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Sheath-like folds and progressive fold deformation in Tertiary sedimentary rocks of the Shimanto accretionary complex, Japan

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Abstract—The Upper Oligocene–Lower Miocene portion of the Cretaceous–Lower Miocene Shimanto accretionary complex on the Muroto Peninsula, southwest Japan, comprises alternating belts of coherent clastic rocks and shaly mélange. Sheath-like folds formed locally during a fold–thrust deformation that affected a 10 km structural thickness of these rocks. In a subsequent event confined to the mélange and adjoining areas, the axes of these folds were rotated nearly 90° within the plane of their axial surfaces. The widespread uniform development of the folds and an accompanying axial-planar pressure-solution cleavage strongly suggest that these deformations were tectonically induced, rather than gravity driven slump features. The sheath-like folds indicate that the most plausible environment for these rocks was in an accreted packet of trench-fill, behind the imbricate toe of the Shimanto accretionary complex. The timing of the deformation is constrained by depositional ages as well as by the probable Early Miocene age of an overlying superficial basin and early Middle Miocene igneous dikes that intrude the sequence. This chronology overlaps with the Late Oligocene–Early Miocene opening of the Shikoku back-arc basin, bordering the Shimanto Belt to the southwest; thus accretion and subduction were active during the basin opening event. These conclusions conflict sharply with earlier held notions of strike-slip and olistostrome tectonics along this plate margin during the Early Miocene opening of the Shikoku Basin.

INTRODUCTION

A WIDE range of fold responses to deformation have been documented within accretionary complexes. In some complexes, such as the Franciscan terrane, folds are only sparsely developed (e.g. Cowan 1982) whereas in others, such as in southern Alaska and the Taconic region of New York, folds comprise a much more significant portion of the deformation geometry (Moore & Wheeler 1978, Moore & Allwardt 1980, Bosworth & Vollmer 1981, Sample & Moore personal communication 1987). These fold systems in accretionary prisms are among the most complicated encountered in sedimentary rocks and have led to ambiguity concerning the mechanisms and the sites of fold deformation within the accretionary edifice.

The Oligocene–Miocene sedimentary strata and mélange of the Shimanto accretionary complex on the Muroto Peninsula, southwest Japan, display a seemingly disordered and random fold system. Traditionally, the apparent geometric disarray of the folds has prompted workers to interpret more coherent folded strata in this area as representing slump folded units, whereas associated mélanges have been viewed as olistostromes (Taira *et al.* 1980, Sakai 1981). Our recent work on these virtually unmetamorphosed rocks indicates that the seemingly chaotic Shimanto Complex, here, is more orderly than previously conceived. We have recognized sheath-like folds and rotated fold axes that define a consistent geometric fabric involving two phases of tectonically-induced fold axis rotation. The earlier phase produced outcrop-scale non-cylindrical and sheath-like folds, whereas the later phase involved the rotation of fold axes within and adjacent to mélange units.

The development of sheath folds has previously been considered compatible with deformation in deeper-seated portions of accretionary complexes (Quinquis *et al.* 1978) and fold axes rotated during progressive deformation have been recognized in some complexes (Moore & Wheeler 1978, Moore & Allwardt 1980, Bosworth & Vollmer 1981, Sample & Moore personal communication 1987). However, in the latter investigations, the data from the fold systems have only been useful in resolving the finite tectonic transport direction within the complexes considered. In contrast, our recognition of the progressive fold deformation in the Shimanto Complex is significant in that it allows for an assessment of both the type and environment of deformation within the Shimanto accretionary complex.

The results of this structural analysis also bear directly upon the interpretation of the Miocene tectonics of southwest Japan. Formerly held notions of the Miocene tectonic history of this region hinged strongly upon the recognition of regional slumping and olistostrome development. Our new structural interpretation shows that deformation was largely tectonic in origin and casts a significantly different perspective on the Miocene history of the southwest Japan plate margin.

TECTONIC SETTING

The Shimanto Belt (Fig. 1) is the result of accretion along the Cretaceous–Early Miocene convergent margin of southwest Japan. It is bounded to the north by the Butsuzo Tectonic Line (Taira *et al.* 1980), a thrust fault that separates the Shimanto Belt from the predominantly Mesozoic accretionary terranes of the Sambosan, Chichibu and Sambagawa belts. To the south, the

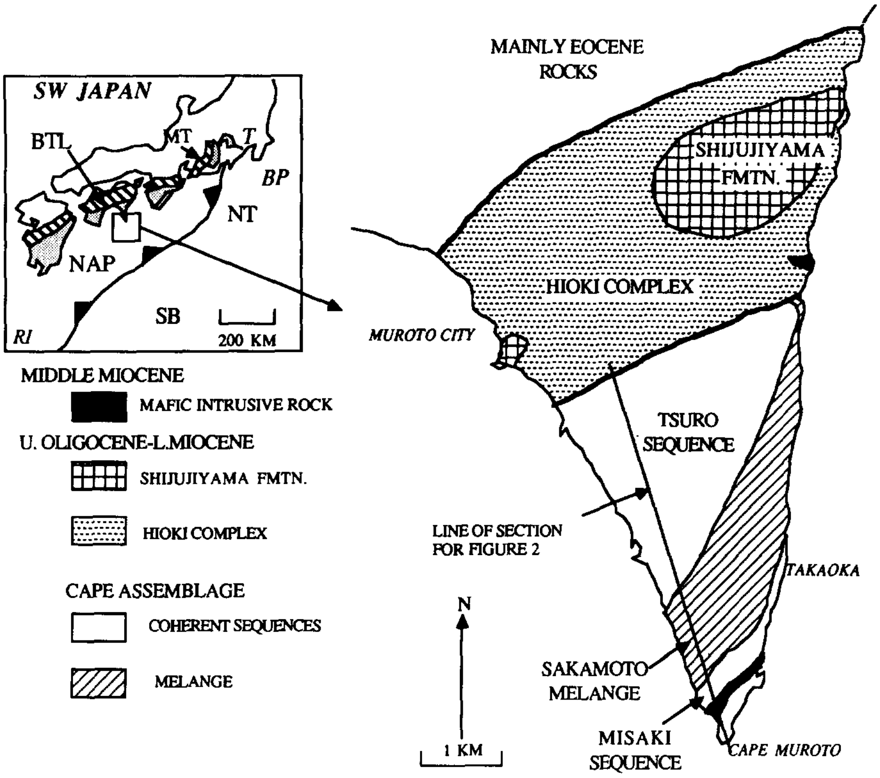


Fig. 1. Location and general geology of the Muroto Peninsula, Southwest Japan. On inset map, BP = Boso Peninsula, BTL = Butsuzo Tectonic Line, RI = Ryuku Islands, MT = Mesozoic accretionary terranes, NAP = Nankai Accretionary Prism, NT = Nankai Trench (axis marked by barbed line), SB = Shikoku Basin, T = Tokyo. Stippled area defines extent of the Shimanto Belt.

Shimanto Belt presumably continues offshore to merge with the active Nankai accretionary complex. The belt extends from the Boso Peninsula, near Tokyo, southwestwards to the Ryukyu Islands. It is composed mainly of clastic sedimentary rocks and subordinate mélange, both of which occupied a variety of sedimentary and tectonic environments within a forearc–trench system (Taira 1981, Taira *et al.* 1982, Suzuki & Hada 1979, 1983). The strata are now disposed in steeply-dipping fault-bounded structural packets that display an overall southward-younging trend (Taira *et al.* 1982).

