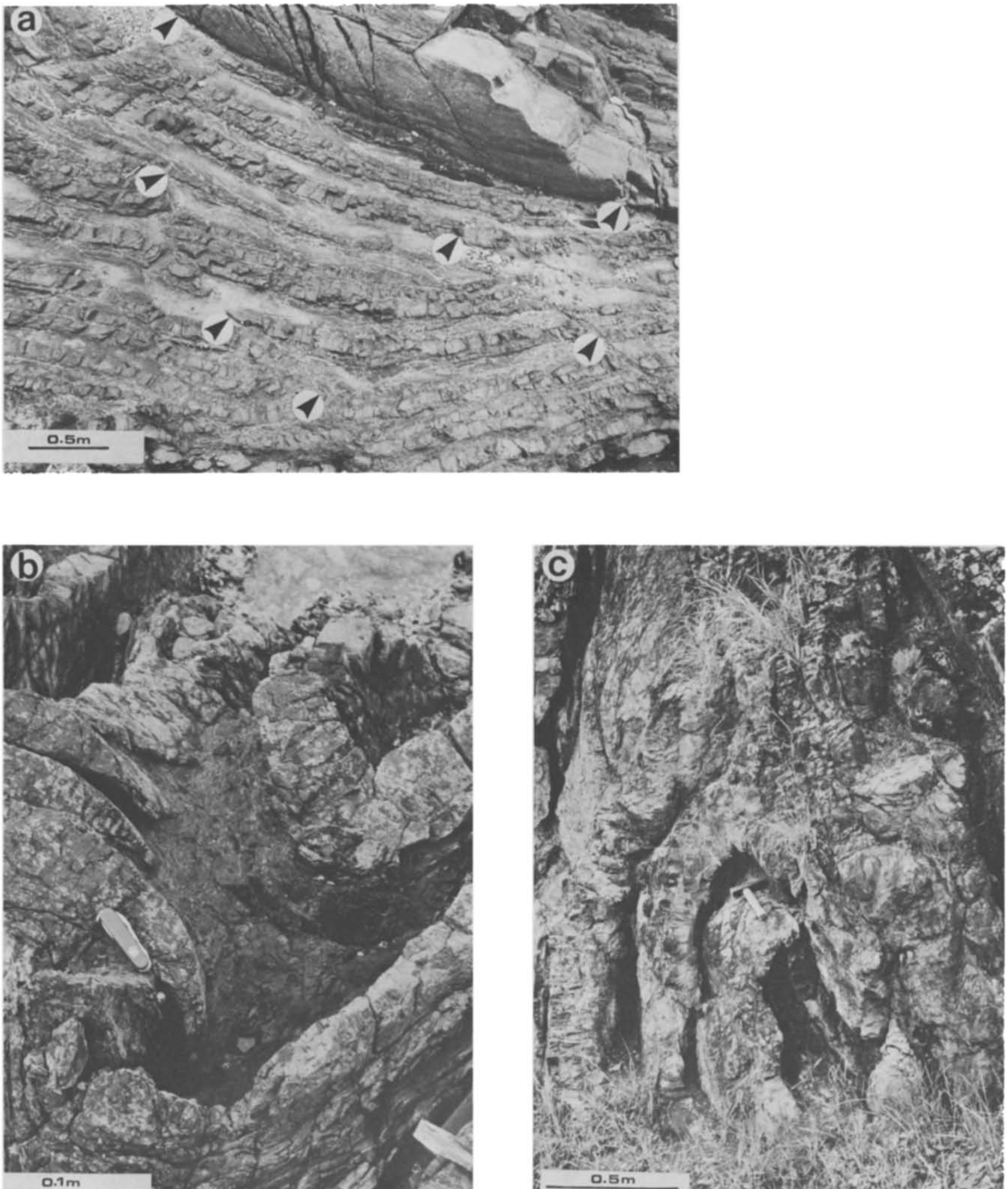

Fig. 5. (a) The black arrows mark the trace of two listric normal faults which detach along the thickened sandstone bed (centre Fig. 3) and are folded around the hinge of the syncline. (b) The tapered ends of beds detached along listric normal faults are isoclinally folded in the core of a downward-facing anticline. (c) A roadside exposure of the nose of a sheath fold in the Tanokuchi Formation, correlated with the Inomisaki sediments along strike.

