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Crowded *Rosselia socialis* in Pleistocene Inner Shelf Deposits: Benthic Paleoecology During Rapid Sea-level Rise

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Predominant equilibrial Rosselia socialis are present at up to thirty stratigraphic levels in middle Pleistocene, siliciclastic inner shelf deposits on the Boso Peninsula, Japan. The ichnofabric composed of R. socialis is interpreted to have formed by a considerably dense population of R. socialis animals (terebellid polychaetes?). The ichnofabric interval represents a transgressive inner shelf deposit strongly affected by a high-frequency, 5th- or 6th-order sea-level rise that probably was rapid enough to influence the ecology of benthic communities. The dense colonization by the R. socialis animals is interpreted to result mainly from rapid transgression caused by short-term sea-level rise. Coastal erosion induced frequent pulses of sedimentation in to the shelfal environment and probably prevented colonization by most benthic animals, except for R. socialis animals, which are thought to be tolerant of such conditions. Ravinement also provided organic detritus, derived mainly from organic-rich coastal deposits of salt-marsh origin, which enabled the detritus-feeding and stress-tolerant R. socialis animals to thrive.

INTRODUCTION

During the Pleistocene, glacial eustasy induced extreme and rapid sea-level fluctuations, the maximum amplitude and rate of which are estimated at 130–150 m and 0.003–0.01 m/year, respectively (Chappel and Shackleton, 1986; Ito, 1994; Miall, 1997). Those sea-level fluctuations undoubtedly promoted severe environmental changes, especially in shallow- and marginal-marine settings, and exerted a strong impact on nearshore benthic communities. Additionally, sea-level fluctuations significantly affected basin-scale mode of sedimentation and sometimes resulted in high-frequency depositional sequences (e.g., Mitchum and Van Wagoner, 1991). Such sequences are those that developed in the Pleistocene upper Kazusa Group distributed in the Boso Peninsula, Japan (Ito, 1992a, 1994; Nara, 1998a). Consequently, paleoecological analyses of high-frequency sequences in the upper Kazusa Group make it possible to assess the environmental changes that influenced the benthic communities at that time.

A characteristic ichnofabric consisting predominantly of stacked *Rosselia socialis* (Nara, 1997) occurs in the lower part of Ichinono alternating beds of sand and mud of Tokunashi and Endo (1983; 1984), hereafter tentatively called as the Ichinono “Member,” of the Kongochi Formation, the uppermost unit of the Kazusa Group (Fig. 1). The

ichnofabric probably was produced by a benthic community living under the strong influence of a transgressive regime.

The aim of this paper is to describe in detail the ichnofabrics in the lower Ichinono “Member,” and to discuss the response of the benthic community to transgressive-induced environmental factors.

GEOLOGIC BACKGROUND

The siliciclastic Kazusa Group accumulated in a forearc basin that developed in response to subduction of the Pacific Plate beneath the Japanese Islands during Pliocene–Pleistocene times (Katsura, 1984, and references therein). The Kazusa Group, which is up to 3000 m thick, accumulated in various depositional environments ranging from deep marine to paralic coastal plain (e.g., Katsura, 1984; Watanabe et al., 1987), and is characterized by alternating sand- and mud-dominated intervals organized into fining- and coarsening-upward successions. It has been interpreted to be a composite of transgressive cycles succeeded by regressive cycles (Ito, 1992a, 1995). The Kazusa Group records high sediment input at the active plate margin (Ito, 1994) and represents a third-order composite sequence superposed by fourth- to sixth-order high-frequency depositional cycles. The cycles were induced by long-term tectonism and short-term glacio-eustasy from 2.4 to 0.45 Ma (Ito, 1992a, 1994, 1995; Ito and Katsura, 1992). Detailed descriptions and environmental interpretations of the Kazusa Group are given elsewhere (e.g., Katsura, 1984).

The middle Pleistocene Kongochi Formation (ca. 0.45 Ma), which is up to 70 m thick, is interpreted to have accumulated in outer shelf to beach settings. It is divided into three fifth- to sixth-order depositional sequences (for detailed description and sedimentological interpretation see; Nara, 1998a).

The Ichinono “Member” of the Kongochi Formation is 8.5–18 m thick and forms the lower part of the middle sequence. It crops out in the central to northern part of the Boso Peninsula (Fig. 2). The ichnofabric described herein occurs exclusively in the lower part of the Ichinono “Member.”

LITHOLOGY AND SEQUENCE STRATIGRAPHY OF THE LOWER ICHINONO “MEMBER”

The lower part of the Ichinono “Member” can be traced for more than 30 km in a NE–SW direction (Nara, 1998a; Fig. 2). The lower Ichinono “Member” erosionally overlies bioturbated offshore sandy mud in the central part of its

Middle Pleistocene	Shimosa Group	Jizodo Formation	
			Izumiyatsu Mud
	Kazusa Group	Kongochi Formation	Nishiyama Alternating Beds of Sand and Mud
			Ichinono Alternating Beds of Sand and Mud (Ichinono "Member")
	Kasamori Formation		

FIGURE 1—Lithostratigraphic position of the Ichinono alternating beds of sand and mud of Tokuhashi and Endo (1983; 1984), here referred to as the Ichinono "Member," Kongochi Formation.