The youngest and most outboard of these exposed Shimanto sequences, the Oligocene–Miocene rocks, are of particular interest in the tectonic history of the Shimanto Belt. These rocks were deposited coevally with the opening of the Shikoku back-arc basin (Fig. 1) at the southern border of the belt (Kobayashi & Nakada 1978, Kobayashi 1983, Seno & Maruyama 1984). The Oligocene–Miocene rocks have been interpreted as a packet of composite olistostromes (Kanmera 1977, reported in Ogawa 1985) that formed after subduction ceased and during the opening of the Shikoku Basin and initiation of strike-slip tectonics along the margin (Sakai 1983, Ogawa 1985). In contrast, other workers have used regional geophysical evidence to show that subduction was continuous along this margin during the Shikoku Basin spreading event (Kinoshita 1980, Seno & Maruyama 1984). The present study supports the latter interpretation.

NEOGENE ROCKS AT MUROTO CAPE

Late Oligocene–Early Miocene clastic sedimentary rocks, herein loosely termed Neogene rocks, of Muroto Cape form a distinct structural packet within the Shimanto Belt. They are juxtaposed against Eocene–Early Oligocene clastic strata to the north along an inferred steep fault (Taira *et al.* 1980, Katto & Taira 1981). There is a marked structural contrast across this fault; the older rocks display a well-developed penetrative cleavage and ubiquitous veining (L. DiTullio personal communication 1985), both of which are less intensely developed in the Neogene rocks. These features suggest that the older rocks come from structurally deeper parts of the accretionary prism.

Reliable reconnaissance and detailed mapping by previous workers (Taira *et al.* 1980, Katto & Taira 1981, Sakai 1981), as well as mapping during the present study, has shown that the Neogene rocks are separated into two structurally discordant units, both of which are composed of variably-deformed mudstone and sandstone, mainly turbidites. To the north is an ENE-trending mélange belt termed the Hioki Complex (Taira *et al.* 1980), whereas to the south lies a NE-trending assemblage of mélange bounded by coherent domains, which is herein termed the Cape assemblage (Fig. 1).

The Hioki Complex attains a structural thickness of approximately 4 km and it is structurally overlain by a distinct sequence of mainly thick bedded, to massive, late Oligocene–Early Miocene fossiliferous sandstone termed the Shijujiyama Formation (Taira *et al.* 1980). The outcrop pattern and limited data on bedding attitudes in the formation suggest that it occupies a synclinal keel above the Hioki Complex (Fig. 1). On the east side of the peninsula, sandstone near the base of the formation is locally interbedded with pillow lava and associated volcanic conglomerate that further serve to distinguish the unit from other Oligocene–Miocene strata in the area. The volcanic conglomerate contains well rounded clasts, suggesting a subaerially exposed volcanic source area. The Shijujiyama Formation is less deformed than the surrounding Hioki Complex and nearby Cape assemblage and sandstones of the formation have higher porosities than those of the latter units. The nature of the contact between the Shijujiyama Formation and the Hioki Complex is ambiguous due to a structural gradation from the complex into the formation and poor exposure. However, the structural setting of the Shijujiyama Formation in a syncline and with structurally gradational contacts with the subadjacent, more deformed rocks leads to the interpretation that the formation represents a superficial basin originally deposited upon the more highly deformed Hioki Complex.

The Cape assemblage is a 5 km thick structural package comprising coherent domains, informally referred to here as the Tsuro sequence (to the N) and the Misaki sequence (to the S) and an intervening mélange, herein termed the Sakamoto mélange (Fig. 1). The coherent strata are composed of approximately equal proportions of sandstone and mudstone that are internally disrupted by a complex network of faults; bedding is usually continuous only over a few meters to tens of meters. The Tsuro sequence contains more sandstone and is structurally more intact than the Misaki sequence. The Sakamoto mélange is a shale–mudstone matrix-dominated mélange containing blocks and rafts of clastic sedimentary rock and minor limestone.

Both the Hioki Complex and Cape assemblage are intruded by mafic dikes that are mainly concentrated along the east coast of the peninsula. Volcanic conglomerate of the Shijujiyama Formation has been hornfelsed locally by one dike that cross-cuts nearby, structurally lower Hioki rocks. Two of the larger dikes, one at the Cape and one in the Hioki Complex (Fig. 1), are coarse-layered gabbros, whereas most of the other dikes are buff weathered aphanitic bodies generally less than 2 m wide. The largest body, that at the Cape, has yielded early Middle Miocene isotopic ages (A. Taira personal communication 1984, Hamamoto & Sakai 1987). In addition, all of the intrusions cross-cut most of the structures in the Neogene rocks. The spatial confinement of these bodies, their mostly post-kinematic age, their common mafic composition and the presence of the volcanics at the base of the Shijujiyama Formation to the east side of the peninsula, suggest that the igneous rocks form a genetically-related suite.

Previous workers in the area have envisaged the deformational environment of the Neogene sequence to be at a shallow structural level, wherein non-penetrative, chaotic deformation might occur. Taira *et al.* (1980) tentatively interpreted the Muroto Peninsula section as being deposited and deformed on the upper slope of the Tertiary accretionary prism. Sakai (1981), in accordance with Kanmera (1977) and Sakai (1983), interpreted the Neogene section as representing a massive olistostrome. He related much of the chaotic nature of the terrane to gravitational slumping, and he thought that zones herein designated as mélange representated shaly parts of the olistostrome that served as a locus for later, unspecified tectonic deformation. The present detailed study demonstrates that a geometrically more consistent fabric than that previously recognized underpins the apparent chaos of rocks of the peninsula.

THE FOLD-RELATED DEFORMATIONS

Three major phases of deformation have been recognized during the present investigation; however, due to the structural intricacy of the area, particularly in the mélanges, it is possible that additional, unrecognized phases may have augmented the deformation scheme described here. The first recognized phase of deformation involved layer-parallel extension and is characterized mainly by boudinage, extension faults and vein-filled extension fractures in bedding. The two later episodes involved layer-parallel shortening, followed by the rotation of fold axes. The second phase is dominated by non-cylindrical folding and reverse faulting throughout the Neogene section, whereas the third phase is marked by the rotation of previously-formed fold axes and is confined to the Sakamoto mélange. This paper is concerned with the nature of these two late fold-related phases of deformation, which are responsible for the major structural framework of the Neogene rocks. The structural geometry and relative chronology of these late phases is best documented in the Cape assemblage, as outlined below.

Non-cylindrical folding and faulting

Structural style. Folds are the most striking manifestation of the second phase of deformation and they are accompanied by faults and an axial-planar cleavage. These structures are best preserved in the coherent domains; in particular, most of the following descriptions apply to structures from the Misaki sequence, where the best three-dimensional exposures occur. The folds are mainly non-cylindrical, ranging from plane non-cylindrical (hinge-lines curved within an axial surface) to folds with warped axial surfaces; the latter display warps both along strike and down-dip of the axial surface. Rarely, the folds are highly non-cylindrical and sheath-like. These extreme cases of highly non-cylindrical sheath-like folds are significant in unravelling the history of the late deformation and hence are described individually, following a general account of the second-phase structures.

