Magnetostratigraphic correlation of Miocene regression-and-transgression boundaries in central Honshu, Japan

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Abstract

Regression-and-transgression boundaries (RTBs) were defined in Miocene strata of the Yatsuo area (RTBs Y1, Y2, and Y3) in a backarc basin, the Mizunami area (RTBs M1, M2, and M3) in an intra-arc basin, and the Kakegawa area (RTBs K1 and K2) in a forearc basin, across central Honshu, Japan. The sedimentary successions of the Yatsuo and Mizunami areas consist of coastal-shelf deposits, and the RTBs are recorded as unconformities or ravinement surfaces. In the Kakegawa area, the middle of a turbidite section (RTB K1) and an erosional surface (RTB K2) in thick mudstone might represent maximum regressions.

The recognized RTBs were formed in Miocene time, except for RTB M3 in Pliocene time. The Miocene RTBs can be correlated within four time zones by means of magnetostratigraphy; Zone Jmi1 (RTB K1) in Chron C5Dn (17.62–17.28 Ma), Zone Jmi2 (RTBs Y1, M1, and K2) in Chron C5Br (16.01–15.16 Ma), Zone Jmi3 (RTBs Y2 and M2) in Subchron C5Bn1r (15.03–14.89 Ma), and Zone Jmi4 (RTB Y3) between 14.89 and 12.3 ± 1.9 Ma. The synchronicities of the RTBs in Zones Jmi2 and Jmi3 in the different tectonic settings suggest that the RTBs were formed by regional sea-level changes.

Key words: magnetostratigraphy, correlation, Miocene, Yatsuo, Mizunami, Kakegawa

Introduction

The cause of relative sea-level changes is one of the most controversial topics in sedimentary geology. Enthusiastic debate has centered on the relative contribution of eustasy and tectonics (e.g. Vail et al., 1977; McKerrow, 1979; Cloetingh, 1988; Miall, 1991, 1992). Central to this argument is the question of whether sea-level changes occurred synchronously in different places. However, it is not easy to reconstruct relative sea-level changes exactly from sedimentary outcrop sections because vertical changes in lithofacies can be controlled by variations in sedimentation rate changes, especially caused by delta lobe shifts, independently of actual sea-level changes. Regression-transgression cycles are comparatively easy to identify in sedimentary sections by analyzing stacking patterns of sedimentary lithofacies and their bounding surface characteristics, and precise correlation of the cycles in different sedimentary basins allows us to determine whether the cycles are locally, regionally, or globally synchronous and whether the

cycles were caused by relative sea-level changes or sedimentation rate changes.

In central Honshu in Miocene time there were several sedimentary basins in which the deposition of shallow marine sequences now provides excellent records for evaluating regression-transgression cycles. Shibata and Itoigawa (1980) described regression-transgression cycles in the Miocene sedimentary successions of central and southwest Honshu based on the assemblage changes of marine molluscan fossils, and discussed their synchronicity. Although the fossil records provide good information on paleowater depth changes, it is crucial to examine the lithofacies changes in the sedimentary successions to identify detailed regression-transgression cycles. To examine the regression-transgression cycles and their synchronicity among the Miocene basins, the first author (Y.H.) has investigated the lithofacies of the Miocene strata in three areas across central Honshu: Yatsuo, Mizunami, and Kakegawa areas, in terms of paleodepositional environments and then identified detailed regression-transgression cycles (Hiroki, 1995).

Fig. 1. (A) Distribution of Miocene strata in central Honshu, Japan and locations of the studied areas. (B) Areas of uplift and subsidence during the Miocene in central Honshu (after Huzita, 1962).

These three areas are located within zones of Miocene subsidence (Fig. 1-A, B). The geographic distribution of subsidence in the Miocene is closely similar to the pattern of present-day sedimentary basins in the Japan Sea, the Seto-Naikai (Seto Inland Sea) and the Pacific Ocean. The Yatsuo, Mizunami, and Kakegawa areas are located in the northern, middle, and southern parts of central Honshu, respectively. The Miocene strata of the Yatsuo area were formed at a flank of a backarc basin, namely the proto-Japan Sea. The sedimentary rocks of the Mizunami area were deposited in an intra-arc basin such as the present-day Seto-Naikai. The sedimentary successions of

the Kakegawa area were deposited in a forearc basin between the proto-Japan arc and the Shikoku Basin. Correlation of the regression-and-transgression boundaries (RTBs) between the studied areas makes it possible to test their synchronicity in the different tectonic settings, and so to provide constraints on the causes of the regression-transgression cycles.

In order to examine the synchronicity of the observed RTBs, it is crucial to correlate the sedimentary successions in the different sedimentary basins. Magnetostratigraphy in combination with biostratigraphic data allows detailed correlation of the Miocene successions to the standard time scale with age resolution of 0.1–1 m.y. (Berggren et al., 1995). According to the published biostratigraphic and magnetostratigraphic data, the regression-transgression cycles have periods of 0.4–3.8 m.y. (Hiroki, 1995). Thus magnetostratigraphy is a useful tool to correlate the RTBs, and we carried out magnetostratigraphic studies in the studied areas.

In this paper, (1) sedimentological and stratigraphical records of eight RTBs in the Yatsuo, Mizunami, and Kakegawa areas are briefly described, (2) the observed RTBs are dated by preliminary magnetostratigraphic data from the Mizunami and Kakegawa areas along with published magnetostratigraphic, biostratigraphic, and radiometric data, and then (3) the RTBs are correlated among the studied areas. Finally, (4) causes of the Miocene regression-transgression cycles are discussed.

Vertical changes in lithofacies assemblages and depositional environments and definition of RTBs

Depositional environments and systems of the Miocene strata in the studied areas have been interpreted on the basis of analysis of lithofacies assemblages in the sedimentary successions, and the regression-transgression cycles were identified by analyzing vertical changes in lithofacies assemblages and bounding surface characteristics between the lithofacies assemblages (Hiroki, 1995). Following Hiroki (1995), we briefly describe the vertical changes in lithofacies assemblages and depositional environments in the sedimentary successions, and define the RTBs in each studied area. Brief descriptions and interpretation of major lithofacies assemblages are summarized in Tables 1–3 for each studied area.

Yatsuo

Lithofacies assemblages and depositional environments

The studied area is located in hilly district area between the Muromaki River and the Sho River (Fig. 2). Sedimentary columnar sections were measured along the Yamada River (Section 1), the Wada River (Section 2), and a road from Ichitani to Higashibessho (Section 3) (Fig. 2). The three sections were compiled to construct a continuous sedimentary section in this

Fig. 2. Geological map and cross-sections of the Yatsuo area. Thick lines and numbers in circles show positions of columnar sections of Figs. 3 and 12.

area (Fig. 3).

The thick Miocene sedimentary succession (about 3,000 m thick) consists of volcanic rocks and sedimentary rocks which unconformably overlie the Hida metamorphic rocks and the early Mesozoic Funatsu Granites (Makiyama, 1930 ; Sakamoto and Nozawa, 1960). The sedimentary succession was divided into five sedimentological units, referred to as Units 1-5 in ascending order (Fig. 3 ; Table 1). The unit boundaries were defined by distinct erosional surfaces and/or at the top of coarsening-upward successions. Figure 3 shows the stratigraphic relationship between our sedimentological units and lithostratigraphic divisions of Hayakawa and Takemura (1987).

Unit 1 represents a single fining-upward succession characterized by upward lithofacies assemblage changes from matrix-supported conglomerates with interbedded sandstones, mudstones, volcanic rocks, and volcanoclastic rocks (Subunit 1A) to interbeds of sandstone and mudstone (Subunit 1C), through massive, horizontally-stratified, and cross-stratified sandstones (Subunit 1B). The thick fining-upward succession shows the vertical lithofacies assemblage changes typical of alluvial fan deposits (e.g. Amajor, 1986 ; Collinson, 1986), and the upward decrease in

grain size is probably a reflection of a depositional environment change from the proximal (Subunit 1A) to the distal (Subunit 1C) part of an alluvial fan system (Collinson, 1986).