outcrop belt (locality 9; Fig. 3) and well-sorted shoreface sands of the lower sequence in the southwestern area (localities 1 and 3–7; Fig. 3). It mainly consists of alternating beds of well-sorted, parallel-, swaly cross- or hummocky cross-stratified fine- to very fine-grained sands (5-to-70 cm thick) and parallel-stratified or massive muds (up to 20 cm thick) that contain mica flakes and detrital plant fragments (ASM; Fig. 4). The base of the Ichinono "Member" at locality 9, however, consists of poorly sorted, massive and muddy, medium-grained sands and overlying laminated muddy sands (BMS; Fig. 4). Amalgamated sand beds (up to 1 m thick) are intermittently present in some horizons of the ASM. Impressions of articulated bivalve shells, such as the nuculanid *Yoldia notabilis* Yokoyama 1922 (misidentified as *Saccella confusa* Hanley 1860 in Nara, 1998a) and the solenid *Solen krusensterni* Schrenck 1867, are observed locally in the ASM. The lower Ichinono "Member" shows an overall fining-up succession (Fig. 3). Intensely bioturbated, muddy, very fine-grained sand beds, which conformably overlie the ASM, are seen at the top of the lower Ichinono "Member" (UMS; Fig. 4).

The BMS at locality 9 are interpreted as sediment gravity flow deposits. The sediments probably flowed down through a submarine channel, shown as the large-scale, concave up cross-section (Fig. 3), in the early transgressive phase. Nara (1998a) interpreted the parallel-, swaly cross- and hummocky cross-stratified sand beds of the ASM as storm-induced, combined-flow deposits in a shelf environment (e.g., Dott and Bourgeois, 1982; Walker and Plint, 1992; Johnson and Baldwin, 1996). Mud beds of the ASM probably represent post-storm and/or fair-weather deposits that accumulated below fair-weather wave base (e.g., Reading and Collinson, 1996; Johnson and Baldwin, 1996). *Yoldia* and *Solen* are known to colonize upper sublittoral soft bottoms (Oyama, 1973). These lines of evidence indicate that the lower Ichinono "Member" accu-

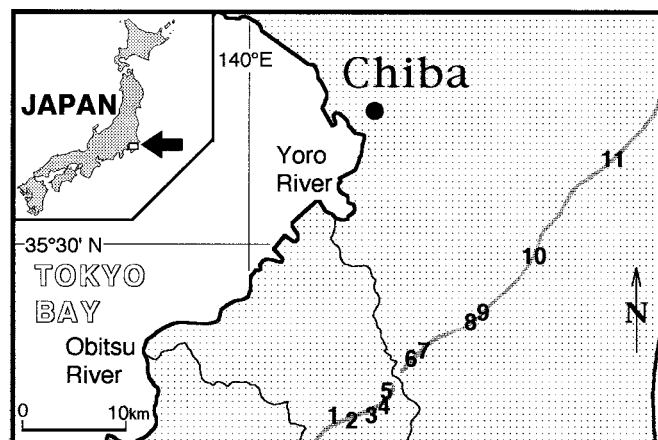


FIGURE 2—Geological sketch map of the middle Pleistocene Ichinono "Member" (dark stippled belts). Numbers indicate localities of outcrops studied.

mulated in a shallow marine environment deeper than mean fair-weather wave base, but within the influence of storm waves, i.e., the inner shelf (or offshore-transition) zone (Ito, 1992a; Nara, 1998a). Nara (1998a) interpreted the erosional base of the southwestern part, across which depositional environments deepened, as a ravinement surface (e.g., Nummedal and Swift, 1987) that formed in response to transgression induced by 5th- or 6th-order glacio-eustatic sea-level rise. The fining-upward trend probably represents subsequent backstepping of paralic to shallow marine depositional systems (Ito, 1992a; Nara, 1998a). The UMS likely formed at the maximum-flooding stage (Nara, 1998a); intense bioturbation probably is attributable to reduced sedimentation rates (cf. Howard, 1975, 1978) resulting from marine inundation of the source area.

The ichnofabric treated here occurs in as many as thirty stratigraphic horizons of the BMS and ASM of the lower Ichinono "Member" (Figs. 3, 4). The UMS does not contain the ichnofabric, although solitary burrows of *R. socialis* are present. The stratigraphic interval characterized by the ichnofabric strictly corresponds to a transgressive systems tract of a high-frequency depositional sequence (Nara, 1998a, 1998b; Figs. 3, 4).

STACKED *ROSSELIA SOCIALIS*

Rosselia socialis Dahmer 1937 is a vertical to subvertical, fusiform, mud-lined burrow (Fig. 5A). Nara (1995) interpreted it as a dwelling structure of a probable detritus-feeding terebellid polychaete based on observations of specimens from Pleistocene shallow marine deposits. The burrow may be conical due to erosional truncation (Nara, 1995). In the Pleistocene of Japan, *R. socialis*, mostly 6-to-20 cm long, but rarely more than 30 cm long, is found in slope to middle shoreface, shelf sand-ridge, bay, lagoon, tidal-flat, flood-tidal delta, and estuarine deposits (Nara, 1997, 2000) and, thus, has a broad environmental distribution in shallow marine settings (for environmental distribution elsewhere see: Uchman and Krenmayr, 1995). Nara (1997) reported a morphological variant of *R. socialis* that apparently consists of vertically stacked, multiple