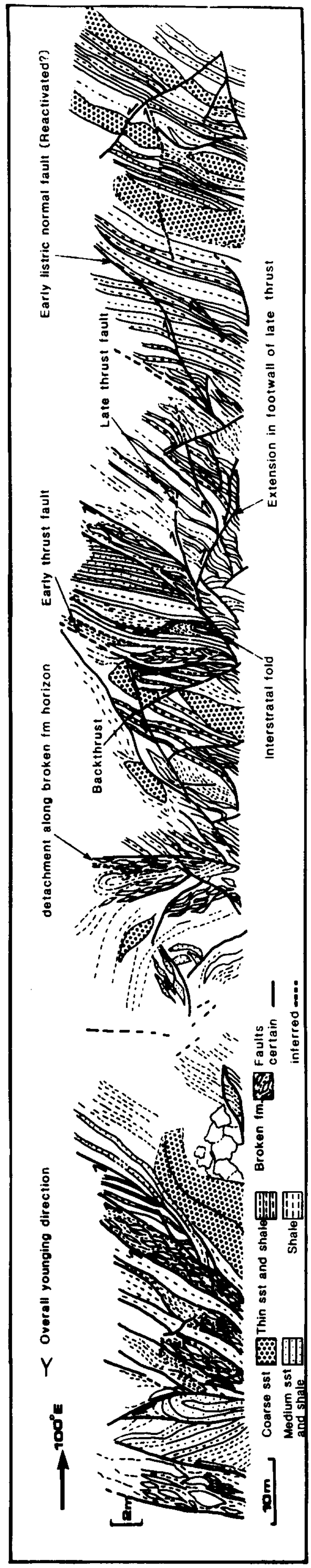

Fig. 6. A road section approximately 0.5 km east of the platform showing similar structural style but in vertical profile. Later faulting and back-rotation complicate the geometries of the early structures, but small isoclinal folds with narrow broken formations as detachments are still discernible. The combination of the platform and road section structures suggests that the style of folding in this area is similar to that of sheath folds found at deeper levels in shear zones.