Unit 2 consists of lower fining-upward and upper coarsening-upward sections. The fining-upward section contains massive, poorly sorted sandstone beds (Subunit 2A) and overlying massive mudstones (lower part of Subunit 2B). The base of the section is marked by a distinct irregular erosional surface (Fig. 4A). The sandstones of Subunit 2A contain abundant fragments of marine molluscan fossils such as *Anadara* sp. and *Ostrea* sp. which lived in the intertidal to shoreface zones (Higo and Goto, 1993 ; Fig. 4 A), and are similar to ravinement deposits formed on the shoreface during shoreface retreat (Swift, 1968 ; Murakoshi and Masuda, 1992). The coarsening-upward section contains massive mudstones (upper part of Subunit 2B) and overlying massive medium-grained sandstones (Subunit 2C). The section is comparable to regressive successions of fan deltas or strand plains (e. g. Elliott, 1986 ; Leckie and Rosenthal, 1987), and may indicate a depositional change from offshore to shoreface.

Unit 3 consists of lower fining-upward and upper

Fig. 3. Synthesized columnar section showing vertical lithofacies changes, upward fining and coarsening, vertical changes in depositional environments, and horizons of regression-and-transgression boundaries (unconformities Y1, Y2, and Y3) in the Yatsuo area.

coarsening-upward sections. The fining-upward section shows lithofacies changes from cross-bedded and massive, coarse-grained sandstones (Subunit 3A) and overlying massive, poorly sorted gravelly sandstone beds containing fragments of *Ostrea* sp. (Subunit 3B), through interbeds of gravelly sandstone and mudstone (Subunit 3C), to massive mudstones (lower part of Subunit 3D). The cross-bedded sandstone of Subunit 3A contain mud and sand rip-up clasts less than 30 cm in diameter and pebbles near the base (lower part of Fig. 4B). The bounding surface between Subunits 3A and 3B shows distinct erosional contact (Fig. 4B). The vertical lithofacies assemblage changes from Subunits 3A to 3D are similar to trans-

gressive sedimentary successions of estuarine fill sediments overlain by inner shelf muds (Demarest and Kraft, 1987), so that Subunit 3A is interpreted as estuarine, Subunit 3B as shoreface, Subunit 3C as offshore-shoreface transition, and Subunit 3D as offshore deposits, respectively. The fragments of *Ostrea* sp. in Subunit 3B suggest reworking and redeposition of intertidal to shoreface deposits by shoreface erosion in the nearshore during shoreface retreat, and the erosional surface between Subunits 3A and 3B can be interpreted as a ravinement surface (Swift, 1968; Moslow, 1984; Murakoshi and Masuda, 1992). The coarsening-upward section shows lithofacies assemblage changes from massive mudstones (upper part of

Table 1. Sedimentological characteristics and depositional environments of lithofacies assemblages of the Yatsuo and Tonami Groups in the Yatsuo area (based on Hiroki, 1995).

Assemblages	Sedimentological characteristics	Environments
Unit 1		
Subunit 1A	Interbedded gravelly sandstones and mudstones at the base, and overlying matrix (poorly sorted mud)-supported conglomerates intercalating massive sandstones, mudstones, andesitic lavas, and volcanoclastic rocks	Proximal part of alluvial fan
Subunit 1B	Trough cross- and horizontally-stratified and massive, medium to fine sandstones with minor beds of gravel	Middle part of alluvial fan
Subunit 1C	Interbedded sandstones and mudstones with parallel lamination and abundant plant fossils	Distal part of alluvial fan
Unit 2		
Subunit 2A	Massive, poorly sorted sandstones containing abundant molluscan fossil fragments such as <i>Anadara</i> sp. and <i>Ostrea</i> sp.	Shoreface
Subunit 2B	Massive mudstones	Offshore
Subunit 2C	Massive, coarse to very coarse sandstones	Shoreface
Unit 3		
Subunit 3A	Cross-stratified, coarse sandstones containing mud and sand rip-up clasts, and overlying massive, medium to coarse sandstones	Estuary
Subunit 3B	Poorly sorted, massive gravelly sandstones containing molluscan fossil fragments such as <i>Ostrea</i> sp.	Shoreface
Subunit 3C	Interbedded gravelly to fine sandstones and mudstones. Trough cross-stratification, ripple and parallel lamination, convolution, normal grading, and burrows in the sandstones	Offshore-shoreface transition
Subunit 3D	Massive mudstones	Offshore
Subunit 3E	Interbedded very fine to fine sandstones and mudstones	Offshore-shoreface transition
Subunit 3F	Massive, medium sandstones containing molluscan fossils	Shoreface
Unit 4		
Subunit 4A	Massive or weakly parallel laminated mudstones	Offshore
Subunit 4B	Sandy mudstones, muddy sandstones, and interbedded sandstones and mudstones. Parallel lamination and bioturbation	Offshore-shoreface transition
Unit 5		
Subunit 5A	Massive, poorly sorted conglomerates containing molluscan fossil fragments and abundant mud rip-up clasts	Shoreface
Subunit 5B	Massive and locally hummocky cross-stratified, fine to coarse sandstones with minor gravel beds. Intense bioturbation in the sandstones	Shoreface

Fig. 4. Outcrop photographs of major erosional surfaces in the upper part of the Kurosedani Formation in the Yatsuo area. A: Distinct irregular erosional surface (indicated by arrows) between lower massive mudstone and upper poorly sorted, gravelly sandstone bed, 25 cm thick. Note shell fragments of *Anadara* sp. and *Ostrea* sp. in the sandstone bed. This outcrop corresponds to the 1,705 m stratigraphic horizon of the columnar section in Fig. 3. B: Distinct erosional surface (indicated by arrows) between lower massive sandstone, 75 cm thick, and upper poorly sorted, gravelly sandstone, 45 cm thick. This outcrop corresponds to the 1,858 m stratigraphic horizon of the section in Fig. 3.

Fig. 5. Geological map and cross-sections of the Mizunami area. Thick lines and numbers in circles show positions of columnar sections of Figs. 6 and 13 and paleomagnetic sampling sites. The geological map was modified from Matsuzawa et al. (1959).

Subunit 3D) to medium sandstones (Subunit 3F), through interbedded sandstones and mudstones (Subunit 3E), and is likely to be a regressive succession of a fan delta or a strand plain, showing depositional changes from offshore to shoreface, through the offshore-shoreface transition.

Unit 4 contains a thick mudstone section (>200 m; Subunit 4A) which is overlain by muddy sandstones, sandy mudstones, and thinly bedded (1–25 cm) fine-grained sandstones and siltstones (Subunit 4B), showing upward coarsening. The top of the coarsening-upward section is truncated by an irregular erosional surface. The erosional surface is locally recognized as resulting from fluvial channeling. Thus the underlying coarsening-upward section is possibly a regressive succession and is interpreted as offshore (Subunit 4A) and offshore-shoreface transition (Subunit 4B) deposits.

Unit 5 is mainly composed of massive medium-grained sandstones with local hummocky cross-stratification (Subunit 5B), interpreted to be deposited as a result of wave activity on shoreface. The base of Unit 5 is marked by the erosional surface. Along Section 3, the surface is covered by massive, poorly sorted conglomerates containing fragments of marine molluscan fossils and mud rip-up clasts (Subunit 5A), which are similar to ravinement deposits, and so interpreted as a ravinement surface formed by shoreface erosion. Along Section 2, the basal part of this unit contains several sets of fining-upward sections, interpreted as fluvial channel fills which are characterized by trough cross-stratified conglomerates, trough

cross-stratified and parallel laminated sandstones, and parallel laminated mudstones in ascending order.

RTBs

Three RTBs were identified in the Yatsuo area (RTBs Y1, Y2, and Y3 from oldest to youngest; Fig. 3). RTB Y1 is recognized as an unconformity between Units 2 and 3. The RTB is underlain by the coarsening-upward succession, characterized by the regressive environmental change from offshore to shoreface, and then overlain by the transgressive estuarine fill deposits. Because estuaries are usually formed by sea water flooding during rise of relative sea-level into fluvial-incised valleys formed during former lowering of relative sea-level (Reinson, 1992), the RTB was possibly formed by fluvial channeling during lowering of relative sea-level.