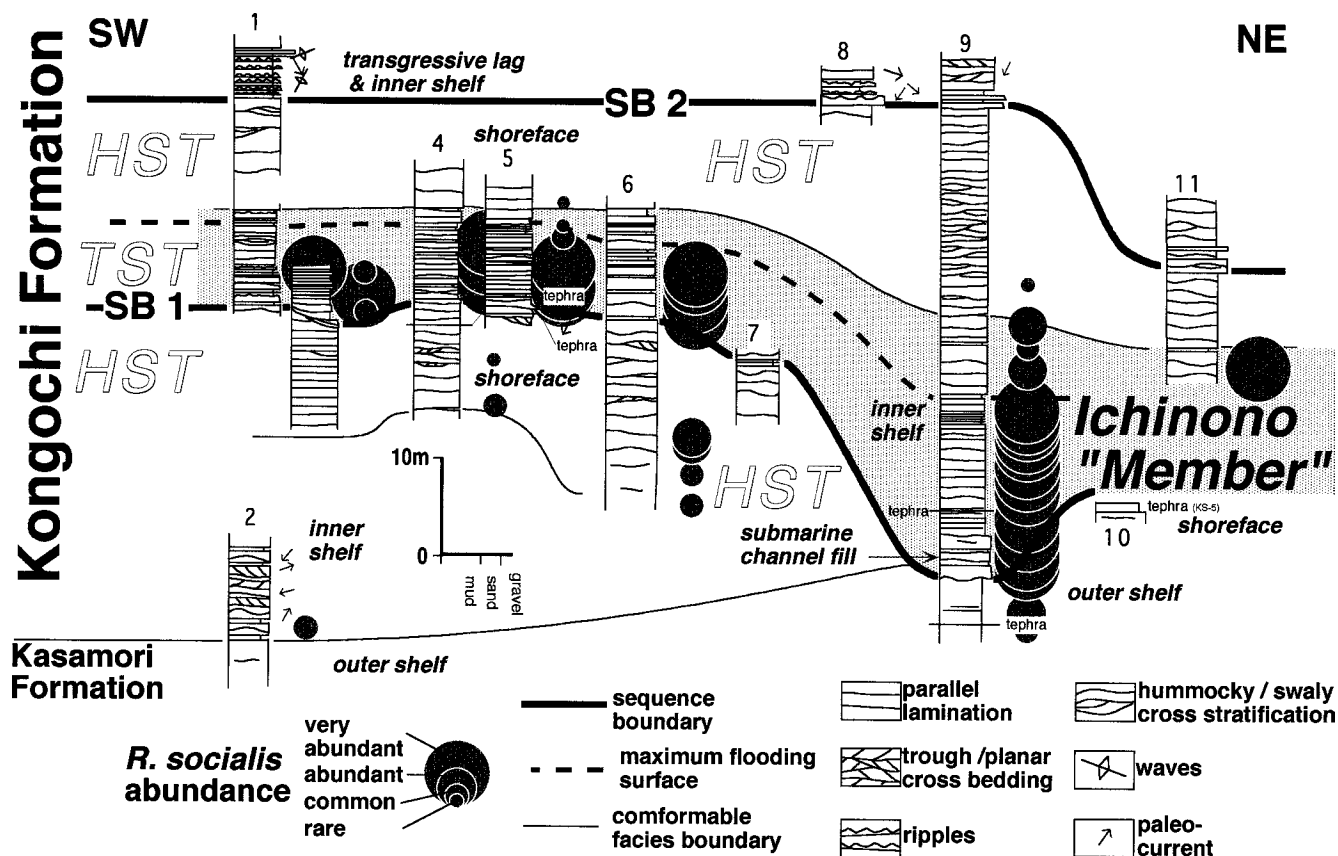


FIGURE 3—Geologic columns, sequence stratigraphy, and relative abundance of *Rosselia socialis* of the Ichinono "Member" (shaded interval). Abundance of *Rosselia socialis* is classified here as rare, common, abundant, and very abundant. Sequence stratigraphic interpretation after Nara (1998a). Localities are shown in Figure 2. SB, sequence boundary; HST, highstand systems tract; TST, transgressive systems tract.

segments sharing a single shaft, each of which looks like a "basic" *R. socialis* with a spindle or cone shape (Fig. 5B). This variant referred to was as "stacked" *R. socialis*. These were interpreted to be equilibrichnia representing the tracemaker's response to intermittent rapid aggradation of the seafloor in decimeter-scale increments caused by event sedimentation.

The longest specimen observed of the stacked type is composed of 15 segments and attains a length of 1.7 m (Nara, 1997, fig. 3E). It was found in delta-front deposits of a flood-tidal delta of the upper Pleistocene Kioroshi Formation, probably formed by high sediment influx (cf. Murakoshi and Masuda, 1991). This indicates that the *R. socialis* animal could tolerate rapid sedimentation, which is stressful or fatal for many benthic organisms.

ROSSELIA ICHNOFABRIC

The *Rosselia* ichnofabric in the lower part of the Ichinono "Member" is characterized by closely packed *R. socialis*. The burrows are sometimes so dense as to leave no separation (Fig. 6C, D). Density of *R. socialis* locally attains more than 400 individuals per square meter; for example 400/m² in Kanazawa (locality 5) or 457/m² in Yui (locality 10). In the ichnofabric, physical sedimentary structures of sand beds tend to be obliterated by the dense occurrence of the *Rosselia* burrow. In some places, the density of *Rosselia* burrows increases slightly upward with-

in individual units. Ichnofabrics characterized by less dense occurrences (Fig. 6A, B) are excluded from treatment herein. Each of the trace fossils in the *Rosselia* ichnofabric described is usually of the stacked type (Figs. 7, 8). The maximum length of an individual may reach 1.2 m, with about 10 stacked segments. The actual length and number of segments are, however, uncertain, because they are truncated by parallel- or hummocky cross-stratified sand beds. Erosional truncation of the trace fossils is common (Fig. 7).