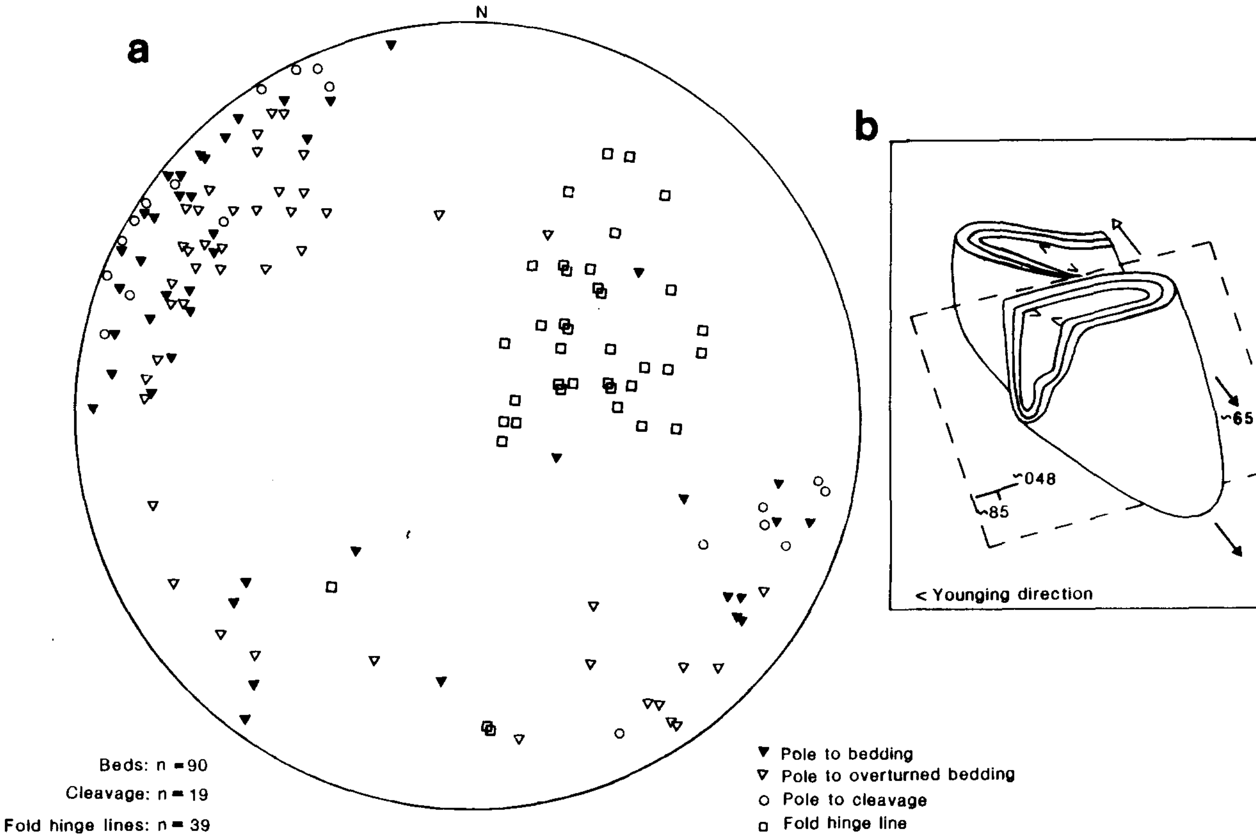

Fig. 7. (a) A composite stereoplot of fold-hinge lines, axial-planar cleavage and bedding for the Inomisaki Platform and road section. (b) The average geometry of the folds at Inomisaki is represented by a tight sheath fold with a steeply southeast dipping axial surface, plunging ~65° NE.

A composite stereoplot for the area (Fig. 7a) confirms this geometry indicating a tight sheath fold plunging about 65° NE with a steeply southeast dipping axial surface (Fig. 7b). Although the cores of sheath folds are not observed in Inomisaki, the Tanokuchi Formation directly along strike to the east (Fig. 2) contains several roadside exposures of the noses of sheath folds (Fig. 5c).

CONDITIONS OF DEFORMATION

The sequence of structures identified cannot be assigned to a unique set of deformation conditions. No diagnostic authigenic minerals are closely related with microstructures, although illite crystallinity values of 0.35 $\Delta 2\theta$ to 0.25 $\Delta 2\theta$ suggest anchizone metamorphism. There is insufficient organic matter to assess vitrinite reflectance values. The lack of pervasive grainscale deformation, even in tightly folded strata, suggests that pore-fluid pressures were high and that strain was accommodated in most horizons by independent particulate flow (Borradaile 1981). As water tended to flow from shales to more permeable sandstone horizons, grain-boundary sliding was facilitated further, causing disaggregation and the extreme thickening of fold hinges. The absence of dewatering structures and hydrofracturing, except for very localized occurrences in fault zones, suggests that either the strain rates accompanying the early stages of deformation were not particularly high or that the faults and permeable strata allowed the rapid escape of pore water during deformation. The tracts of broken formation which serve as detachment horizons for isoclinal folds may have been early conduits for these dewatering processes. The focusing of fluids along these horizons could lead to localized disaggregation and shearing.