RTB Y2 is recognized between Units 3 and 4. The unit boundary is underlain by the coarsening-upward succession showing the regressive environmental changes from offshore to shoreface, through the offshore-shoreface transition. Although we could not observe the boundary between Units 3 and 4 because of no exposure, the development of offshore deposits over the shoreface deposits possibly indicates a transgression event, and so the RTB is defined at the shoreface/offshore facies boundary, possibly as an unconformity.

RTB Y3 is recognized as an unconformity between Units 4 and 5. The unconformity is underlain by the coarsening-upward succession showing the environmental change from offshore to the offshore-shoreface transition, indicating regression. The ir-

regular erosion of the underlying Mitani Mudstone at the base of Unit 5 (Fig. 2) and the overlying fluvial channel fill deposits along Section 2 indicate that the base is a type 1 unconformity (Van Wagoner et al., 1988), formed by fluvial incision during relative fall of sea-level. Along the other sections where the base is covered by the poorly sorted conglomerates, the unconformity is considered to be replaced by the ravine-ment surface during the subsequent transgression (Demarest and Kraft, 1987).

The fining- and coarsening-upward successions in Units 2-5 indicate transgression and regression respectively. The repetition of the fining- and coarsening-upward successions in the thick sedimentary succession is explained by repetition of progress (regression) and retreat (transgression) of an alluvial-coastal-shelf system with its general upward shift during overall relative sea-level rise. RTB Y3 has already been recognized as the Ikahama Unconformity by earlier researchers (e.g. Hayakawa and Takemura, 1987). The analyses of lithofacies assemblages and their stacking patterns allowed us to identify the another unconformities at the top of the Shiotani Sandstone (RTB Y2) and within the upper Kurosedani Formation (RTB Y1).

Mizunami

Lithofacies assemblages and depositional environments

The studied area is located in a hilly district around Akeyo-machi, Mizunami City, north of the Toki River (Fig. 5). Sedimentary columnar sections were measured along a small valley at Shimizu (Section 1), a narrow pass at Tsukiyoshi across a hill on the right bank of the Hiyoshi River (Section 2), and a small valley pass beside an athletic field at Togari (Sections 3 and 4). Bore hole data (Gimei no. 68 obtained by Chubu Works, Power Reactor and Nuclear Fuel Development Corporation) were referred to for the lower succession of the Miocene strata (Fig. 5). The sections were compiled with reference to volcanic ash key beds to construct a continuous sedimentary section (Fig. 6).

The Miocene sedimentary succession (170 m thick) of the Mizunami Group unconformably overlies the basement rocks, which consist of granite, quartz-porphry, and Paleozoic sedimentary rocks, and is unconformably overlain by the Pliocene Seto Group (Itoigawa, 1974a; Fig. 6). The sedimentary succession was divided into five sedimentological units, referred to as Units 1-5 in ascending order (Fig. 6; Table 2). The unit boundaries were defined at distinct erosional surfaces. Figure 6 shows the stratigraphic relationship between our sedimentological units and the lithostratigraphic divisions of Itoigawa (1974a).

Unit 1 represents a fining-upward succession

Mizunami

Fig. 6. Synthesized columnar section showing vertical lithofacies changes, upward fining and coarsening, vertical changes in depositional environments, and horizons of regression-and-transgression boundaries (unconformities M1, M2, and M3) in the Mizunami area. See Fig. 3 for legend.

characterized by lithofacies assemblage changes from basal conglomerates (Subunit 1A) to tuffaceous mudstones and sandstones (Subunit 1C), through fine to coarse sandstones (Subunit 1B). The conglomerates are composed of angular to subangular, pebble to cobble size clasts with a sandy matrix. Plant fossils are abundant in the mudstones. Nonmarine molluscan fossils such as *Viviparus* sp. and *Anodontia* sp. were reported from this unit (Itoigawa, 1974b). The vertical lithofacies assemblage changes are similar to those of alluvial fan deposits (e.g. Amajor, 1986; Collinson, 1986) and probably reflect a depositional environment change from the proximal to the distal part of an alluvial fan system.

Unit 2 is mainly composed of muddy sandstones and sandy mudstones containing abundant molluscan fossils and calcareous nodules (Subunit 2B). The sandstones and mudstones are generally massive due to intense bioturbation, but locally contain wave ripple lamination. There are abundant *Ophiomorpha*-type burrows in the sandstones. The basal part of this unit is characterized by upward fining from a

Table 2. Sedimentological characteristics and depositional environments of lithofacies assemblages of the Mizunami and Seto Groups in the Mizunami area (based on Hiroki, 1995).

Assemblages	Sedimentological characteristics	Environments
Unit 1		
Subunit 1A	Massive conglomerates. Angular to subangular, pebble to cobble size clasts. Sandy matrix	Proximal part of alluvial fan
Subunit 1B	Massive, fine to coarse sandstones	Middle part of alluvial fan
Subunit 1C	Massive mudstones with pebble layers, and overlying massive, medium sandstones	Distal part of alluvial fan
Unit 2		
Subunit 2A	Swaley and hummocky cross-stratified, medium sandstones intercalating thin mudstone beds. Wave ripple lamination at the top and mud rip-up clasts at the base of the sandstone beds. Poorly sorted, coarse sandstones containing pebbles and mud rip-up clasts at the base of the subunit	Shoreface
Subunit 2B	Muddy sandstones and sandy mudstones showing massive or ripple lamination. Abundant molluscan fossils, calcareous nodules, burrows, and intense bioturbation	Offshore-shoreface transition
Subunit 2C	Interbedded medium sandstones and muddy sandstones, and overlying massive, medium sandstones. Abundant molluscan fossils, calcareous nodules, <i>Ophiomorpha</i> -type burrows, and intense bioturbation	Shoreface
Unit 3		
Subunit 3A	Interbedded medium sandstones and fine tuff beds. <i>Ophiomorpha</i> -type burrows. Trough cross-stratification and shell fragments in the sandstones	Estuary
Subunit 3B	Massive, sandy mudstones intercalating tuff beds. Molluscan fossils, calcareous nodules, burrows, and bioturbation in the mudstones. Abundant <i>in situ Felaniella usta</i> molluscan fossils at the base of the subunit	Offshore
Subunit 3C	Massive and low angle trough cross-stratified, pumice tuff. Well rounded, pebble to cobble size pumices	Offshore?
Unit 4		
Subunit 4A	Conglomerates containing reworked coral and abundant molluscan fossils, and muddy sandstones showing intense bioturbation	Shoreface
Subunit 4B	Massive diatomaceous mudstones	Offshore
Unit 5		
Subunit 5	Massive conglomerates. Well rounded, pebble to cobble size clasts. Sandy matrix	Proximal part of alluvial fan

Fig. 7. Outcrop photograph of a major erosional surface in the uppermost part of the Togari Member in the Mizunami area. Note distinct erosional surface (indicated by arrows) between lower massive, coarse- to medium-grained sandstone and upper medium-grained sandstone. Arrows labelled Tu indicate a pair of volcanic ash layers named the Tu Tuff (or *Avec* Tuff). Y and T indicate the Yamonouchi Member and Togari Member respectively. This outcrop corresponds to the 100–110m stratigraphic horizon of the section in Fig. 6.

10-cm-thick coarse-grained sandstone bed, containing mud rip-up clasts and pebbles (base of Subunit 2A), to the muddy sandstones of Subunit 2B, through medium-grained sandstones showing swaley and hummocky cross-stratification and wave ripple lamination (Subunit 2A). The base of the succession is a distinct erosional surface. The uppermost part of this unit is characterized by upward coarsening from the muddy sandstones of Subunit 2B, through interbedded medium-grained sandstones and muddy sandstones, to coarse- to medium-grained sandstones (Subunit 2C). The swaley and hummocky cross-stratification and wave ripple lamination in the sandstones of Subunit 2A indicate deposition under wave action, probably in the shoreface. The wave ripple laminated sandstones and mudstones of Subunit 2B can be interpreted as deposits in the offshore-shoreface transition above the storm wave base. The coarsening-upward section resembles the progressive succession of a strand plain or a fan delta (e.g. Elliott, 1986 ; Leckie and Rosenthal, 1987), and the sandstones of Subunit 2C are interpreted as shoreface deposits.