The dense *R. socialis* ichnofabric is laterally continuous. A bedset characterized by the ichnofabric can be traced laterally among several outcrops that are about 250 m apart. Very likely, its extent is greater, but limited exposures do not allow confirmation over the whole region.

The level of segments of adjoining stacked *Rosselia* apparently defines beds and bedsets (Fig. 8). Segments occurring in the same horizon have a similar morphology (Fig. 8). At horizons where the tops of the cone-shaped segments occur, an erosional surface, muddy intraclasts, and/or reworked fragments of *R. socialis* (arrow in Fig. 8) are observed locally.

Obliquely oriented cylindrical burrows filled with structureless sand (*Palaeophycus*? isp.) locally occur within the ichnofabric (Fig. 9A). Such burrows sometimes penetrate the lining of *R. socialis*. Rare, thinly mud-lined, sinuous burrows (up to 2 cm in width), which are obliquely to hor-

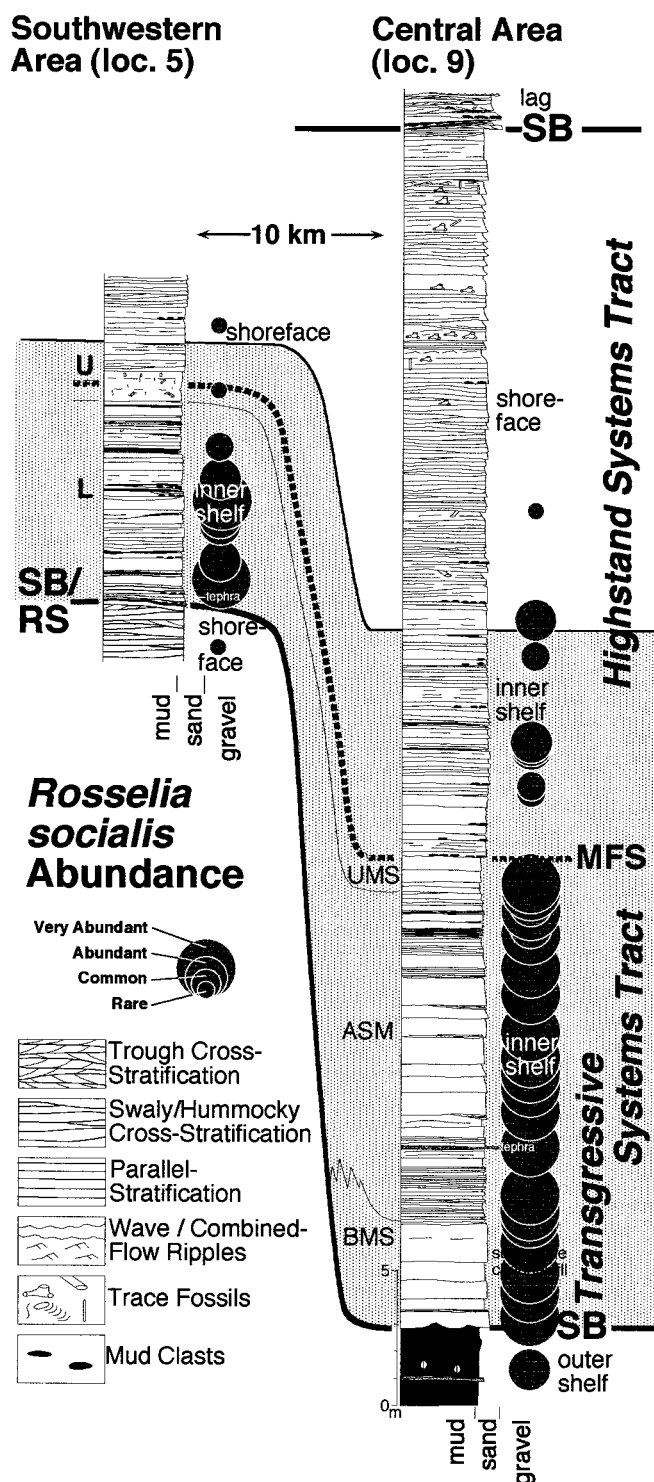


FIGURE 4—Detailed columns with environmental interpretations and relative abundance of *Rosselia socialis* of the Ichinono "Member" (shaded portion) in two well-exposed areas (localities 5 and 9, Fig. 2). MFS: maximum flooding surface, RS: ravinement surface, SB: sequence boundary, BMS: basal muddy sands, ASM: alternating beds of sands and muds, UMS: bioturbated muddy sands, U and L: upper and lower parts of the Ichinono "Member." See text for detail.