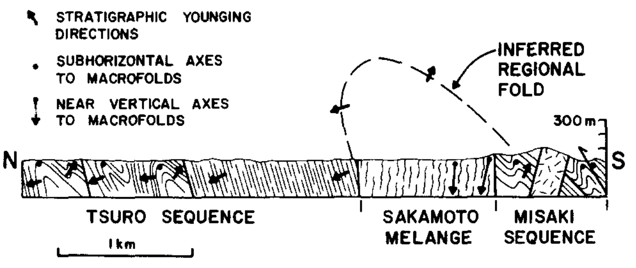


Fig. 2. Simplified interpretive cross-section of the Cape assemblage. Location of section shown in Fig. 1.

The framework of the second-phase structures, where best observed in the Misaki sequence, consists of NE-trending, subhorizontal asymmetric folds that are moderately overturned to the northwest and have steep SE-dipping axial surfaces. The folding is observed at two scales, one at outcrop or mesoscale with meter-scale wavelengths and the other at a macroscale with a 20–50 m range in wavelengths. The folds at both scales are typically preserved as half-wavelength segments in fault-bounded lenses. However, it is clear from detailed mapping of fold asymmetry and vergence that the mesoscale folds (mesofolds hereafter) are parasitic on the macroscale folds (macrofolds hereafter). The attitude of the enveloping surface to the macrofolds is not clear, mainly due to later tectonic disruption of the folds and the lack of marker beds.

A structurally-modified regional fold that encompasses most of the Cape assemblage is inferred from a cross-section of this unit (Fig. 2); the steeply-dipping overturned portion of the Tsuro sequence is interpreted as the northern limb of the fold, with the Sakamoto mélange representing the disrupted core zone, and the Misaki sequence with an inferred moderate southeast sheet-dip forms the southern limb (Fig. 2). The macrofolds are interpreted as parasites on this regional fold.

Classification of the folds is tenuous at best, due to the widespread development of early-phase extensional structures, such as pinch-and-swell of bedding and minor bedding extension faults, that affect bedding thicknesses. The folds display complex forms due to the varied responses of the sandstone and shale layers to deformation and the presence of the early extensional features. In most sandstone layers, the lack of a systematic relationship between bedding thickness and position around a fold suggests that early extensional structures control sandstone bedding thickness. Where early extentional structures are poorly developed, folded sandstone beds are of class 1B (parallel) to 1C (Ramsay 1967). In contrast, the mudstone and shale layers exhibit a distinct thickening in the hinges and thinning in the limbs of most mesofolds; this systematic relationship suggests that folding was responsible for shale and mudstone layer thickness variations, and folds in these layers are classified as class 2 (similar) or 3 types (Ramsay 1967). The difference in shape between folds in the sandstone and shale beds appears to reflect the contrasting mechanisms of strain accommodation during deformation. The class 1B–C fold style as well as local slickenlines on folded sandstone bedding surfaces suggest that a component of flexural slip was involved in the folding of the sandstone. In contrast, the similar style of the shale–mudstone beds is more indicative of a flow mechanism of folding. In all likelihood, these separate responses to folding by the sandstone and shale layers are ultimately linked to different mechanical properties of these layers at the time of deformation.

Locally, a weakly- to moderately-developed continuous (on outcrop-scale) cleavage is axial planar to both mesofolds and macrofolds. The weak development of the cleavage makes it difficult to demonstrate its axial-planar nature in most outcrops; however, where measured, the cleavage is parallel to axial surfaces of nearby mesofolds and macrofolds. In thin section, it is a rough cleavage (Powell 1979), defined in many places by a concentration of opaque material. Cleavage surfaces truncate remnants of microfossils, quartz grains and calcite veins; the latter are also buckled, with the cleavage approximately axial planar to the micro-buckles (Fig. 5). Calcite within these buckled veins displays deformation twins that may have developed during buckling. Most of these attributes strongly indicate that this cleavage is of pressure solution origin.

The basic fold architecture is intensely dissected by an anastomosing pattern of moderately to steeply SE-dipping faults with non-cylindrically curved surfaces that trend subparallel to the fold axial surfaces and are generally spaced on a meter scale. In places, these faults telescope the hinge areas of folds, display down-dip slickenlines, and are associated with asymmetric NW-verging minor folds in the Misaki sequence. The faults appear to preferentially telescope the short, upright-to-overturned limbs of these folds. Thus, based on these characteristics the faults are interpreted as thrusts that are related to the folding.

The relationship between folds and faults is locally complex. On the east side of Muroto Cape, a fault-bounded macrosyncline and accompanying mesofolds have been overturned and refolded by a later set of mesofolds (Fig. 3a); all of the folds are coaxial and all also affect early extension structures. This localized geological scenario considered in conjunction with fold–fault relationships described above leads to the interpretation that there was interaction between folds and the enveloping thrust faults during an inhomogeneous progressive deformation. The limbs of the macrosyncline may have been rotated back into the shortening field of the strain ellipsoid during thrusting along nonplanar faults, thus causing a local refolding episode during the second phase of deformation. In addition to these relationships of folds and faults, the localization of highly non-cylindrical mesofolds in close proximity to faults indicates a genetic link between folding and faulting.

Sheath-like mesofolds. In the field, individual mesofolds typically exhibit gentle lobate forms with hinge lines that plunge up to 30° in opposing directions in

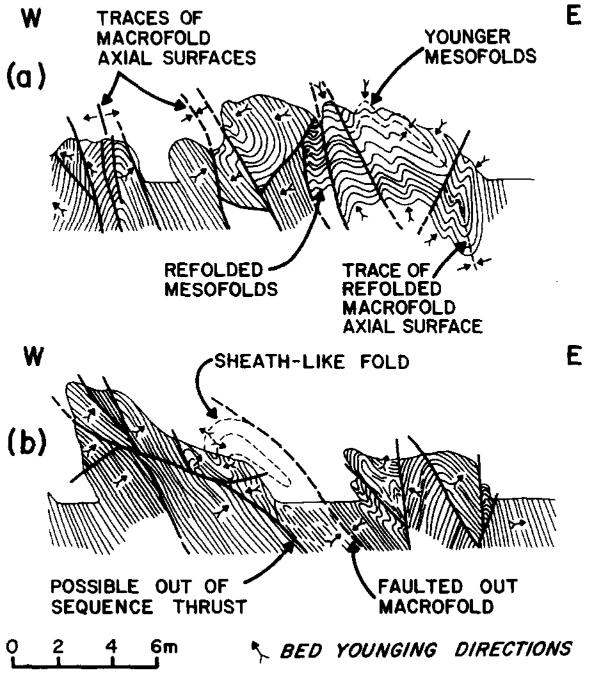


Fig. 3. Detailed cross-sections simplified from field sketches of the character of folds and faults at Muroto Misaki: (a) localized refolded macrofold discussed in text; (b) sheath-like fold in faulted-out syncline. The western-most fault that cuts down section may be a back-breaking or out of sequence thrust fault.

the lesser deformed Tsuro and Misaki sequences (Fig. 4a & d). Other local individual folds in these sequences with steeper plunges suggest that greater hinge-line curvatures are present (Fig. 4a & d). Six highly non-cylindrical sheath-like mesofolds with hinge lines that form an angle between 25 and 45° to a common sheath axis (Fig. 6a & b) have been observed in the Misaki sequence. One of these sheath-like folds is well within the sequence at the Cape, and the others are exposed at Takaoka, near the contact of the Misaki sequence with the Sakamoto mélange. The orientations of the folds at the two locales are divergent. The sheath axis through the fold at the Cape is steeply SE-plunging, whereas sheath axes of the folds at Takaoka are subhorizontal. This divergence of orientation is due to the late-phase rotation of fold axes in the Takaoka area, as discussed below.