Unit 3 is mainly composed of massive sandy

Fig. 8. Geological map and cross-section of the Kakegawa area. Thick lines and numbers in circles show positions of columnar sections of Figs. 9 and 14 and paleomagnetic sampling sites.

mudstones intercalated with tuff beds (Subunit 3B). The mudstones are massive with moderate to intense bioturbation and contain molluscan fossils, calcareous nodules, and burrows. The base of this unit is marked by an erosional surface (Fig. 7) covered by interbeds of fine tuff and cross-bedded, medium-grained sandstone (Subunit 3A). The sandstone beds show thick-thin-thick-thin succession with intercalation of the fine tuff beds. The interbeds are overlain by the massive sandy mudstones (Subunit 3B), showing upward fining. The interbeds of Subunit 3A indicate repetition of high and low energy flows and are interpreted as mud couplets formed by tidal currents, possibly in an estuary (Nio and Yang, 1989). The upward fining from the interbeds to the mudstones may reflect an environmental change from estuary to offshore or inner shelf. In its upper part, the unit contains cross-stratified pumice breccia (Hazama Member; Subunit 3C). Although there are no exposures near the top of Subunit 3C along the measured Sections, grayish clean sandstones of the Shukunohora Sandstone have been recognized over the Hazama Member in the northern area (e.g. Itoigawa, 1980). The top of the unit is an angular unconformity between the Akeyo and Oidawara Formations (Kitamura, 1959; Itoigawa, 1960). The clean sandstones below the unconformity may be shoreface sands deposited during regression.

Unit 4 is mainly composed of homogeneous, diatomaceous, light gray colored, massive mudstones (Subunit 4B). The base of the unit is the angular unconformity. Conglomerates and poorly sorted

muddy sandstones cover the unconformity (Subunit 4A). They contain corals and abundant and varied marine molluscan fossils from a water depth range from 0 to 200 m (Itoigawa et al., 1974). Such a wide range of water depth can be explained by reworking of previously deposited foreshore to nearshore deposits by shoreface erosion and their mixing with deeper offshore sediments.

Unit 5 is the Pliocene Seto Group which overlies the Miocene strata with an unconformity (e.g. Itoigawa, 1960). The unit is composed of massive conglomerates of well rounded pebbles and cobbles, probably deposited in a proximal alluvial fan.

RTBs

Three RTBs were identified in the Mizunami area (RTBs M1, M2, and M3 from oldest to youngest; Fig. 6). RTB M1 is recognized as an unconformity between Units 2 and 3. The RTB is underlain by the coarsening-upward succession characterized by the environmental change from the offshore-shoreface transition to the shoreface, indicating regression, and then overlain by the estuarine deposits. The estuary was probably formed during relative sea-level rise by sea water flooding into fluvial-incised valleys formed during the preceding lowering of relative sea-level (Reinson, 1992). Absence of fluvial facies on the unconformity is probably due to reworking of initially deposited fluvial deposits during the transgression.

RTB M2 is recognized as the angular unconformity between Units 3 and 4. The unconformity is underlain by the regressive succession represented by offshore mudstones of Subunit 3B to shoreface clean

Kakegawa

Fig. 9. Synthesized columnar section showing vertical lithofacies changes, depositional environment, horizons of regression-and-transgression boundary K1 in a turbidite section and submarine erosional surface K2, possibly indicating maximum regressions, in the Kakegawa area. See Fig. 3 for legend.

sandstones of the Shukunohora Sandstone, and then overlain by the poorly sorted sandstones and conglomerates of Subunit 4A showing features typical of ravinement deposits during transgression (Swift, 1968; Murakoshi and Masuda, 1992).

RTB M3 is recognized as an unconformity between Units 4 and 5. The RTB truncates the offshore mudstones and is overlain by the cobbles and pebbles of proximal alluvial fan deposits. The lithofacies assemblage arrangement above and below the RTB obviously indicates regression and fluvial incision of the underlying marine sediments in response to base level lowering of fluvial during relative sea-level fall.

The unit boundaries between Units 2 and 3, 3 and 4, and 4 and 5 were interpreted as unconformities. The sedimentary succession of the Mizunami area consists of three cycles of transgression-regression. Unconformities M2 and M3 have been well recognized by former researchers (e.g. Itoigawa, 1980). Unconformity M1 was newly identified near the top of the Togari Member.

Kakegawa

Lithofacies assemblages and depositional environments

The studied area is located in a hilly district between the Haranoya River and the Kurami River (Fig. 8). Sedimentary columnar sections were measured along a small tributary stream of the Haranoya River (Section 1), a pass from Hirashima to Sakashita, Kami-Taruki (Section 2), and a pass running northward from Ishigatani, Kami-Saigo (Section 3) (Fig. 8). The three sections were compiled to construct a continuous, comprehensive sedimentary section (Fig. 9).

The Miocene sedimentary rocks are bounded on the north by an ENE-WSW fault, separating the Miocene sequence from Paleogene sedimentary rocks of the Mikura Group (Fig. 8). The sedimentary succession was divided into seven sedimentological units, referred to as Units 1-7 in ascending order (Fig. 9;

Table 3. Sedimentological characteristics and depositional environments of lithofacies assemblages of the Kurami and Saigo Groups in the Kakegawa area (based on Hiroki, 1995).

Assemblages	Sedimentological characteristics	Environments
Unit 1	Massive, fine to medium sandstones containing molluscan fossils	Offshore?
Unit 2	Interbedded fine sandstones and mudstones containing calcareous nodules	Offshore
Unit 3	Massive mudstones containing molluscan fossils	Offshore
Unit 4	Interbedded massive, medium to very fine sandstones and mudstones.	Offshore
Unit 5	Massive mudstones intercalating tuffaceous mudstone beds. Calcareous nodules and molluscan fossils in the upper part	Offshore
Unit 6	Massive mudstones containing angular to subangular clasts, and massive, medium sandstones with intense bioturbation	Offshore
Unit 7	Massive mudstones	Offshore

Fig. 10. Typical vector-demagnetization diagrams of progressive demagnetization of natural remanent magnetization by alternating field demagnetization of specimens from the Mizunami (A) and Kakegawa (B) areas. Solid (open) circles are projections of vector end-points on horizontal (N-S vertical) planes before tilt correction.

Table 3). The unit boundaries were defined by the characteristics of the lithofacies assemblages. Figure 9 shows the stratigraphic relationship between our sedimentological units and the lithostratigraphic divisions of Makiyama and Sakamoto (1957). The Awagatake Sand and Mudstone in the lower part of the Matsuba Formation was defined by Hiroki (1995).

The Miocene sedimentary succession (2,400 m thick) is mainly composed of dark gray massive mudstones (Units 3, 5, and 7) and contains marine molluscan fossils through the section (e.g. Makiyama and Sakamoto, 1957; Shibata and Kato, 1975). The lowermost part of the section represents a fining-upward succession which is characterized by a lithofacies assemblage change from bluish gray colored, massive, fine- to medium-grained sandstones (Unit 1; Amakata Sandstone), through interbedded fine-grained sandstones and mudstones (Unit 2; lowest part of the Towata Mudstone), to the massive mudstones (Unit 3; Towata Mudstone). Sandstone beds are intercalated within mudstones at 450–1,000 m of the measured graphic log (Unit 4; Awagatake Sand and Mudstone; Fig. 9). The sandstone beds are very fine- to fine-grained and 10–100 cm in thickness. The sandstones are massive.

A distinct erosional surface is recognized between Units 5 and 6 at 2,300 m of the log, which corresponds to the disconformity (Ibaraki et al., 1983) between the Kurami and Saigo Groups. The erosional surface indicates local erosion of more than 80 m of the underlying Kurami Group. The surface is covered by bluish gray mudstones containing dispersed, angular to sub-angular mudstone clasts, and locally by yellowish colored, massive, intensely bioturbated medium-grained sandstones (Unit 6).