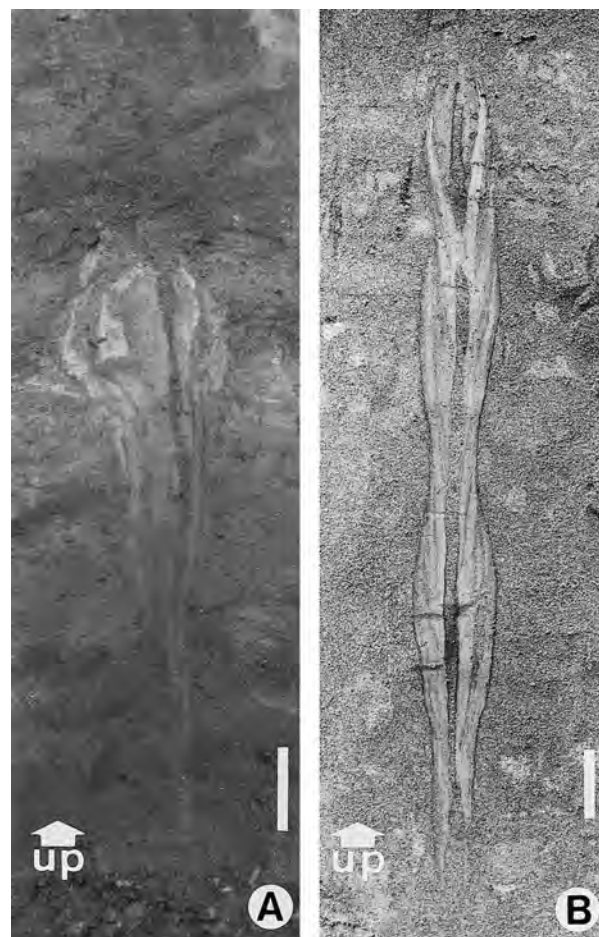


FIGURE 5—Vertical sections of *Rosselia socialis* (A) and its morphological variant, stacked *R. socialis* (B). A and B occur in sandy mud (outer shelf deposits) near locality 9 and bioturbated sand (lower shoreface deposits) at locality 4, respectively. Both are from highstand deposits of the lower sequence of the Kongochi Formation. Scale bars = 3 cm.

izontally oriented and sometimes filled with meniscate alternation of sand and sandy mud, and biogenic mottling also are observed locally (Fig. 9B).

POPULATION DENSITY

The density of *Rosselia socialis* in the ichnofabric is quite high, as noted above. In general, intensely burrowed sediments have been interpreted as a result of low sedimentation rates (Howard, 1975, 1978); that is, apparent high density tends to be regarded as accumulation of individuals formed at different times (e.g., Ito, 1992b). However, in the present case, the crowded occurrence of *R. socialis* is interpreted to represent a large population of producers that lived contemporaneously (Fig. 10). This is because the neighboring producers clearly responded simultaneously to the same depositional events as suggested by their shape and mode of occurrence (Fig. 8; cf. Hardy and Broadhurst, 1978). Just after rapid sedimentation, the densely colonized producers would have adjusted their life position to the raised sea floor in the same way, and then made a new linings during quiet periods of