The structural setting of these folds is best exemplified by the sheath-like fold at the Cape (Fig. 6a). Here, the axis through the center of the sheath-like fold is steeply SE-plunging, transverse to the trend of other mesofolds in the area. The sheath-like fold occurs in a complicated thrust zone that faults out the core of a macrosyncline (Fig. 3b). Field relationships (Fig. 3b) indicate that the sheath-like fold is most likely a refolded parasitic fold on the reclined, upward-facing long limb of the syncline. A plausible interpretation of the development of the sheath-like fold involves inhomogeneous progressive deformation; originally this fold may have formed coaxially with other nearby mesofolds and was subsequently deformed into a sheath form by thrusting subparallel to the axial surface of the syncline. Refolding of the sheath-like fold could well be the result of continued movement in the thrust zone, similar to that proposed above for the single refolded macrosyncline.

At Takaoka, the deformation has been more intense and the structural setting of the sheath-like folds is not as clear as at the Cape. Axes through the center of the sheath-like folds at Takaoka plunge gently to the north, nearly orthogonal to the steep axial plunges of most other mesofolds in the area (Fig. 4c). A group of anastomosing steep faults isolate the mesofolds in meter-scale tectonic packets. The mesofolds at Takaoka probably evolved in a manner similar to those at the Cape: that is, they originally formed with axes transverse to the fault movement direction and subsequently the fold hinge-lines were rotated towards the movement direction during faulting; however, a later rotation apparently has been induced upon these folds to produce their present disposition, approximately 90° askew from the Cape sheath-like mesofold.

One mesofold of particular interest associated with the sheath-like folds at Takaoka, displays discordant parasitic folds with curvilinear hinge lines (Fig. 7). This non-cylindrical, gently plunging mesofold is subhorizontally truncated by a minor fault; its aspect is reminiscent of a truncated version of the nearby sheath-like mesofolds. The parasitic fold axes are steeply plunging, nearly perpendicular to the preserved axis of the host fold as well as to the axes of nearby sheath-like folds and fault slickenlines, but parallel to the axes of other steeply plunging mesofolds in the area. The discordant parasitic folds probably initiated as higher order folds, transverse to the movement direction, on the limb of a sheath-like fold during continued fault movement.

In summary, the axis of the sheath-like fold at the Cape is oriented suborthogonal to the trend of the larger scale folds on the peninsula (Fig. 8a) and thus suborthogonal to the strike of the Shimanto Belt and the modern Nankai trough. In contrast, the sheath-like folds at Takaoka are oriented nearly perpendicular to the Cape sheath-like fold. These structural geometries are critical in the chronologic and kinematic analyses of the second and third phase deformations, as outlined in following sections.

Rotation of fold axes

Following the fold–thrust event, fold axes in the Sakamoto mélange and immediately bordering zones of the coherent sections were rotated into a near vertical attitude within the plane of their axial surfaces (Figs. 8b and 9). Notably, this event involved only the rotation of pre-existent folds; no new folds were generated in the sedimentary strata. This rotation event is gradational in nature, as is evident on a stereoplot of macrofold axes (Fig. 9); here, axes located in the centers of coherent domains are sub-horizontal, whereas those at the margins of the coherent domains and in the mélange are moderately to steeply plunging. The rotation of associated mesofolds mimics rotation of the macrofolds; axes of mesofolds in the Misaki and Tsuro sequences are

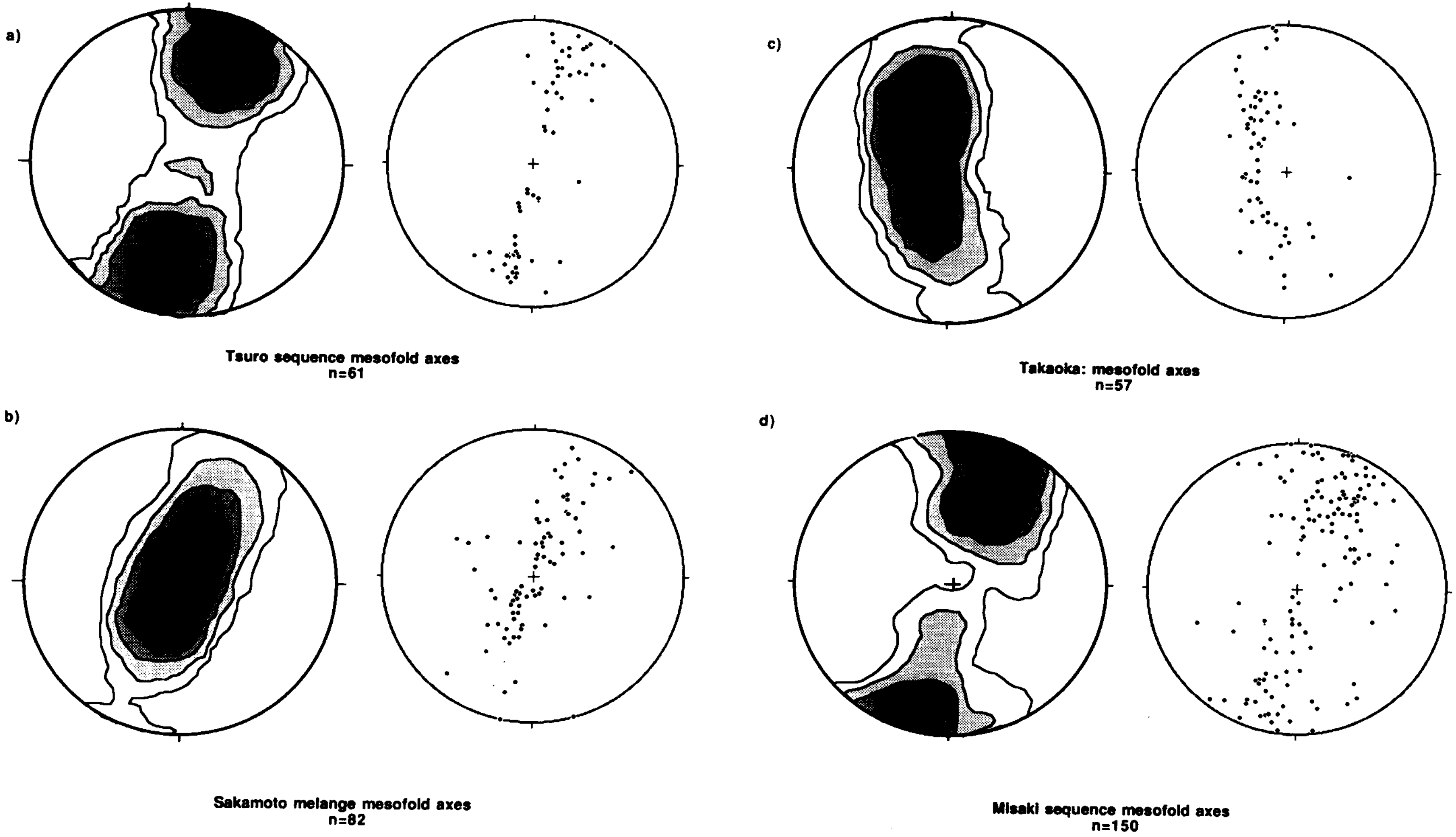


Fig. 4. Lower hemisphere equal-area projections depicting the change in orientation of fold axes from coherent domains to the mélange. The change in strike of the plane defined by axes in the Takaoka area is due to a regional warp that is also reflected in a change of orientation of bedding as well as all other structures in this area. Kamb (1959) statistical contouring method used, contour interval = 2σ.