The marine molluscan fossils and the lack of evi-

Fig. 11. Mean directions of high-coercivity remanent magnetization of the sampling sites in the Mizunami (A) and Kakegawa (B) areas. Solid (open) circles are on lower (upper) hemisphere of equal area projection after tilt correction. Solid diamonds show present axial dipole field direction on lower hemisphere projection. A plot (solid circle) in the Mizunami area is from Hayashida (1986).

dence of wave action such as wave ripple lamination and hummocky cross-stratification through the section indicate that the whole section was deposited in offshore or shelf environments. The sandstone beds of Unit 4 may indicate deposition by turbidity currents (Walker, 1992). The matrix-supported mudstone clasts in the mudstones of Unit 6 indicate deposition by debris flow (Fisher, 1971). The erosional surface between Units 5 and 6 is probably a marine erosional surface because there is no evidence of sub-aerial exposure above and below it.

RTBs

Because the whole succession is composed of offshore deposits, direct evidence of transgression and regression could not be obtained. However, the turbidite section at 450–1,000 m and the distinct erosional surface at 2,300 m are conspicuous in the thick muddy succession. Some authors have suggested sea-level control on turbidite deposition (e.g. Mutti, 1985; Posamentier and Vail, 1988; Masuda et al., 1989), and turbidite successions could be relatively dominant in lowstand systems tracts (Ito and Katsura, 1993). Thus the turbidite section in the Kakegawa area could have been formed during a lowstand stage of relative sea-level or a maximum regression. It is unclear what mechanism formed the erosional surface at 2,300 m. Because the surface shows no evidence of subaerial exposure, it might have been formed by slope failure or by erosion during bypassing of coarse sediments from the upper slope during sea-level lowering (e.g. Ito, 1995). Therefore, we consider the turbidite facies and the erosional surface as event deposits, and that an event surface formed during maximum regressions. We refer to the middle of the turbidite section and the surface as RTBs K1 and K2 respectively.

Table 4. Paleomagnetic data obtained from the Mizunami and Kakegawa areas.

Level from basement (m)	Sample	L	N	J (mA/m)	I (°)	D (°)	Strike & dip	I _c (°)	D _c (°)	α 95 (°)	k	Lat (°N)	Long (°E)	P
Mizunami area														
Akeyo Fm														
Yamanouchi Mm														
133.53	MZ37	Ms	9	2.20	-40.0	231.9	—	-40.0	231.9	7.3	44.4	-43.5	48.3	R
130.68	MZ35	Ms	4	3.77	-47.0	234.2	—	-47.0	234.2	11.1	69.8	-43.9	40.3	R
128.03	MZ32	Tuff	6	2.24	-50.1	226.0	—	-50.1	226.0	10.0	45.8	-51.6	40.4	R
125.63	MZ31	Ms	3	4.61	-60.3	226.2	—	-60.3	226.2	16.2	59.2	-53.7	23.6	R
124.64	MZ30	Ms	5	10.10	-41.0	246.9	—	-41.0	246.9	7.4	83.6	-31.6	39.3	R
123.59	MZ29	Ms	11	18.04	-46.0	242.5	—	-46.0	242.5	5.5	69.7	-36.9	37.3	R
122.57	MZ28	Ms	4	8.14	-43.9	245.0	—	-43.9	245.0	3.9	547.7	-34.2	38.0	R
121.32	MZ27	Ms	5	7.89	-51.5	250.9	—	-51.5	250.9	7.4	108.0	-32.3	28.3	R
120.92	MZ26	Tuff	5	2.29	-37.1	228.3	—	-37.1	228.3	12.4	39.3	-45.4	53.1	R
117.17	MZ22	Ms	3	2.22	-68.9	216.2	—	-68.9	216.2	13.5	84.5	-59.3	2.2	R
116.37	MZ21	Ms	3	2.16	-41.5	226.2	—	-41.5	226.2	12.8	94.0	-48.6	50.3	R
Togari Mm														
107.02	MZ18	mdy Ss	3	4.75	-40.8	239.2	—	-40.8	239.2	21.6	33.7	-37.8	43.5	R
106.39	MZ17	Tuff	10	1.46	-55.4	225.6	—	-55.4	225.6	7.7	40.6	-53.3	32.6	R
104.04	MZ15	Ss	4	6.32	-53.7	218.0	—	-53.7	218.0	21.6	19.1	-59.0	38.0	R
Tsukiyoshi Mm														
77.62	MZ11	Tuff	5	1.59	-64.6	216.6	—	-64.6	216.6	11.3	46.9	-60.5	13.7	R
66.47	MZ07	Ms	5	1.79	-42.2	222.4	—	-42.2	222.4	14.3	29.7	-52.0	52.1	R
61.27	MZ06	Ms	3	2.90	-56.8	198.1	—	-56.8	198.1	13.8	80.3	-75.3	33.8	R
57.57	MZ05	Ms	3	3.82	-48.7	200.9	—	-48.7	200.9	17.1	52.8	-71.5	59.2	R
50.42	MZ04	Ms	6	4.95	-37.6	217.1	—	-37.6	217.1	14.7	21.9	-54.6	60.9	R
41.00	MZ02	mdy Ss	7	3.71	-43.0	213.0	—	-43.0	213.0	16.7	14.0	-59.8	58.1	R
Kakegawa area														
Saigo Group														
Saigo Mudstone Mm														
2340.36	K28	Ms	2	0.14	38.4	36.9	N67.4°E20°S	46.1	54.0	—	—	43.7	221.6	(N)
Kurami Group														
Matsuba Fm														
Masago Mudstone Mm														
2244.54	K27	sdv Ms	2	0.10	-31.5	211.6	N67.4°E20°S	-41.5	224.7	—	—	-49.9	51.5	(R)
2212.40	K26	Ms	3	0.28	-46.3	226.7	N67.4°E20°S	-49.6	251.2	15.5	64.6	-31.2	30.5	R
2097.10	K25	Ms	4	0.04	-33.8	187.9	N67.4°E20°S	-50.1	198.5	12.0	59.6	-74.0	57.0	R
2039.54	K24	Ms	5	0.16	47.8	5.8	N67.4°E20°S	63.9	24.0	7.4	107.4	68.9	190.1	N
Matsuba Tuffaceous Siltstone Mm														
1995.66	K23	tf Ms	3	1.66	59.1	5.9	N67.4°E20°S	74.7	44.7	9.9	155.9	51.3	170.7	N
1995.56	K22	tf Ms	5	1.17	-41.4	184.1	N67.4°E20°S	-58.3	197.3	7.5	104.7	-75.6	26.0	R
1935.11	K20	Ms	6	2.50	60.3	2.7	N33.4°E18°S	64.7	37.2	3.5	366.8	59.8	193.6	N
1849.36	K19	Ms	14	1.55	49.9	3.6	N36.4°E28°S	57.1	41.8	3.9	102.4	56.4	210.6	N
1811.65	K18	tf Ms	4	0.21	-42.2	174.4	N53.4°E28°S	-71.5	199.6	16.4	32.3	-64.8	344.0	R
1766.11	K17	tf Ms	7	0.43	55.4	0.0	N53.4°E40°S	67.5	81.6	5.3	128.8	31.1	185.5	N
1579.87	K16	Ms	2	0.04	-36.2	182.7	N49.4°E45°S	-56.4	229.7	—	—	-50.1	29.9	(R)
1442.02	K14	Ms	3	0.35	-32.7	171.9	N37.4°E44°S	-53.6	212.1	63.4	4.9	-63.6	40.1	(R)
1346.86	K13	Tuff	12	2.17	-26.3	149.5	N37.4°E44°S	-63.9	181.6	5.6	61.3	-79.2	324.0	R
1249.87	K12	Ms	8	0.03	37.0	20.6	N67.4°E44°S	56.9	67.4	12.7	19.9	36.7	204.0	N
1109.03	K11	Ms	5	0.20	51.5	4.4	N67.4°E44°S	71.5	94.6	5.6	189.4	26.0	176.1	N
998.32	K10	Ms	4	0.17	53.8	356.6	N67.4°E44°S	76.5	111.2	6.8	183.7	22.7	163.9	N
Awagatake Sandstone Mm														
830.98	K09	Ms	3	0.32	59.4	22.0	N67.4°E44°S	61.8	114.3	19.5	41.0	8.2	180.3	N
751.91	K08	mdy Ss	6	0.54	50.0	358.6	N67.4°E44°S	75.4	90.8	3.7	323.2	30.1	170.3	N
627.28	K07	mdy Ss	2	0.29	56.3	8.6	N67.4°E44°S	68.1	106.9	—	—	17.2	176.9	(N)
458.12	K05	Ss	10	0.46	51.1	4.5	N67.4°E44°S	71.4	93.2	5.2	86.0	26.6	176.6	N
Amamiya Fm														
Towata Mudstone Mm														
230.86	K04	Ms	4	0.05	-29.8	216.5	N81.4°E20°S	-42.6	227.9	18.9	24.6	-47.6	48.4	R
181.23	K03	Ms	2	0.67	-29.8	226.5	N67.4°E44°S	-34.6	251.1	—	—	-26.0	42.1	(R)
Amakata Sandstone Mm														
18.54	K01	Ss	4	0.16	54.4	4.0	N67.4°E44°S	71.1	103.6	15.7	35.1	21.2	174.1	N