The deformation mechanisms identified in thin-section may again reflect the local variations in pore-fluid pressures, more than the overall depth of burial. Early cataclasis may have provided a dewatering path as microporosity was increased during deformation. The resulting increase in fluid flow may have raised pore-fluid pressure so as to inhibit cataclastic processes and initiate pressure solution. Cataclastic processes will be suppressed if the pore-fluid pressure is raised to a level where the effective stress becomes zero (Blenkinsop & Rutter 1986).

The controls on the development of cleavage are not well understood. A cleavage can develop early in the burial history of a sediment without the presence of a 'tectonic' strain (Maltman 1984). The absence of a pervasive cleavage in the platform may suggest that the local stresses or temperatures were insufficient to cause reorientation or recrystallization of micas. Later overprinting by a regional NE-trending cleavage is common in most coastal sections, but is not apparent here. This may be due to the bulk lithology being less sensitive to cleavage generating processes or to partitioning of deformation (Lister & Williams 1983) on the regional scale.

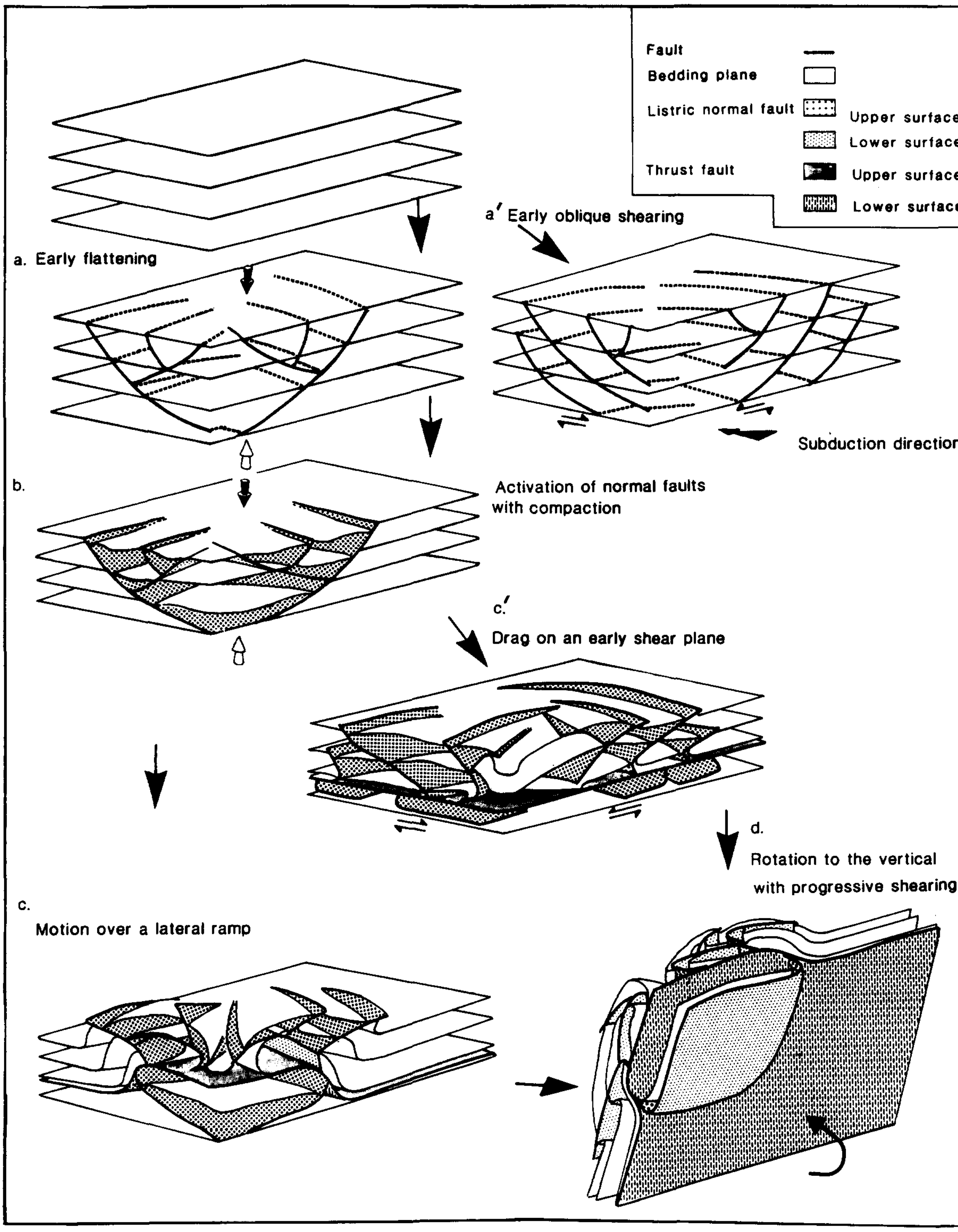

Fig. 8. Proposed model for the evolution of the structures on the coastal platform at Inomisaki. (a) Sediments in a lower slope setting develop early listric normal faults in response to (a) instabilities associated with early compaction and/or (a′) early oblique shearing related to the subduction kinematics. Motions on faults in the accretionary 'basement' will affect the overlying cover which may develop listric normal faults with R_1 shear-type geometries. (b) Both (a) and (a′) may be further activated with continued compaction which may result in some modification of the fault geometry. (c) The subsequent folding of the listric normal faults may have been the result of thrust faults in the basement propagating through the slope cover. Continued motion along these faults may have formed hangingwall anticlines and footwall synclines as lateral and frontal ramps were encountered (c) or the folds may have originated as drag structures on the early shear plane (c′). (d) As the accretionary complex continued to shorten, the lower slope deposits were back-rotated with progressive shearing, modifying the early fold geometry to that of sheath folds aligned closely to the local shear direction. The early listric normal faults would then be isoclinally folded with apparent changes from extensional to contractional motion along the fault in some of the tightly folded areas.