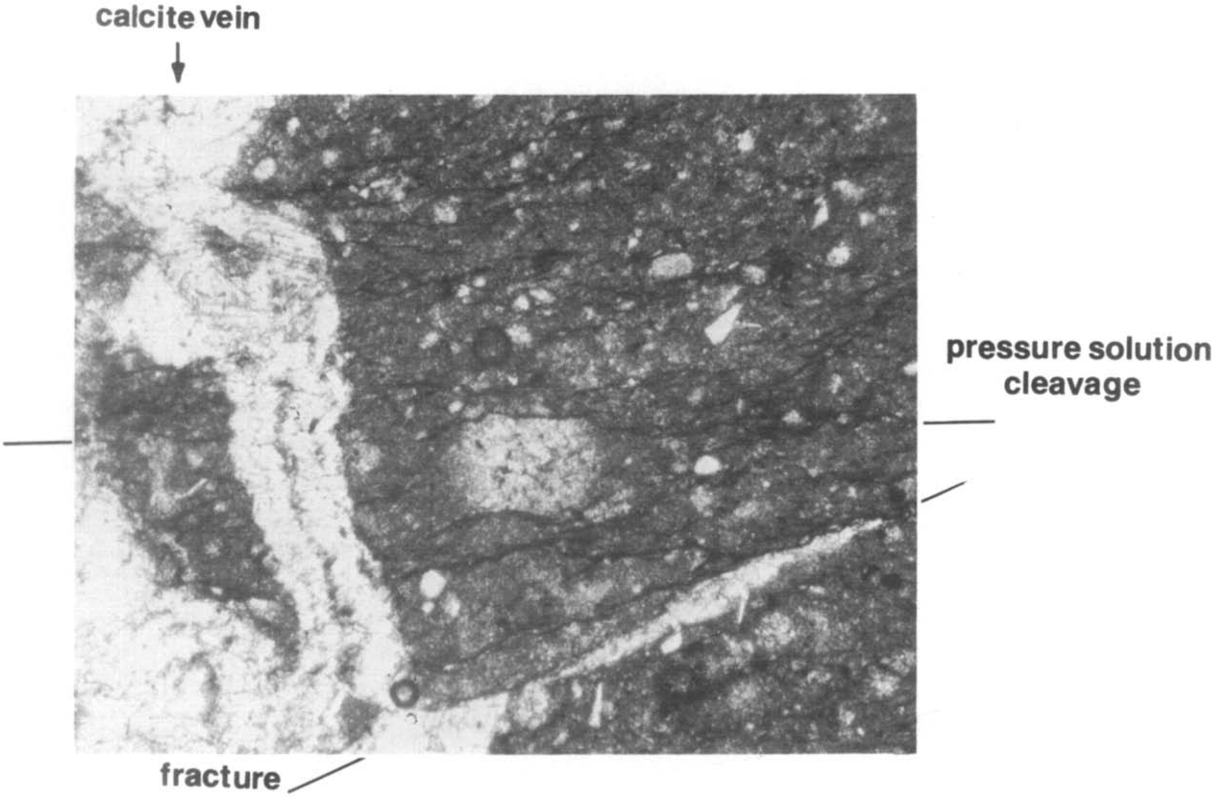


Fig. 5. Photomicrograph of the rough, axial-planar pressure-solution cleavage (from pebbly mudstone of the Misaki sequence). Note the truncation of the microfossil pseudomorph (center) by cleavage traces, the cross-cutting relationship of the cleavage and the calcite vein and the selvages of opaque material that define the cleavage planes. Cleavage is parallel to bedding; the microfossil pseudomorph is approximately 0.6 mm in diameter.