L : lithology (Ss:sandstone, Ms:mudstone, sdv:sandy, mdy:muddy, tf:tuffaceous); N : number of specimens which yielded primary magnetization after progressive demagnetization; J : mean intensity of remanent magnetization after removal of low-coercivity component of magnetization; I, D : mean *in-situ* inclination and declination before tilt correction; Strike & Dip : strike and dip for tilt correction; I_c, D_c : mean inclination and declination after tilt correction; k : precision parameter; α 95 : radius of the 95% confidence circle; Lat, Long : latitude and longitude of virtual geomagnetic pole position; P : magnetic polarity (N:normal polarity, R:reversed polarity, parentheses indicate uncertain interpretation due to large α 95 or insufficient number of data (N<3)).

Yatsuo

Fig. 12. Synthesized columnar section showing biostratigraphic zones, paleomagnetic polarities, polarity chrons, and positions of the regression-and-transgression boundaries (=unconformities) in the Yatsuo area. (a) : Itoh (1986), (b) : Tsuchi (1981), (c) : Hayakawa (1983), (d) : Itoh (1986), (e) : Itoh (1988), (f) : Itoh and Hayakawa (1988), (g) : Itoh and Hayakawa (1989), (h) : Shibata (1973). See Fig. 3 for legend.

Magnetostratigraphy

Sampling and experimental procedures

Two to five cylindrical samples were collected from 42 horizons of the Mizunami area and from 28 horizons of the Kakegawa area. The paleomagnetic sampling was carried out along the sections along which the sedimentary columns were measured. Samples were oriented with a magnetic compass. Strike and dip of the strata were measured for later tilt correction of the paleomagnetic direction. Each core sample, 2.5 cm in diameter, was cut to specimens of conventional size (2-2.2 cm in length) for magnetic measurement.

Magnetic cleaning was performed for the specimens from each horizon by means of alternating field demagnetization (AFD). The specimens were progressively demagnetized up to 70-100 mT with AFD after measuring the natural remanent magnetization (NRM). The measurement of remanent magnetization of the specimens was carried out with a 2G Enterprises cryogenic magnetometer 740-R at the Tokyo Institute of Technology and a 2G Enterprises cryogenic magnetometer 750 at the University of Tokyo.

Paleomagnetic analyses

The magnetic stability was examined by construc-

Mizunami

Fig. 13. Synthesized columnar section showing sampling horizons, paleomagnetic polarities, biostratigraphic zones, polarity chrons, and positions of the regression-and-transgression boundaries (=unconformities) in the Mizunami area. (a) : Hayashida (1986), (b) : Koizumi (1981), (c) : Ibaraki (1981), (d) : Saito (1963). See Fig. 3 for legend.

tion of vector-demagnetization diagrams, using the results of progressive AFD. Figure 10 shows typical examples of the demagnetization diagram of each studied area.

The diagrams show that the NRM of the specimens are composed of two magnetic components; low- and high-coercivity components. They show significant changes in vector direction during the progressive demagnetization, and the trajectory of the magnetization vector of further demagnetization steps is nearly linear toward the origin. The magnetic directional change occurs at 0–5 mT in the Mizunami area and at 0–40 mT in the Kakegawa area. The low-coercivity components are normal polarity, whereas the high-coercivity components are reversed polarity. The directional changes probably indicate removal of a soft secondary viscous remanent magnetization acquired during the current Brunhes normal polarity chron.

The magnetic directions are identified by fitting the least-squares-best-line (unanchored to origin)

(Kirschvink, 1980) to the segments of the stable high-coercivity components on the vector demagnetization plots (Table 4). Tilt correction was omitted for the Mizunami data because the Miocene strata of the area are nearly horizontal. The mean magnetic directions of the Mizunami sampling sites plot in the third quadrant of the stereonet and are directed upward, indicating reversed polarity (Fig. 11-A). Although all our samples from the Mizunami area show reversed polarity, they are in an antipodal direction to a normal polarity direction of the Hongo Formation (Hayashida, 1986). The antipodal character of the polarities suggests that the magnetic directions represent the geomagnetic field directions at the time of deposition. After tilt correction, the mean magnetic directions of the Kakegawa sampling sites plot both in the first quadrant with normal polarity and in the third quadrant with reversed polarity (Fig. 11-B). The two clusters of magnetic directions form an antipode, suggesting that the magnetic directions are of

primary origin. Specimens showing erratic changes in remanence direction during progressive demagnetization were abandoned from the determination of primary magnetic remanence.

Identification of paleomagnetic polarity zones and correlation to geomagnetic polarity time scale

Polarity chrons were assigned to the strata according to the interpreted magnetic polarity data and the published biostratigraphic information in each studied area, on the basis of the geomagnetic polarity time scale (GPTS) of Berggren et al. (1995).

Yatsuo area

Paleomagnetic studies of the Yatsuo area have been carried out by Itoh (1986, 1988) and Itoh and Hayakawa (1988, 1989), and they established magnetostratigraphy for the Yatsuo and Tonami Groups. The established magnetostratigraphy is shown in Figure 12. The Higashibessho Formation contains two normal and one reversed polarity zones. The Kurosedani Formation and the Nirehara Formation are both reversed polarity. The biostratigraphic correlation of the Higashibessho Formation to Blow's Zone N9 (Blow, 1969; Tsuchi, 1981) and to the *Denticulopsis lauta* Zone (Itoh, 1986) allows us to assign the polarity zones of the formation to Subchrons C5Bn2n, C5Bn1r, and C5Bn1n (Koizumi, 1992; Berggren et al., 1995). The correlation of the upper part of the Kurosedani Formation to Zone N8 (Tsuchi, 1981) and a K-Ar age of 16.0 ± 0.9 Ma for the Iwaine Formation (Shibata, 1973) suggest assignment of the reversed polarity zone in the formation to Chron C5Br (Berggren et al., 1995). It is uncertain which polarity chron can be assigned to the normal polarity site of the Tenguyama Formation because no precise radiometric ages or fossil information have been obtained to date.

Mizunami area

The Mizunami Group contains reversed and normal polarities (Fig. 13). Our paleomagnetic data show that the whole of the Akeyo Formation represents reversed polarity. Although we could not detect paleomagnetic polarity for the Oidawara Formation because of the erratic demagnetization behavior of the samples, Hayashida (1986) has obtained a reversed polarity site from the formation. Hayashida (1986) also reported a normal polarity site from the Hongo Formation.

Saito (1963) correlated the Oidawara Formation to the *Globorotalia fohsi barisanensis* Zone of the planktonic foraminiferal biostratigraphy. The base of the *G. fohsi barisanensis* Zone can be marked by the FAD (first appearance datum) of *Orbulina suturalis* (Saito, 1963). Since the FAD of *O. suturalis* is correlated to Chron C5Bn (Berggren et al., 1995), the reversed polarity in the Oidawara Formation is assigned to Subchron C5Bn1r within Chron C5Bn (Fig. 13). The Oidawara Formation also contains the

Denticulopsis lauta diatom Zone (Koizumi, 1981). Since the *D. lauta* Zone contains Subchron C5Bn1r (Koizumi, 1992), the diatom biostratigraphy supports the polarity chron assignment for the Oidawara Formation. The planktonic foraminiferal assemblage of the Shukunohora Sandstone, included in the uppermost part of the Akeyo Formation, indicates Blow's Zone N8 (Ibaraki, 1981), in which reversed polarity Chron C5Br is included (Berggren et al., 1995). Unfortunately, no paleomagnetic data were obtained from the Shukunohora Sandstone because of a lack of exposure along the measuring route. The sandstone is the marginal facies of the Hazama Member (Itoigawa, 1980), and there could be no significant hiatus in the Hazama Member. Thus we suppose that the reversed polarities in the upper part of the Akeyo Formation (samples MZ17-37) are correlated to Chron C5Br (Fig. 13).