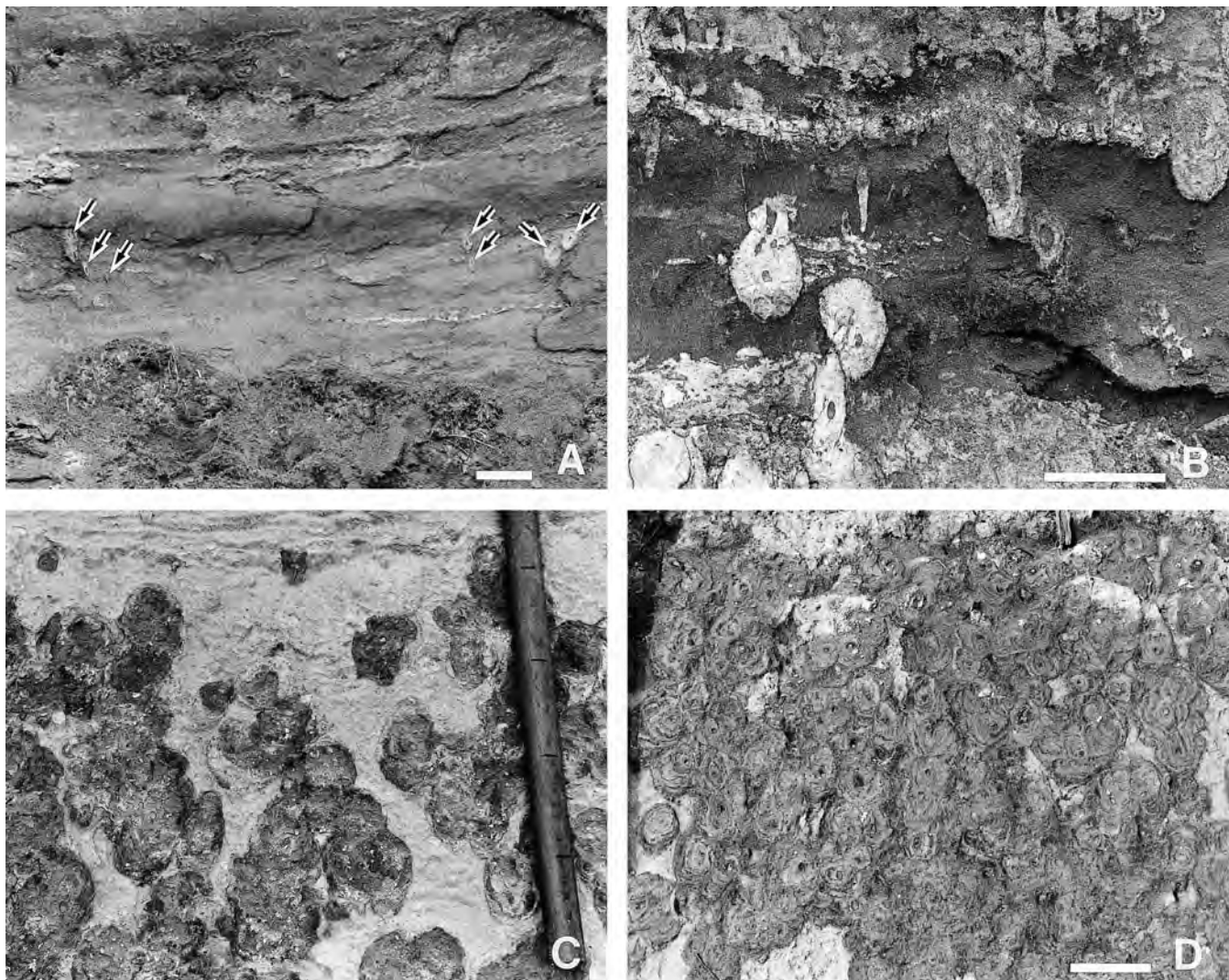


FIGURE 6—Photographs showing abundance of *Rosselia socialis*. Abundance has been estimated based on extensive field observations, and is classified using a 4-grade system particularly applicable for vertical to oblique sections. Rare occurrences mean that the horizontal distance between two specimens is nearly 1 m or more (A). The distance of burrows for assignment to common varies from nearly 20 cm to 1 m (B). Abundant is characterized by a distance of a few cm to 20 cm (C). Very abundant implies an even more crowded appearance (D). Although these criteria are only semi-quantitative, they facilitate field estimation of density and are helpful in establishing general trends. The ichnofabric treated here refers to the latter two grades. Each arrow in A shows an occurrence of *R. socialis*. A: vertical to bedding; B, C, D: oblique to bedding. Scale bars in A, B, and D = 10 cm. The wooden bar in C is 47 cm long.

non-deposition. Population density of the producer is estimated to attain as much as 457 individuals/m².

PALEOENVIRONMENTAL CONDITIONS

The mode of stacking in *Rosselia socialis* reflects the depositional history of the host sediments on a bed-by-bed scale (Nara, 1997). Specimens showing similar morphology were interpreted as having formed under similar depositional conditions (Nara, 1997). Stacked specimens morphologically similar to those described here also occur in other stratigraphic horizons, such as the lowest sequence of the Kongochi Formation, which represents highstand lower shoreface deposits (Fig. 5B; Nara, 1997, fig. 3). This means that similar ecologic conditions occurred repeatedly. Stacked *R. socialis* seen in other places, however, usu-

ally occur sparsely, classified here as “rare” or “common” (Fig. 6A, B), and nowhere form an ichnofabric like that of the lower Ichinono “Member.” Although gregarious occurrence of stacked *R. socialis* is seen locally in such horizons, it is restricted spatially; normally less than a few meters wide. That is, formation of the ichnofabric treated here is not simply attributable to the sedimentary conditions that influenced ecology of *R. socialis* producers as reflected by their burrow shapes.

The ichnofabric described herein is characteristic of transgressive deposits of on a storm-dominated shelf. Considering this, the major factor to allow dense and dominant colonization by *R. socialis* animals can be explained as follows. In a marine setting, transgression is usually associated with a decrease in sedimentation rate as the result of marine inundation, reduction of sediment supply,



FIGURE 7—Ichnofabric dominated by stacked *Rosselia socialis*. Numerous *Rosselia socialis* occur in alternating beds of sand (darker beds) and mud (light-colored beds). Erosional truncation of the ichnofabric is evident at some horizons (arrows). Scale bar = 50 cm. Kanazawa (loc. 4).

and the development of nearshore sediment-traps such as spreading shelves and drowned river-mouths (estuaries; e.g., Dalrymple, 1992). Evidence of such transgressive sediment starvation is found at several horizons in shallow marine deposits of the middle to late Pleistocene Shimosa Group, which conformably overlies the Kazusa Group (Kondo, 1989; Kamataki and Kondo, 1997a, b; Kondo et al., 1998). Meanwhile, significant amounts of sediment, eroded from a coast by ravinement processes mainly caused by storms, were redeposited on certain parts of the shelf (Nummedal and Swift, 1987; Saito, 1989; Kotake and Nara, 1995; Emery and Myers, 1996; Johnson and Baldwin, 1996). Such depositional processes are considered to have been frequent during Ichinono times. The prevalence of stacked *Rosselia* specimens in the lower Ichinono "Member" supports this view. For example, the longest specimen of *R. socialis* in the lower Ichinono Member suggests that 1.2 m of event deposits accumulated as the result of at least 10 episodes within a short time, at the longest estimate, within the life span of the producers (the terebellid polychaetes). The life span of the terebellid polychaete is not known. Nishi and Nishihira (1995), however, estimated the life span of another large polychaete, the *Spirobranchus giganteus/corniculatus* complex (Sabelliidae), using annual growth rings of corals in which it burrows. According to them, the oldest individual of the polychaete is nearly 40-years old.

Episodic and relatively rapid sedimentation probably caused severe disturbance in the shelf environment. This may have prevented colonization by the other benthic organisms that were intolerant of such conditions (cf., Kotake and Nara, 1995). The bivalves *Yoldia notabilis* and *Solen krusensterni*, locally present, are extant species that have a relatively large foot and are highly mobile; thus, they easily can escape after rapid burial (Y. Kondo, person. commun., 1999). The ravinement process probably were compounded by other environmental stresses, as discussed below.