INTERPRETATION OF THE STRUCTURE OF THE INOMISAKI PLATFORM

The structures at Inomisaki are interpreted as a progressive deformation sequence associated with the shortening and shape changes induced by subduction related movements in the accretionary basement. A model for this sequence is shown in Fig. 8. The listric normal faults formed whilst the sediment was partially lithified and are recognized as a common early structural feature in the sediments of the Japan trench slope (Lundberg & Leggett 1985). Early normal faults may have formed in response to:

(a) early extension associated with axially-symmetric flattening;

(b) slope instabilities caused by high pore-fluid pressures, slumping or earthquakes;

(c) tectonic stresses which have generated similar fractures with orientations in accordance with R_1 shears, related to early shortening on low-angle thrusts planes.

The resulting fault geometry would have a dominant set of synthetic listric normal faults. In this particular example their orientation is consistent with sinistral faulting although this may be very localized.

During burial and subsequent deformation it is envisaged that the normal faults were further activated with some adjustment of their geometries during compaction. Almost synchronous with this phase was the development of isoclinal folds shown on the platform map (Fig. 3), which drastically modify the original normal fault geometries. The folds could have originated as drag related structures on early shear planes or during motion of sediments over lateral and frontal ramps. In either case the broken formations acted as zones of detachment and shearing, which may have propagated from major thrusts in the accretionary basement. Once the folds initiated the progressive shortening of the frontal part of the prism lead to back-rotation of the sediments with further shearing and layer-parallel extension. Fold hinges became progressively more closely aligned to the local shear direction. This is closely analogous to the progressive shearing observed in deeper level shear zones (Quinquis *et al.* 1978).