Because of the absence of biostratigraphic data, polarity chron assignment is uncertain for the reversed polarities of the lower Akeyo Formation (samples MZ 02-15 below RTB M1) and the normal polarity of the Hongo Formation. RTB M2 is represented by the angular unconformity with a time gap of less than 1 m.y. (duration from Chron C5Br to Subchron C5Bn1r), though the difference in strike and dip of the strata above and below the unconformity is very small (Kitamura, 1959). Orientation of the strata above and below RTB M1 are almost the same, which leads us to assume that the time gap at RTB M1 is insignificant, probably several hundred thousand years. Thus Chron C5Br may be assigned to the reversed polarities in the lower part of the Akeyo Formation as well as to its upper part. As discussed in the former section, the erosional surface between the Hongo and Akeyo Formations is interpreted as a ravinement surface. Ravinement surfaces are formed by shoreface erosion during transgression and generally represent insignificant time gaps (Nummedal and Swift, 1987). Thus it is considered that the Hongo Formation is almost conformably overlain by the Akeyo Formation of Chron C5Br, and that the normal polarity site of the Hongo Formation is correlated to Chron C5Cn (Fig. 13).

Kakegawa area

The interpreted paleomagnetic polarities of the Kakegawa area are shown in the columnar section of Figure 14 with the polarity data obtained by Hayashida (1994). In the section, seven major and three minor magnetic polarity zones were defined (the major polarity zones are numbered in ascending order in Fig. 14). The measured section contains four normal (Zones 1, 3, 5, and 7) and three reversed (Zones 2, 4, and 6) major polarity zones. A site of the lower part of the Amamiya Formation shows normal polarity (K01 in Zone 1). The sites of the middle part shows reversed polarities (K03 and K04 in Zone 2).

Kakegawa

Fig. 14. Synthesized columnar section showing sampling horizons, paleomagnetic polarities, biostratigraphic zones, polarity chrons, and positions of the regression-and-transgression boundaries in the Kakegawa area. (a) : Hayashida (1994), (b) : Ibaraki et al. (1983). See Fig. 3 for legend.

The Matsuba Formation contains two normal and two reversed major polarity zones (Zones 3–6). The Saigo Group shows normal polarity and contains a normal polarity zone (Zone 7). A minor normal polarity zone is represented by a site of normal polarity (Hayashida, 1994) in the reversed polarity Zone 4. Two minor reversed polarity zones are identified by the reversed polarities (K18, K22, and data from Hayashida, 1994) in the normal polarity Zone 5.

According to Ibaraki et al. (1983), the Kurami Group is correlated to Blow's Zones N6–8 (Fig. 14). The lower part of the Towata Mudstone Member is correlated to Zone N6. The uppermost part of the Matsuba Tuffaceous Siltstone Member is correlated to Zone N7. The Masago Mudstone Member and the Saigo Group are correlated to Zone N8.

Blow's Zone N8 and normal polarity of the Saigo Group suggest that the normal polarity Zone 7 of the group is correlated to Subchron C5Bn2n. Because Blow's Zone N8 contains a reversed polarity Chron C5Br, the reversed polarity Zone 6 in the Masago Mudstone Member is correlated to Chron C5Br. Since the Kurami Group contains no unconformity, the lower five major polarity zones can be correlated to Chrons C5Cn (Zone 5), C5Cr (Zone 4), C5Dn (Zone 3), C5Dr (Zone 2), and C5En (Zone 1) in descending order. Blow's Zone N7 contains Chrons C5Cn and C5Cr, while Blow's Zone N6 contains Chrons C5Dn, C5Dr, and C5En (Berggren et al., 1995). Therefore, the assigned planktonic foraminiferal zones (Blow's Zone N7 for the Matsuba Tuffaceous Siltstone Member and Zone N6 for the Towata Mudstone Member) confirm our polar-

Fig. 15. Chronostratigraphy of the Miocene strata in the Yatsuo, Mizunami, and Kakegawa areas. The seven Miocene regression-and-transgression boundaries, represented by depositional hiatuses or a horizon in a turbidite section in the figure, occurred within four time zones; Zones Jmi1 (K1), Jmi2 (Y1, M1, and K2), Jmi3 (Y2 and M2), and Jmi4 (Y3). Geomagnetic polarity time scale and planktonic foraminiferal zones are from Berggren et al. (1995).

ity chron assignment. Two minor zones of reversed polarity in the normal polarity Zone 5 are correlated to Subchrons C5Cn2r and C5Cn1r in Chron C5Cn. In the GPTS of the Berggren (1995), no normal subchron is identified in Chron C5Cr. The normal polarity in the reversed polarity Zone 4 in the middle part of the Matsuba Tuffaceous Siltstone Member might represent an excursion event in the reversed Chron C5Cr.

Correlation of the RTBs

Based on the polarity chron assignment for the sections, we determined ages of the strata and the RTBs defined in the first part of this paper, and constructed a chronostratigraphy of the Miocene strata in each of the studied areas (Fig. 15). The RTBs are represented by time gaps, except for RTB K1. Of the eight RTBs, seven occurred during Miocene time (RTBs Y1, Y2, Y3, M1, M2, K1, and K2; Fig. 15). RTB M3 is underlain by the sediments of Chron C5Bn1r and overlain by the Pliocene deposits (Fig. 13). Therefore, RTB M3 shows a time gap from 15.03 Ma to the Pliocene, suggesting that it was formed in Pliocene time. Except for RTB M3, the Miocene RTBs are correlated to each other and occurred within four zones, referred to as Zones Jmi1, Jmi2, Jmi3, and Jmi4 from oldest to youngest ("Jmi" means *Japanese Miocene*).

Zone Jmi1

Zone Jmi1 is represented by RTB K1. RTB K1 is correlated within Chron C5Dn (17.62–17.28 Ma; Berggren et al., 1995) (Fig. 15) and is the oldest of the Miocene RTBs in the studied areas. Because the Miocene strata in the Yatsuo and Mizunami areas are younger than 17.0 Ma and 16.5 Ma respectively (Fig. 15), there would be no records showing correlative RTBs with RTB K1 in these areas.

Zone Jmi2

Zone Jmi2 involves RTBs Y1, M1, and K2. RTBs Y1 and M1 are correlated within Chron C5Br (16.01–15.16 Ma; Berggren et al., 1995) (Fig. 15). Therefore, these RTBs are correlative within 1 m.y. (duration of Chron C5Br). The submarine erosional surface K2 is underlain by the strata of Chron C5Br and is overlain by the strata of Subchron C5Bn2n. Although the strata overlying this surface are slightly younger than RTBs Y1 and M1, RTB K2 could be correlated to RTBs Y1 and M1.

Zone Jmi3

Zone Jmi3 involves RTBs Y2 and M2. RTB Y2 is correlated within Subchron C5Bn1r in Chron C5Bn (Fig. 15). RTB M2 is underlain by the deposits of Chron C5Br and overlain by those of Subchron C5Bn1r (Fig. 15). These RTBs are overlain by the contemporaneous strata of Subchron C5Bn1r, indicat-

ing that the RTBs were synchronously formed in the Yatsuo and Mizunami areas. The underlying strata of RTB M2 are slightly older than RTB Y2. This is probably due to differences in degree of erosion of underlying strata during transgression. It is, therefore, likely that Zone Jmi3 occurred within Subchron C5Bn1r (15.03–14.89 Ma; Berggren et al., 1995).