Peat or rooted muddy deposits of probable salt marsh origin, important sources of terrestrial organic matter (Emery and Myers, 1996), commonly are found in coastal plain deposits of the upper Kazusa and the Shimosa Groups (e.g., Tokuhashi and Endo, 1984; Tokuhashi and Kondo, 1989; Ito, 1992a; Nara, 1998a). Such organic-rich

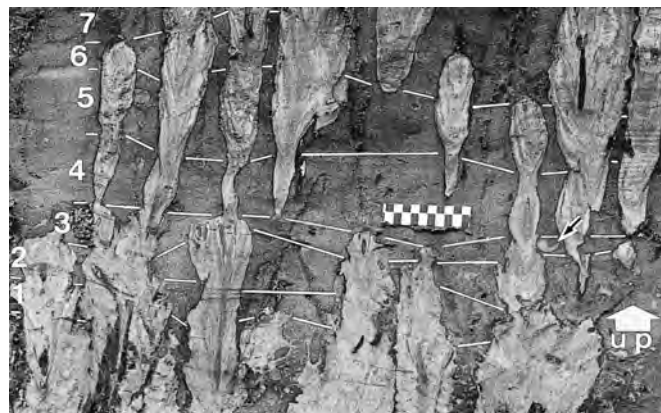


FIGURE 8—Close-up of vertical section of the *R. socialis* ichnofabric. Thickly mud-lined burrows of stacked *R. socialis* are seen in amalgamated sand beds locally showing swaly or trough cross-stratification (not visible in the photo). Primary sedimentary structures are masked or obliterated due to the dense formation of *R. socialis*. No other trace fossil or bioturbation is observed. The small arrow indicates a re-worked *R. socialis* fragment. Points of stacking within each burrow are correlated by white lines. The producers of the burrows apparently responded at least 7 times to rapid deposition of sand (1–7). Segments of adjoining individuals occurring in the same horizon tend to be of the same type; for example, most segments occurring in horizon 3 are cone-shaped, whereas those in horizons 4 and 5 are mostly spindle-shaped. Scale marked in cm. Locality 9 near Misawa.

deposits also may have existed in coastal environments during the deposition of the lower Ichinono "Member." Hence, transgressive coastal erosion during Ichinono times might have provided abundant organic detritus to the inner shelf. Organic detritus originating from plants in nearshore and coastal areas is known as one of the basic sources of food for marine benthic animals (e.g., Darnell, 1967; Griggs et al., 1969; Barnes and Hughes, 1999). Such mechanisms of nutrient flux from shallow to deeper marine environments have been suggested by many workers (e.g., Heezen et al., 1955; Griggs et al., 1969; Kotake, 1994). Although particulate organic matter (POM) derived directly from terrestrial vascular plants is known to be rather indigestible for most benthic detritus feeders, organic detritus that is highly degraded by microbial activity, and associated living organisms such as bacteria, fungi, and meiofauna, can be effectively consumed and digested (e.g., Lopez and Levinton, 1987; Bertness, 1999; Barnes and Hughes, 1999; McLusky, 1999; Little, 2000). Coastal plain plants and sediments also provide dissolved organic matter (DOM) to marine environment (e.g., McLusky, 1999). The terebellid polychaetes, probable candidates for the *R. socialis* producer, are known to utilize such DOM directly (Fauchald and Jumars, 1979). POM that was converted from DOM through the microbial loop also is a possible food resource for benthic animals (Little, 2000). Such mechanisms of food supply are interpreted to have fed large populations of detritus-feeding and stress-tolerant *R. socialis* animals (Figs. 10, 11). High population densities of the *R. socialis* tracemaker probably inhibited the larval settlement of other benthic animals on the seafloor by means of passive micro-predation, which is known in the terebellids (Fauchald and Jumars, 1979). Dense tube-building also may have prevented immigration of free-living macrobenthos through seafloor stabilization. These