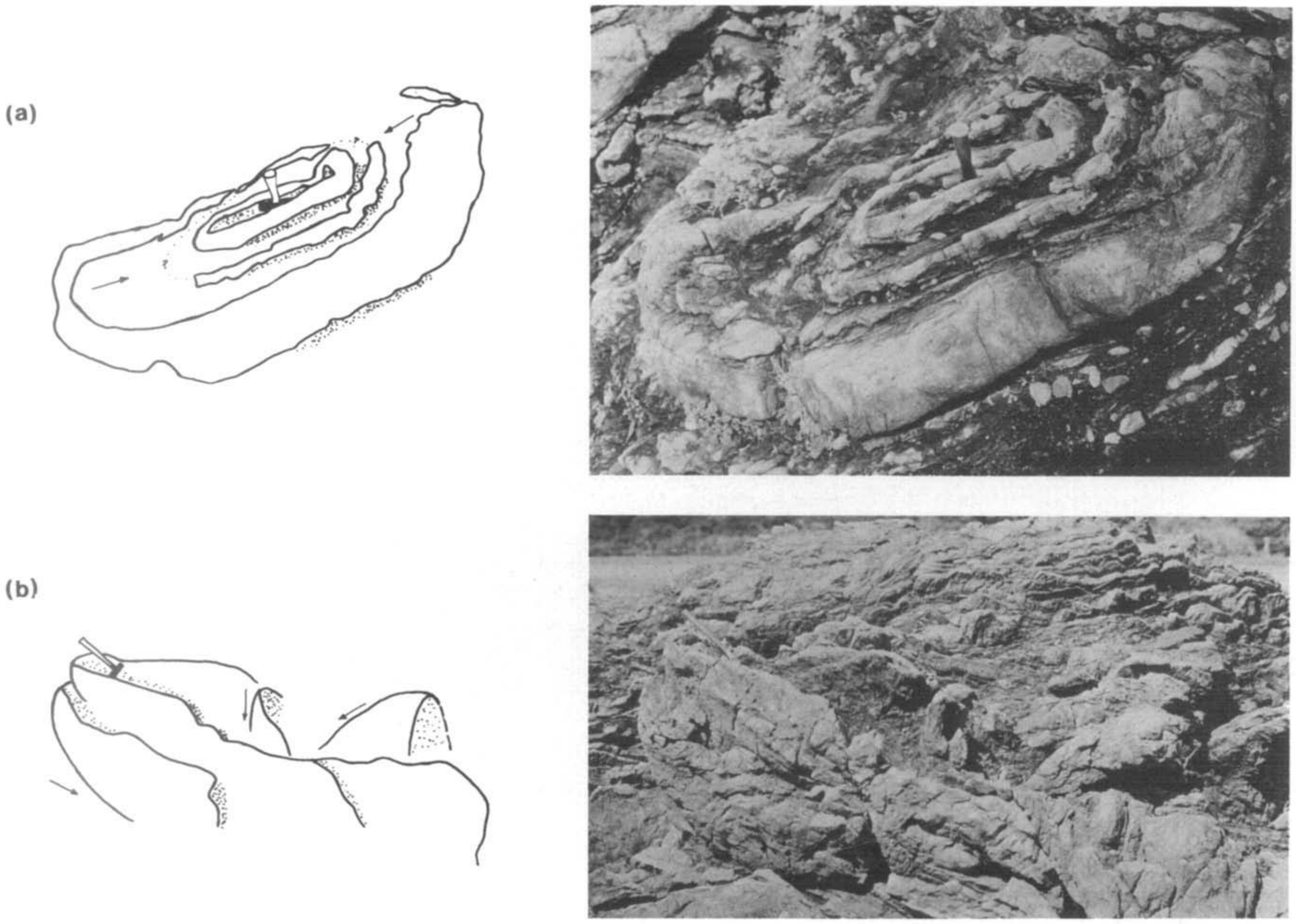


Fig. 6(a). The sheath-like mesofold at the Cape with arrows showing plunge of hinge-line. Hammer oriented along steeply plunging axis of the sheath; north is to the bottom of photograph. (b) Sheath-like mesofold from the Takaoka area. The arrows in the sketch depict the hinge-line orientation. Hammer handle in upper left for scale; north is to the right side of photograph. The difference in orientation of the axes of these two folds is due to the late-phase rotation of fold axes affecting folds within and in proximity to the Sakamoto mélange.

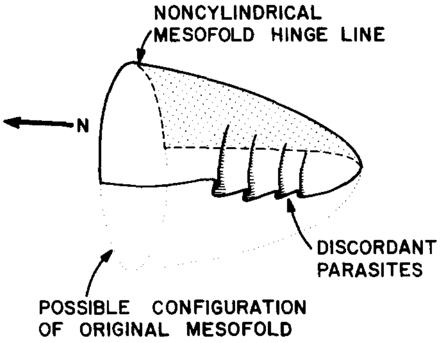


Fig. 7. Sketch from photograph of a non-cylindrical fold at Takaoka with discordant parasitic folds, and inferred original configuration in dotted line. The fold in the field is truncated by a near-horizontal fault, the trace of which corresponds to the dashed and solid lines terminating the parasitic folds at the center of the diagram.

gently to moderately plunging (Fig. 4a & d), while those of folds in the Sakamoto mélange have been rotated to near vertical (Fig. 4b). The folds at Takaoka in the Misaki sequence are intermediate in attitude between the coherent domains and the mélange (Fig. 4c), reflecting the transitional effects of this rotation on the margin of the coherent domain. Remarkably, the sheath-like mesofolds formed during the fold–thrust event also appear to have been rotated during this phase; the sheath-like mesofold in the coherent Misaki sequence is steeply plunging, whereas those at Takaoka, on the border of the Sakamoto mélange, have been rotated to near horizontal plunges. Thus, the relative angular relationships among macrofolds, mesofolds and sheath-like mesofolds established during the fold–thrust event were maintained during the rotation event (Fig. 8).

In the mélange and bordering areas of the coherent domains, rotated folds at all scales face in both directions along the strike of their axial surfaces, indicating that fold rotation was of both clockwise and counterclockwise sense within the plane of the axial surfaces (Fig. 8). This is particularly well displayed at Takaoka, where north-facing, steeply-plunging mesofolds are structurally juxtaposed against south-facing, steeply-plunging mesofolds. Within the Misaki sequence, near its contact with the Sakamoto mélange on the west side of the peninsula, steeply-plunging macrofolds that close seaward display opposing younging directions, again demonstrating the heterogeneity of rotation sense during this event. Similar relationships are also found among macrofolds in the Tsuro sequence, near its contact with the Sakamoto mélange on the east side of the peninsula.

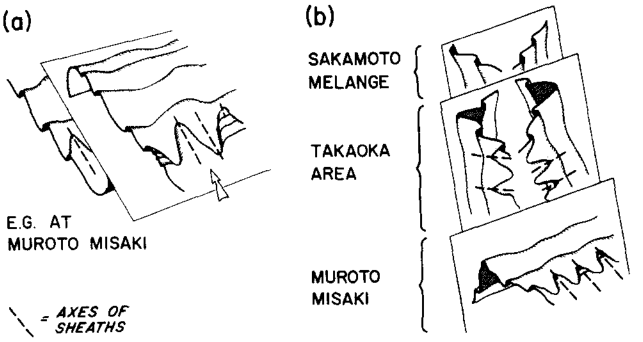
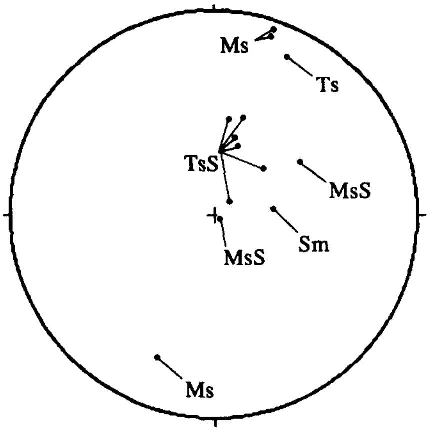


Fig. 8. Simplified schematic sketch depicting (a) the approximate geometry of the fold–thrust event, and (b) rotation of folds in the Sakamoto mélange and bordering areas depicting the late deformation. The steep anastomosing network of faults that dissect the macrofolds have been deleted for simplification. Note that both illustrations employ present orientation data; north is approximately perpendicular to the page.



Macrofold axes (n=13)

Fig. 9. Lower-hemisphere equal-area projection showing the change in plunge of macrofolds from coherent sequences to the mélange and neighboring areas. Macrofold axes determined by bedding measurements around the folds. Note that the plane defined by these axes is approximately parallel to that defined by mesofold axes in Fig. 5. Ms = Misaki sequence, Sm = Sakamoto mélange, Ts = Tsuro sequence, MsS = Misaki sequence near border with Sakamoto mélange, TsS = Tsuro sequence near border with Sakamoto mélange.

Macrofolds in these zones are dissected by a network of steep faults and it appears as though the macrofolds have been rigidly rotated within fault-bounded packets. These packets range in scale from a meter across up to nearly the half-wavelength of the macrofolds. The mesofolds, including the sheath-like ones, appear to have been rotated as rigid markers within these structural packets. Thus, the rotation event clearly postdates the fold–thrust event that produced mesoscale sheaths. This curious kinematic scheme inferred from field data is discussed more fully in the subsequent section.

Deformational environment

First-order considerations. In the regional context of the accretionary prism, there is a spectrum of deformational environments, ranging from near-surface slumping to deep-seated tectonic underplating, in which noncylindrical folding and rotation of fold axes could proceed. The first-order dilemma in analyses of these deformational environments is the distinction between gravity driven surficial deformation and tectonic deformation (e.g. Cowan 1982, Byrne 1984). Although a single, decisive criterion for their distinction is lacking, the following characteristics, when considered together, strongly support a tectonic origin for the second-phase fold–thrust deformation in the Cape assemblage.

(1) The fold–thrust system is uniformly developed throughout the 5 km structural thickness of the Cape assemblage. It involves at least three and probably four orders of folds. Discordant parasitic folds formed on the limbs of mesoscale folds that are themselves clearly minor folds related to macrofolds; the macrofolds, in turn, appear to be parasitic on a regional fold, encompassing most of the Cape assemblage. Mesoscale and regional folds within this pattern are closely associated with an anastomosing system of thrust faults. Locally within these thrust zones, mesoscale fold axes were deformed into sheath-like forms. Based upon fold style, this deformation was evenly distributed through strata of apparently contrasting physical properties. This internal consistency of the structural geometry through the 5 km thickness of the Cape assemblage is difficult to reconcile with a surficial, gravitational slump environment.

