RELATIONSHIPS BETWEEN COMPOSITION OF ORGANIC MATTER, DEPOSITIONAL ENVIRONMENTS, AND SEA-LEVEL CHANGES IN BACKARC BASINS, CENTRAL JAPAN

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ABSTRACT: **Sedimentary organic matter is a potential indicator of paleoenvironments. In this study we examine the relationship among composition of kerogen (insoluble organic matter), sedimentary environments, and sea-level changes in Miocene to Pleistocene sediments of the Niigata and Akita backarc basins, central Japan. Our primary analytical tool is a ternary diagram with apexes consisting of woody–coaly organic matter, herbaceous with pollen and spores, and amorphous organic matter (AOM) with alginite (organic-walled marine microfossils). The composition of kerogen plots into distinct regions on the ternary diagram: fluvial to estuarine, prodeltaic, shelf, slope and basin-floor submarine fans, and distal basin-floor sediments. The fluvial and estuarine sediments have high proportions of woody–coaly and herbaceous organic matter with pollen and spores, and a lesser proportion of AOM + alginite, because pollen and spores were mainly deposited in estuaries. Because abundant coarse-grained, terrigenous organic matter was supplied by delta distributaries, the prodeltaic sediments have high proportions of woody–coaly organic matter. The composition of kerogen in the shelf sediments is similar to the kerogen in slope and basin-floor submarine-fan sediments, as plotted on the ternary diagram. Both kinds of kerogen accumulations have high proportions of woody–coaly organic matter and AOM with alginite and lesser proportions of herbaceous organic matter with pollen and spores. This relationship suggests that turbidity currents supplied the terrigenous sediments. The sediments on the distal basin-floor contain high proportions of AOM.**

Each pattern in the ternary diagram reflects a difference in hydrodynamic behavior, distance from land, and the supply of terrigenous organic matter. The sub-ternary diagram, which has apexes of WFA (weakly fluorescent amorphous organic matter), NFA (nonfluorescent amorphous organic matter) + FA (fluorescent amorphous organic matter), and alginite, further suggests the origin of AOM. The NFA in shelf sediments and WFA in distal basin-floor sediments are inferred to consist of terrestrial higher plant and marine organic matter, respectively. A δ^{13}C value of kerogen rich in NFA (-24.6 and -27.3‰) suggests land plants, whereas kerogen rich in WFA (-20.0 to -23.6‰) suggests marine plankton. These inferences agree with those derived from the sub-ternary diagram. Furthermore, compositional changes of the kerogen in turbidites reflect relative sea-level changes, as seen by shifts in compositions on the ternary diagram. The use of ternary diagrams like those used here is recommended for future studies of kerogen, depositional environment, and sea-level relationship.

INTRODUCTION

Organic petrography has been used to recognize the petroleum potential of source rocks and to interpret sedimentary environment, because kerogen (insoluble organic matter) can be obtained from almost all sedimentary rocks. Previous workers have established that the composition of kerogen varies along with siliciclastic environment (Bustin 1988; Parry 1981; Watanabe and Akiyama 1998), and similar studies have been done for carbonate sediments (Gorin and Steffen 1991; Steffen and Gorin 1993; Bombardire and Gorin 1998; Wood and Gorin 1998). The distribution pattern of organic matter is also thought to be controlled by relative sea-level changes. Examples include the Neogene and Quaternary clinoform deposits on the continental margin of North America (Pasley et al. 1991), Upper Jurassic sediments in Tethys (Pittet and Gorin 1997), and Devonian and Carboniferous sediments in southeast Wales (Davies et al. 1991). Paleodepth and paleosalinity are recognized as additional controls on kerogen occurrence (Sato 1980; Ujiié 1992; Ujiié and Jingu 1992). All of these earlier studies suggested that the kerogen modal composition of marine mudstone differs according to depositional setting. Such differentiation should be apparent in a ternary diagram. Shimazaki (1986), in fact, proposed a ternary diagram for the composition of kerogen, but unfortunately it does not reflect sedimentary environments, because kerogen composition was plotted according to stratigraphic position. Parry (1981) also proposed a ternary diagram for the modal composition of kerogen, but the distribution of kerogen composition in their diagram does not agree well with the environmental subdivisions of a delta system. This discordance may stem from the fact that sedimentary environments could be approximated by Parry (1981) from slabs and geophysical logs.