Zone Jmi4

Zone Jmi4 is represented by RTB Y3. RTB Y3 is underlain by the marine sediments of Chron C5Bn1n, and in turn overlain by the marine deposits of the Tenguyama Formation. According to Hayakawa (1983), a tuff layer in the lowermost Tenguyama Formation has yielded a fission track age of 12.3 ± 1.9 Ma. Thus the RTB involves a time gap of about 3 m.y. (14.89 Ma– 12.3 ± 1.9 Ma). There is no correlatable event with RTB Y3 in the Mizunami and Kakegawa areas because of lack of Miocene strata younger than 15 Ma in these areas (Fig. 15).

Discussion

In this study, a total of eight RTBs were recognized among the Yatsuo (RTBs Y1, Y2, and Y3), Mizunami (RTBs M1, M2, and M3), and Kakegawa (RTBs K1 and K2) areas. The RTBs in the Yatsuo and Mizunami areas represent unconformities or ravinement surfaces, and those of the Kakegawa area represent turbidites (RTB K1) and the submarine erosional surface (RTB K2) in the thick mudstone. They were dated based on magnetostratigraphy in combination with the biostratigraphic and radiometric dating data. Out of the eight RTBs, seven (RTBs Y1, Y2, Y3, M1, M2, K1, and K2) were formed in Miocene time, and one (RTB M3) in the Pliocene. The Miocene RTBs were grouped into four zones based on their ages, referred to as Zones Jmi1 (RTB K1), Jmi2 (RTBs Y1, M1, and K2), Jmi3 (RTBs Y2 and M2), and Jmi4 (RTB Y3) from oldest to youngest. They occurred within Chron C5Dn (17.62–17.28 Ma), Chron C5Br (16.01–15.16 Ma), Subchron C5Bn1r (15.03–14.89 Ma), and within 14.89– 12.3 ± 1.9 Ma, respectively. The studied areas were located in different tectonic settings; the Kakegawa area in a forearc basin, the Mizunami area in an intra-arc basin, and the Yatsuo area in a backarc basin. Thus vertical movements of the basement must have been different in each area. In spite of the different basement movements, the RTBs of Zones Jmi2 and Jmi3 are largely synchronous in these areas, suggesting that they were not formed by neither local sedimentation rate changes nor local sea-level changes caused by tectonic crustal movements, but by possibly regional sea-level changes. The correlations of the submarine erosional surface K2 with unconformities Y1 and M1 support the interpretation that the submarine erosion occurred as a result of sea-level lowering.

Miocene sedimentary basins are widely scattered in

southwest Honshu (Huzita, 1962), and the Miocene deposits in these basins indicate similar ages during 22–15 Ma (e.g. Kimura et al., 1993). This period is during the opening of the proto-Japan Sea (Tamaki et al., 1992), so tectonics may have caused regional sea-level changes. Paleomagnetic studies have shown a quick rotation of Southwest Japan at 15 Ma (e.g. Otofuiji et al., 1985), which coincides with Zone Jmi3. Therefore the synchronous RTBs of Zones Jmi2 and Jmi3 may have been formed by regional sea-level changes. The other possible cause is eustasy. Haq et al. (1987) reported two eustatic sea-level falls at 16.5 Ma and 15.5 Ma. These falls are correlative to Zones Jmi2 and Jmi3, although the eustatic falls show slightly old ages. An explanation for the age differences is the use of different time scales (that of Haq et al. (1987) is 0.1–0.3 m.y. older than of Berggren et al. (1995) at 15–20 Ma), and thus the eustatic sea-level falls could have formed the synchronous RTBs. To confirm the eustatic origin of the RTBs, we have to examine the synchronicity globally.

Unfortunately, we could not define a regression-transgression cycle during Chron C5Dn (Zone Jmi1) in the Yatsuo and Mizunami areas and during 14.89– 12.3 ± 1.9 Ma (Zone Jmi4) in the Mizunami and Kakegawa areas because of the absence of sediments of those periods. Hence, it is uncertain whether or not the RTBs of Zones Jmi1 and Jmi4 were synchronously formed in the studied areas.

Itoigawa and Shibata (1973) defined sedimentary cycles in some Miocene sedimentary basins, including the Bihoku, Tsuzuki, Awa, Ichishi, Morozaki, and Mizunami basins. The cycles are characterized by water depth changes represented by changes of molluscan assemblage, and are most likely related to sea-level fluctuation. Itoigawa and Shibata (1973) discussed the similarity of lithology, molluscan assemblages, and occurrence of planktonic molluscs in the cycles among the basins and suggested the possibility of correlating the cycles. Unfortunately, without precise chronostratigraphic data of comparable quality to the dating controls in our areas, we can not precisely correlate between our four zones (Jmi1–4) and the sedimentary cycles in the other areas. If we obtain more precise chronostratigraphic data in the other areas, we will correlate them.

Conclusions

(1) Regression-and-transgression boundaries (RTBs) were recognized in the Miocene strata of the Yatsuo (RTBs Y1, Y2, and Y3), Mizunami (RTBs M1, M2, and M3), and Kakegawa (RTBs K1 and K2) areas.

(2) Except for RTB M3, these RTBs were formed in Miocene time. RTB M3 is in Pliocene time.

(3) On the basis of magnetostratigraphic correlations, the Miocene RTBs were formed within four time zones; Zones Jmi1 (RTB K1), Jmi2 (RTBs Y1, M1, and

K2), Jmi3 (RTBs Y2 and M2), and Jmi4 (RTB Y3) from oldest to youngest. Zone Jmi1 occurred in Chron C5Dn (17.62–17.28 Ma), Zone Jmi2 in Chron C5Br (16.01–15.16 Ma), Zone Jmi3 in Subchron C5Bn1r (15.03–14.89 Ma), and Zone Jmi4 between 14.89 and 12.3 ± 1.9 Ma.

(4) The RTBs of Zones Jmi2 and Jmi3 are largely synchronous in the different tectonic settings, suggesting that the RTBs were formed by regional sea-level changes.

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* : in Japanese with English abstract

** : in Japanese

〈 地 層 名 〉

Akeyo	明世	Kurami	倉真	Shukunohora	宿の洞
Amakata	天方	Kurosedani	黒瀬谷	Tenguyama	天狗山
Amamiya	天宮	Masago	真砂	Tochiage	栃上
Asatani	浅谷	Matsuba	松葉	Togari	戸狩
Awagatake	粟ヶ岳	Mitani	三谷	Toki	土岐
Hazama	狭間	Mizunami	瑞浪	Tonami	砺波
Higashibessho	東別所	Nirehara	楡原	Towata	戸綿
Hongo	本郷	Oidawara	生俵	Tsukiyoshi	月吉
Iozen	医王山	Saigo	西郷	Yamanouchi	山野内
Iwaine	岩稲	Seto	瀬戸	Yatsuo	八尾
Izeki	井関	Shiotani	塩谷		

(要 旨)

Hiroki, Y. and Matsumoto, R., 1999, Magnetostratigraphic correlation of Miocene regression-and-transgression boundaries in central Honshu, Japan. *Jour. Geol. Soc. Japan*, 105, 87-107. (廣木義久・松本 良, 1999, 本州中部における中新世海退-海進境界の磁気層序による対比. 地質雑, 105, 87-107)

富山県八尾, 岐阜県瑞浪, 静岡県掛川の中新統中に8つの海退-海進境界を認めた. 八尾と瑞浪地域の新統は沿岸～陸棚の堆積物からなり, 海退-海進境界は不整合あるいはラビンメント面で示される. 掛川地域の新統は陸棚の泥岩相からなり, その泥岩相中に挟まれるタービダイト相および海底浸食面それぞれを最大海退期の堆積物と浸食面と解釈した. 磁気層序によると, 8つのうち7つの境界は中新世に形成されており, それらは古い方から Jmi1～Jmi4 の4つのゾーンに対比できる. 各々のゾーンの年代はクロン C5Dn, C5Br, C5Bn1r, 14.89-12.3±1.9 Ma である. これらのうちゾーン Jmi2 と Jmi3 中の境界はテクトニックセッティングの異なる地域でほぼ同時期に形成されていることから, 局所的なイベントではなく, 広域的な海水準変動に関連したものと考えられる.