(2) The second-phase folds are accompanied by an axial-planar pressure-solution cleavage; this cleavage occurs locally throughout the assemblage. The pressure-solution cleavage affects quartz grains, calcite veins and carbonate replacements of microfossils. Although axial-planar cleavages have been reported for some slump folds (Williams *et al.* 1969, Woodcock 1976), these cleavages are characterized only by the preferred orientation of detrital platy minerals. Furthermore, pressure-solution features have not been reported from DSDP coring of modern accretionary prisms; for example, coring near the toe of the modern Nankai accretionary complex has reached a depth of more than 0.5 km and recorded sediments with a minimum porosity between 30 and 40%, without sign of pressure-solution features (Bouma & Moore 1975). These data suggest that pressure solution within accretionary complexes occurs at stress conditions associated with porosities lower than 30% and thus probably operates at a structural level below that at which surficial slumping normally takes place.

(3) The style and geometry of second-phase folds are unlike those of folds attributed to slumping in the nearby Eocene rocks of the peninsula. In the Eocene section, folds that are related to slump zones are confined to chaotic pebbly mudstone and gritty mudstone matrixes, and they are typically rootless, small-scale and ductile (at outcrop scale), with highly convolute and discontinuous forms and highly attenuated limbs. Significantly, the slump folds also predate other structures in the Eocene strata.

Contrary to the slump-origin proposed for the Cape assemblage folds by previous workers (Taira *et al.* 1980, Sakai 1981), the characteristics listed above which strongly suggest that the fold–thrust deformational event took place within the confines of a systematic, widely distributed tectonic strain system.

Second-order refinements. Accepting a tectonic origin for the second-phase fold–thrust structures, further refinements can be made in the analysis of the deformational environment of this event, including the type of deformation path, the order of magnitude of strains involved, the tectonic polarity of the deformation, and the structural level.

There is scant evidence for establishing the type of deformation responsible for the fold–thrust event. The pervasiveness of thrust faulting throughout the assemblage suggests that a significant component of simple shear was involved. However, the event appears to have been more complex than a progressive simple-shear deformation, as illustrated by the refolding of the macrosyncline described above. Generally, material planes that have been extended cannot reenter the shortening field of the finite-strain ellipsoid during a progressive simple-shear deformation. The progressive refolding of the macrosyncline limbs indicates that local heterogeneities, such as irregular fault surfaces, perturbed the deformation scheme from one of simple shear.

Recent work on simple shear systems, both in laboratory experiments and by mathematical modelling, have indicated that high shear strains ($\gamma = 5 - 15$) are necessary for the rotation of linear elements to cluster tightly in the X direction of the strain ellipsoid and for the formation of highly non-cylindrical folds (Cobbold & Quinquis 1980, Skjernaa 1980). These models account for neither variable strain rate nor variable material properties of the rocks involved; however, because they deal with passive rotations of uniform material lines they most likely represent minimum strains necessary for the formation of highly non-cylindrical folds. Thus, it is suggested that the sheath-like mesofolds were formed under high strain conditions.

Many workers have demonstrated that the rotation of linear elements, in particular fold axes during progressive deformation is towards the X axis of the finite-strain ellipsoid, which at high strains is nearly coincident with the tectonic transport direction (e.g. Flinn 1962, Skjernaa 1980). This process is independent of both the type of deformation and the type of folding (active vs passive). It is clear from the data outlined above for the Cape assemblage that during the generation of sheath-like mesofolds, the mesofold axes were rotated from a NE–SW to NW–SE trend, roughly within the plane of the axial surface. Thus, the bulk tectonic transport direction during the fold–thrust event was along a NW–SE trend, that is, suborthogonal to the strike of the Shimanto Belt and the active Nankai Trench. The landward vergence of the fold system (Fig. 2) indicates a SE over NW tectonic polarity.

The lack of regional metamorphism in these rocks combined with the development of only a weak penetrative cleavage despite pervasive folding, indicate that the fold–thrust deformation proceeded at a shallow structural level in the Shimanto accretionary complex. This interpretation is further tempered by the regional setting of the Shijujiyama Formation on top of the slightly older Hioki Complex. The interpretation that the Shijujiyama rocks represent a superficial basin indicates that the Hioki Complex and probably the adjoining Cape assemblage were deformed within a few kilometers of the surface of the accretionary complex.

The third deformation phase involving the rotation of fold axes in the Sakamoto mélange and adjoining areas is somewhat of an enigma. The deformation did not generate any new folds in the sedimentary rocks, but solely involved the rotation of pre-existing fold axes. The extent and uniformity of the rotation evident in the Sakamoto mélange indicate that moderate to high strains were likely operative during this deformation. The rotation of macrofold axes to steep plunges within the plane of their axial surfaces strongly suggests that the X principal strain axis was oriented suborthogonal to the Shimanto Belt, consistent with the kinematics and strain deduced for the fold–thrust event. However, the subhorizontal sheath-like fold axes suggest a possible strike-slip motion in the mélange and abutting areas. Such an interpretation is precluded by the variability of macrofold and mesofold facing directions. We believe that the sheath-like mesofolds formed during the fold–thrust event and were rigidly rotated away from the X axis in fault-bounded packets during a later phase of this deformation, rather than continuing to elongate in the X direction. We suggest that such a curious scenario, where the sheath-like folds are rigidly rotated away from the X axis, reflects the strengthening of the sedimentary pile during progressive deformation. The interpretation of such a change in mechanical response to a progressive deformation is complex and beyond the scope of this analysis.

In summary, the rotation event is viewed here as a continuation of the fold–thrust progressive deformation that was partitioned into the shale-rich parts of the deforming mass, that is, the mélange and immediately adjacent areas. The change in the style of strain is attributed to evolving rheological properties of the sedimentary sequence during progressive deformation. It is uncertain if any significant strain was sustained by interior portions of the coherent sequences during the rotation event.

Location in the accretionary complex. The sum of attributes of the deformational events thus portrays a shallow structural environment in which high tectonic strains were developed suborthogonal to the trend of the Shimanto accretionary complex. The most plausible deformational environment in which such a shallow, high-strain deformation could be achieved in the Shimanto accretionary complex setting appears to be in either a lower-trench slope basin or in structural packets accreted at, or near, the toe of the complex. However, the equivalent degree and intensity of deformation as observed in the Cape assemblage has yet to be disclosed either on seismic profiles of active slope basins or by observations of on-land examples (Moore & Karig 1976, Karig 1983, 1985). The high strains necessary for the formation of the sheath-like folds as well as the pervasive nature of thrusting in the Misaki sequence and the later rotation of folds in the mélange all favor a deformational environment within the accretionary edifice where trench-fill sediments have been stripped off the downgoing oceanic slab and deformed in thrust-bounded structural packets. In addition, the presence of the less-deformed Shijujiyama Formation in a superficial basin above the more-deformed Hioki mélange is highly reminiscent of a slope basin–accreted strata relationship (Moore & Karig 1976); the similar structural style of the Hioki mélange and bordering Cape assemblage supports the interpretation of the latter representing accreted trench strata.