The purpose of this study is to present ternary diagrams that clearly express the relationship between sedimentary environments and the composition of kerogen. Detailed sedimentary environments, depositional systems, and depositional sequences in our study area have been delineated in previous studies (Takano 1998, 2002; Hoyanagi et al. 2000; Omura 2000). We show that the factors that control the composition of kerogen in each sedimentary environment, including the origin and deposition of organic matter and relative sea-level changes, can be deciphered in these ternary diagrams.

GEOLOGICAL SETTING

The Niigata and Akita sedimentary basins are located on the eastern margin of the Japan Sea and are considered to be backarc basins (Fig. 1). The Niigata sedimentary basin is filled with Miocene volcanics and Miocene to Pleistocene siliciclastics more than 5,000 m thick, and evidently formed in close connection with the opening of the Japan Sea (Tamaki et al. 1992). Folded Tertiary strata in the Niigata backarc basin have NNE–SSW and NE–SW-trending axes. Oil and gas are produced from these Neogene rocks, so many detailed geological studies have been undertaken for petroleum exploration (Kageyama and Suzuki 1974; Watanabe 1976; Maiya 1978; Tsuda 1978; Sato et al. 1987; Suzuki 1989; Kobayashi and Tateishi 1992; Kurokawa 1999).

Facies and depositional-system analyses have shown that the Niigata sedimentary basin was filled under a range of environmental conditions: basin floor, submarine-fan, slope, shelf, deltaic, estuarine, and fluvial systems (Fig. 2; e.g., Takano 2002). The Akita sedimentary basin, also situated on the eastern margin of the Japan Sea, is similar to the Niigata backarc basin and has also been studied extensively for petroleum resources (Sato et al. 1988a, 1988b; Matoba et al. 1990; Shiraishi and Matoba 1992).

Sequence stratigraphic studies have been carried out for the upper Miocene and Pleistocene sediments in the Niigata backarc basin. The third-order depositional sequences in the late Miocene strata, which consist of submarine-fan turbidites, exhibit a vertical stacking pattern, whereas those in the Pliocene to Pleistocene strata consist mainly of deltaic sediments with a progradational stacking pattern (Takano 2002).

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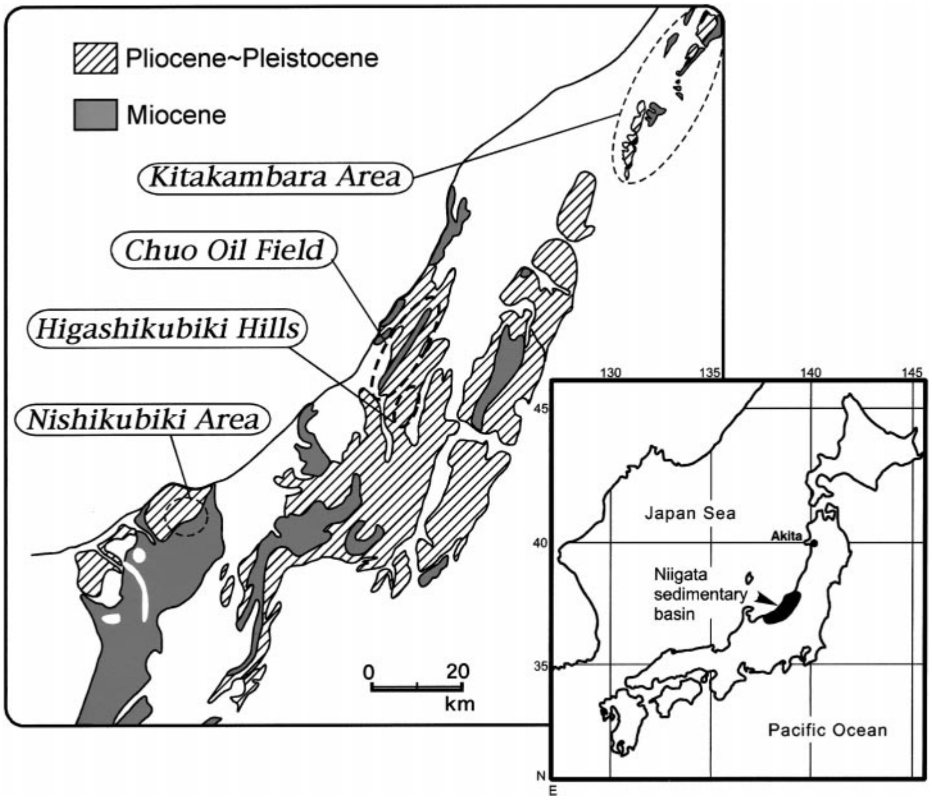


FIG. 1.—Inset map shows location of Niigata and Akita sedimentary basins. Larger map shows outcrops in the Niigata sedimentary basin.