A common interpretation of areas with similar structural styles to those described here is that they were generated by surficial processes (Roberts 1972). The folds on the Inomisaki Platform have similar geometries to slump folds. The only definitive criteria for recognition of slump folds (Helwig 1970, p. 174) is their truncation by the slip scars of younger slumps or cross-cutting bioturbation. Neither of these features is seen and there are additional factors which argue against the formation of these folds at the surface. The folds at Inomisaki are intrafolial, but their axial trend is consistent with both interstratal folds and with larger scale folds (1–2 km wavelength) to the south. The folds also lie sub-parallel to the regional foliation. Similar fold styles are found to the north, towards Tosa Saga, where fold axes and foliation are consistently rotated approximately 10° clockwise of the fold axial plane orientations on the Inomisaki Platform. Fold formation below surface levels explains the absence of erosional surfaces. The platform displays evidence for early extensional structures overprinted by later compressional ones. Farrell (1984) noted that the reverse sequence is more common in a surficial environment, because the detachment surface is more likely to seize up near the rear of a slump sheet as fluid escapes from faults.

In summary the folds are interpreted as early thrust related structures with synform–antiform pairs accommodating the strain above and below the originally sub-horizontal detachment surface. These are represented by narrow tracts of broken formation which have been back rotated to a sub-vertical position. If the folds were surficial slumps they would cut down through the underlying strata and the strain would be focused on the younger side of the detachment. Although intragranular deformation is minor it does not necessarily suggest near surface deformation. Zones of high pore-fluid pressure can persist to several kilometres depth in an accretionary complex (Shipley & Moore 1986) and it is likely that early thrust horizons were focused along these where low effective stresses favoured intergranular deformation.

The structures at Inomisaki could be just a small part of a much larger structure, either as parasitic structures on a large scale sheath fold for instance, or as accommodation structures in a larger fold and thrust system, but there is insufficient field evidence to prove or disprove either case.

DISCUSSION

The exact depositional setting of the Inomisaki sediments is not known. They could be placed equally well in the trench or the outer or inner part of the trench slope. The coherent nature of these sediments favours a slope basin setting, where sediments are deformed, but are less sheared than those which are frontally accreted. However, the nature of the bulk lithology of the sediments will affect their response to deformation, such that their coherent nature alone is not diagnostic. Carson *et al.* (1982) concluded that the slope sediments of the Japan Trench could be significantly modified by subduction processes. It is proposed here that the Inomisaki sediments have been deformed by subduction–accretion processes, in response to deformation in the underlying accretionary basement, rather than by surface processes. The early extensional phase could have been equally well related to motion on a thrust plane or early flattening. This was followed by shortening accomplished by simultaneous motion on broken formation zones resulting from the propagation of major thrusts in the accretionary basement. Folds formed in response to drag on these detachment surfaces or motion over lateral or frontal ramps. Continued shearing and layer-parallel extension with back-rotation of the sediments resulted from further shortening in the accretionary basement.

If these structures have developed in a thrust environment then the orientation of structures on the platform suggest that the thrusting also had a sinistral component. Work on Kodiak Island (Moore & Wheeler 1978) suggests that the kinematics of small-scale structures are representative of relative motions of a subducting and an overriding plate. It may be that the Inomisaki structures reflect a regional sinistral component of motion in the Eocene.

The style of deformation reported here could be described as 'soft sediment' deformation, but this term is misleading since this style may persist over a range of depths depending upon the effective stress conditions (Jones & Addis 1986). Models of subduction-zone deformation which present a steady unidirectional change in deformation mechanisms are oversimplified. Although there will be a general transition from one dominant mechanism to another over depths of several kilometres, more local variations may result from differences in pore-fluid pressures, strain rates and lithology (von Huene & Kulm 1973, Shephard & Bryant 1983, Knipe 1986). In an accretionary setting the distinction between structures formed in unlithified, partially lithified and consolidated sediments is not clear.

The interaction of sedimentation and tectonics in subduction zones must lead to widespread deformation of partially lithified sediments. The resulting structures can be used to interpret large scale kinematics of an accretionary belt and should not be dismissed as local soft sediment structures.

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