Structurally-shallow accretion of trench strata can occur by either offscraping at the toe of the accretionary complex (Seely *et al.* 1974, Karig & Sharman 1975) or subcretion (Karig & Kay 1981, Karig 1983), i.e. underplating, near the toe of the complex. Although subcretion is generally considered to proceed at greater depths, toward the rear of an accretionary complex, recent evidence suggests that shallow subcretion is a viable process (Leggett *et al.* 1985). Distinction between these two accretionary environments is probably beyond the resolution of structural features preserved on the Muroto Peninsula. However, the situation of the lesser-deformed Shijujiyama Formation atop the more-deformed accreted strata and the similar ages of these two units indicate a short time interval between accretion, some deformation, erosion of accreted strata and deposition of Shijujiyama strata. This sequence of events favors an offscraping environment of deformation for the accreted strata, since it would be easier to exhume deformed, offscraped strata than to unearth somewhat deeper-seated, underplated material.

Structural data from the Cape assemblage as well as evidence from studies of modern accretionary prisms suggest that the second-phase fold–thrust event does not mark the actual offscraping event. The fold–thrust deformation postdates a pervasive extensional deformation and also affects chaotic rocks of the Sakamoto mélange, indicating that some manifestation of the mélange predates the folding. In modern accretionary complexes pervasive layer-extension structures have not been encountered in undisturbed trench strata. Also seismic reflection profiles of the toe region of modern complexes indicate that the earliest structures are bedding parallel shortening features spatially associated with thrust faults; only local broad, fault-related folds have been observed in packets of otherwise planar strata (Karig 1985, Leggett *et al.* 1985). It is conceivable that the mélange and early extension features in the Cape assemblage may represent the early thrust faults and internal deformation of thrust packets, as resolved by geophysics, and thus be manifestations of the offscraping event. In addition, a thin unit of varicolored hemipelagic mudstones in the Tsuro sequence appears to be repeated on the overturned northern limb of the regional fold that encompasses the Cape assemblage (Fig. 2). This repetition apparently predates the folding event and may represent an early thrust phase. The Cape assemblage fold–thrust deformation is thus envisioned as taking place within thrust packets of already accreted strata.

This conclusion relegates the fold–thrust and rotation deformational environments to the broad, seismically opaque portion of accretionary complexes that spans the region between the seismically-defined thrust zone at the foot of the trench inner slope and the forearc area (Aoki *et al.* 1982, Karig 1983, Leggett *et al.* 1985). It is within this 'blind zone' of the complex, that is, beyond geophysical resolution and submerged out of view of direct observation, that gently to moderately landward-dipping strata at the toe of the complex are rotated into the steep dips so commonly observed in the onland, rearward portions of accretionary prisms. In the case of the Cape assemblage, it appears that this rotation was accomplished by tight landward-vergent folding and thrusting and subsequent fold rotation in the shale rich mélange zones.

Timing of the deformation

The timing of the offscraping deformation is constrained by the depositional ages of the Cape assemblage and Shijujiyama Formation and by the time of intrusion of mafic igneous bodies in the assemblage. The tightest depositional age constraint on rocks of the Cape assemblage is given by an Aquitanian (Early Miocene, *ca* 22–24 Ma) foraminifera fauna from a block in the Sakamoto mélange (Saito 1980).

The Shijujiyama Formation appears to be a superficial basin that postdates at least some of the deformation in the underlying Hioki Complex; thus the Shijujiyama Formation is likely to have been deposited during the ongoing deformation of underlying accreted rocks. The formation preserves a mainly molluscan fauna that is loosely constrained as Late Oligocene–Early Miocene in age (Sakai 1981). If this fauna represents the age of the formation, rather than the age of an eroded and transported fauna, then the inception of deformation of the accreted strata must have been soon after their inferred Aquitanian deposition.

The intrusive rocks in the Cape assemblage have yielded two isotopic age dates; however, the data from which these ages are interpreted has yet to be released and thus the value of these ages is equivocal. An 18 Ma ^{40}Ar/^{39}Ar hornblende date was determined by Russian researchers (Taira personal communication 1984, H. Sakai personal communication 1985) and a 14.4 ± 0.4 Ma Rb/Sr whole rock–biotite age was determined by Hamamoto & Sakai (1987). These ages accord well with the ages of a suite of granitoids that is widespread through the Shimanto Belt (Oba 1977); thus these ages appear to be valid ages of intrusion. As such, they indicate that most of the deformation in the Cape assemblage must be of Early Miocene age.

Consideration of the age and structural relationships of the Cape assemblage, Shijujiyama Formation, and intrusive rocks in the assemblage strongly suggests that the Cape assemblage was subjected to at least three phases of deformation very soon after deposition in the Early Miocene.

TECTONIC IMPLICATIONS

The folded strata of the Cape assemblage are not chaotic, as originally perceived, but display a complex systematic pattern that can be related to a regional non-cylindrical folding event followed by an event involving the rotation of the pre-existing fold axes in the Sakamoto mélange. The pervasive, uniform development of the folds throughout the 5 km structural thickness of the Cape assemblage accompanied by an axial-planar pressure-solution cleavage strongly suggests that the folds are of tectonic origin. This interpretation opposes the previously held notion that the deformation was surficial and slump-related; however it does not discount the proposal that the mélanges were originally olistostromes (Sakai 1981). Rather, it demonstrates that structures formerly cited as evidence for an olistostromal origin are, in this case, of tectonic origin. If the mélange units were olistostromal in origin, it is very likely that the structures related to slumping have been homogenized, in large part, by the later tectonic overprint.

The tectonic event responsible for the generation of sheath-like mesofolds and later rotation of fold axes corresponds most closely to the deformation envisaged within an offscraped structural packet of trench-fill sediments, behind the imbricate wedge at the toe of the complex. The accretion event appears to have been initiated very shortly after deposition of the Cape assemblage and was completed in a brief period of time between 22 Ma and approximately 16 Ma. In the regional tectonic framework this event overlaps with the opening of the Shikoku Basin. Geophysical and stratigraphic evidence indicate that rifting of the basin was initiated in the Late Oligocene between 30 and 25 Ma, and that the opening was completed by the early Middle Miocene, between 15 and 18 Ma (Kobayashi 1983, Seno & Maruyama 1984). Thus it appears that accretion and ensuing deformational events, which must have started well before the time of intrusion of igneous rocks into the Cape assemblage, coincided with the middle to late stages of spreading of the Shikoku Basin.

This tectonic scenario, as deduced from the structural analysis of folds in the Cape assemblage, fully supports the geophysical evidence that subduction was continuous along the Neogene Shimanto Trench during the Shikoku Basin spreading event (Kinoshita 1980, Seno & Maruyama 1984). The pervasive nature of the folding event indicates that subduction-related deformation was dominant within the Cape assemblage. It is possible, however, either that some strike-slip movement accompanied subduction or that subduction was oblique.

The structural data from the Muroto area dispels the simplicity of the notion of an Early Miocene olistostrome belt related to strike-slip movement along the southwest margin of Japan (Kanmera 1977, Sakai 1983, Ogawa 1985) and calls for a reassessment of other parts of the belt. If an olistostromal belt ever existed, its representative in the Muroto area must have occupied a trench-fill or near-trench environment that was subsequently accreted into the Shimanto Complex; the subduction-related deformation would have effectively obliterated the olistostromal features.

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