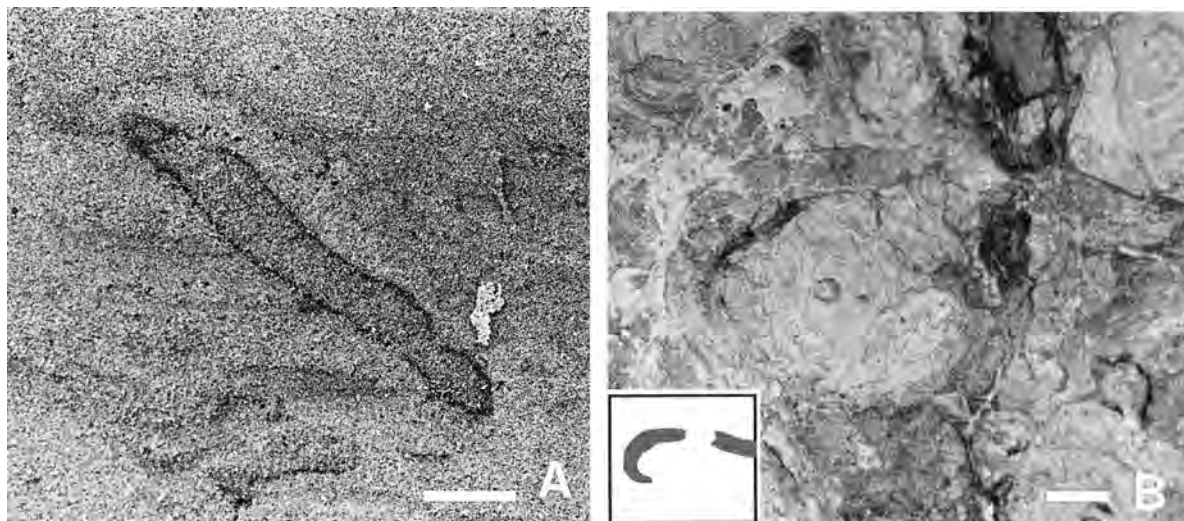


FIGURE 9—Ichnofossils found within the *Rosselia* ichnofabric of the Kongochi Formation. (A) Slightly sinuous, cylindrical burrow (*Palaeophycus*? isp.) in parallel laminated fine-grained sand of storm origin in the lower part of the Ichinono “Member” (locality 5). Burrow fringe is stained probably due to the influence of ground water. (B) Sinuous, thinly mud-lined burrow (see inset) cross-cuts *R. socialis*.

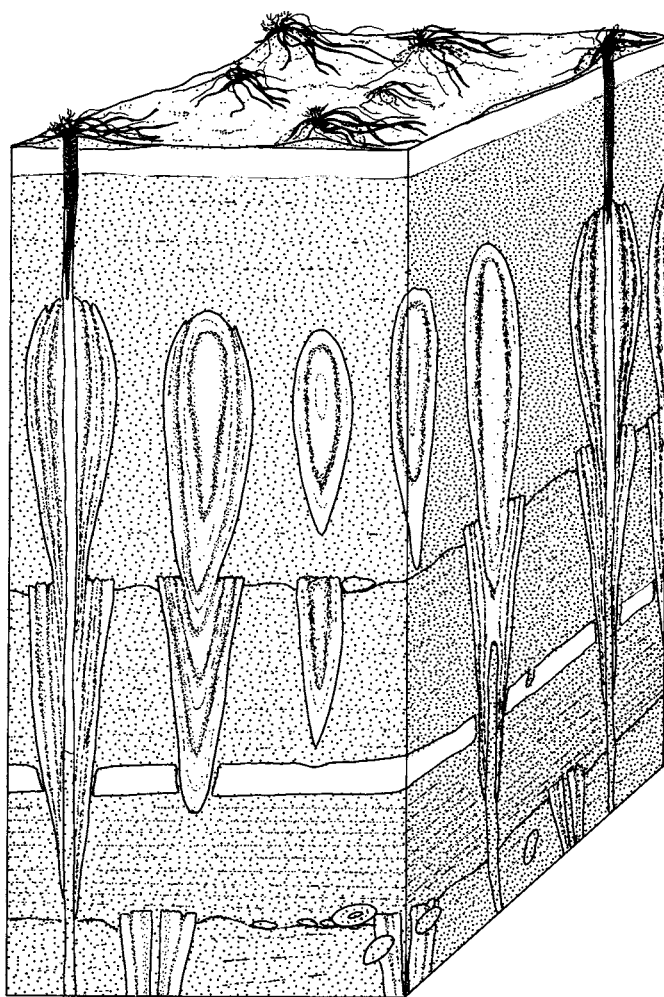


FIGURE 10—Ichnofabric formed by a benthic community dominated by *Rosselia socialis* animals with a high population density. Illustrated block is approximately 40 cm high.

processes contributed to the establishment of a community strongly dominated by *R. socialis* animals, which was responsible for the ichnofabric.

CONCLUSIONS

An ichnofabric characterized by dense occurrences of stacked *Rosselia socialis* occur in up to thirty horizons of middle Pleistocene transgressive inner shelf deposits of the lower Ichinono “Member.” Judging from the morphology and mode of occurrence of *R. socialis*, the ichnofabric is interpreted to have been formed by a dense population of producers, probably terebellid polychaetes. The benthic community dominated by *R. socialis* animals probably formed under the influence of transgressive ravinement processes, which induced frequent rapid sedimentation events on the shelf. These events proved stressful or fatal to most benthic animals in the shelfal environment. The

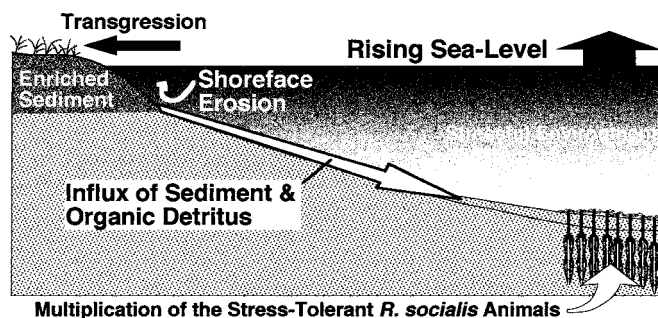


FIGURE 11—Inferred pattern of sediment and nutrient transport on the “Ichinono shelf” during the formation of *Rosselia* ichnofabric described here. Transgressive ravinement probably produced episodic pulses of rapid sedimentation and caused considerable environmental stress. This may have prohibited colonization by most benthic organisms except for the *Rosselia socialis* animals, which were tolerant of such conditions. At the same time, the ravinement process, which likely eroded organic-rich marsh deposits, provided abundant organic detritus to the shelf and maintained large populations of the detritus-feeding *R. socialis* animals. See text for full discussion.

processes also provided much organic detritus, mainly from coastal plants and/or enriched marsh deposits, and allowed the detritus-feeding and stress-tolerant *R. socialis* animals to thrive.

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