METHODOLOGY

Sedimentary environments have been reconstructed for the Niigata and Akita backarc basins, on the basis of detailed facies analysis, and depositional sequences of 0.1 to 3 Myr duration also have been recognized for the late Miocene to Pleistocene interval (Figs. 1, 2; Endo and Tateishi 1985; Kazaoka 1988; Takano 1990, 1995; Urabe et al. 1995; Hoyanagi et al. 2000; Omura 2000). Two hundred and ninety samples overall were collected from all sedimentary environments seen in outcrops and cores in the two basins. All organic particles were concentrated from muddy sediments by HCl and HF treatment without a sieve or density preparation (Fig. 3).

The kerogen composition of each sample was determined by counting 300 points at intervals of 100 μm under transmitted and reflected fluorescent-light microscopy (330–385 nm excitation filter, 420 nm absorption filter). Our study incorporates these new data as well as data in Omura et al. (2000) and Omura et al. (2001). We plotted the modal composition of kerogen in ternary diagrams, instead of the pie and bar charts used by Omura et al. (2000) and Omura et al. (2001), in order to show the proportion of three components clearly. The apexes of ternary diagram are woody–coaly organic matter, herbaceous organic matter with pollen and spores, and amorphous organic matter (AOM) with alginite (marine organic-walled microfossils). Because amorphous organic matter can be subdivided into NFA (nonfluorescent amorphous organic matter), and FA (fluorescent amorphous organic matter), and WFA (weakly fluorescent amorphous organic matter) (Sawada and Akiyama 1994), we present a subternary diagram with the apexes of WFA, alginite, and NFA + FA.

We mainly analyzed samples from outcrops, where sedimentary environments have been reconstructed using facies analysis, although we also studied 27 samples from drill cores to test for features that may have been the result of weathering in surface samples.

The total organic carbon (TOC) content was measured for 31 samples with a CHN Yanaco MT-5 Analyzer. Samples were heated in a furnace at 950°C, a calibration line was made with Antipyrine (C, 70.19%; N, 14.88%), and the analytical precision was approximately 0.03%.

We used stable carbon isotope analysis to confirm the origin of AOM, which is only assumed in the ternary diagrams. The samples for stable carbon isotope analysis consisted of separated organic matter rich in NFA or WFA. Stable carbon isotope analyses were carried out at the Faculty of Science, Shinshu University, using an elemental analyzer (FlashEA1122, ThermoQuest Ltd.) and a mass spectrometer (Delta Plus, ThermoQuest Ltd.). A few milligrams of each sample was heated to 950°C in the furnace of the elemental analyzer, and the resulting purified CO_2 gas was fed directly into a mass spectrometer using a pure helium carrier gas. Carbon isotope results are expressed as per mil (‰) relative to the V-PDB standard. We measured a blank with each sample and a working standard (Atropine; $\delta^{13}C = -23.2‰$) with every eight samples. The analytical precision was 0.1‰ in carbon for C.

SEDIMENTARY ENVIRONMENTS AND SYSTEMS TRACTS OF SAMPLES

Siltstone, mudstone, sandy siltstone, sandy mudstone, very fine sandstone, and fine sandstone were chosen for analysis because fine-grained sediments contain more sedimentary organic matter than do coarse-grained sediments. We collected samples (290 total) from all sedimentary environments, including distal basin floor, submarine fan on a slope and basin floor, shelf, deltaic, estuarine, and, fluvial (Appendix 1, see acknowledgments). Two hundred and eighty one samples came from several localities in the Niigata back-arc basin: the Kitakambara district, the Chuo Oil Field, the northeast part of the Higashikubiki Hills, and the Nishikubiki district (Fig. 1). Nine samples were collected from the Gojonome district in the Akita basin (Fig. 1). Two hundred and sixty-three samples of our 290 samples were collected from unweathered outcrops along rivers, but we still removed the outer surfaces of the samples and used only the inner

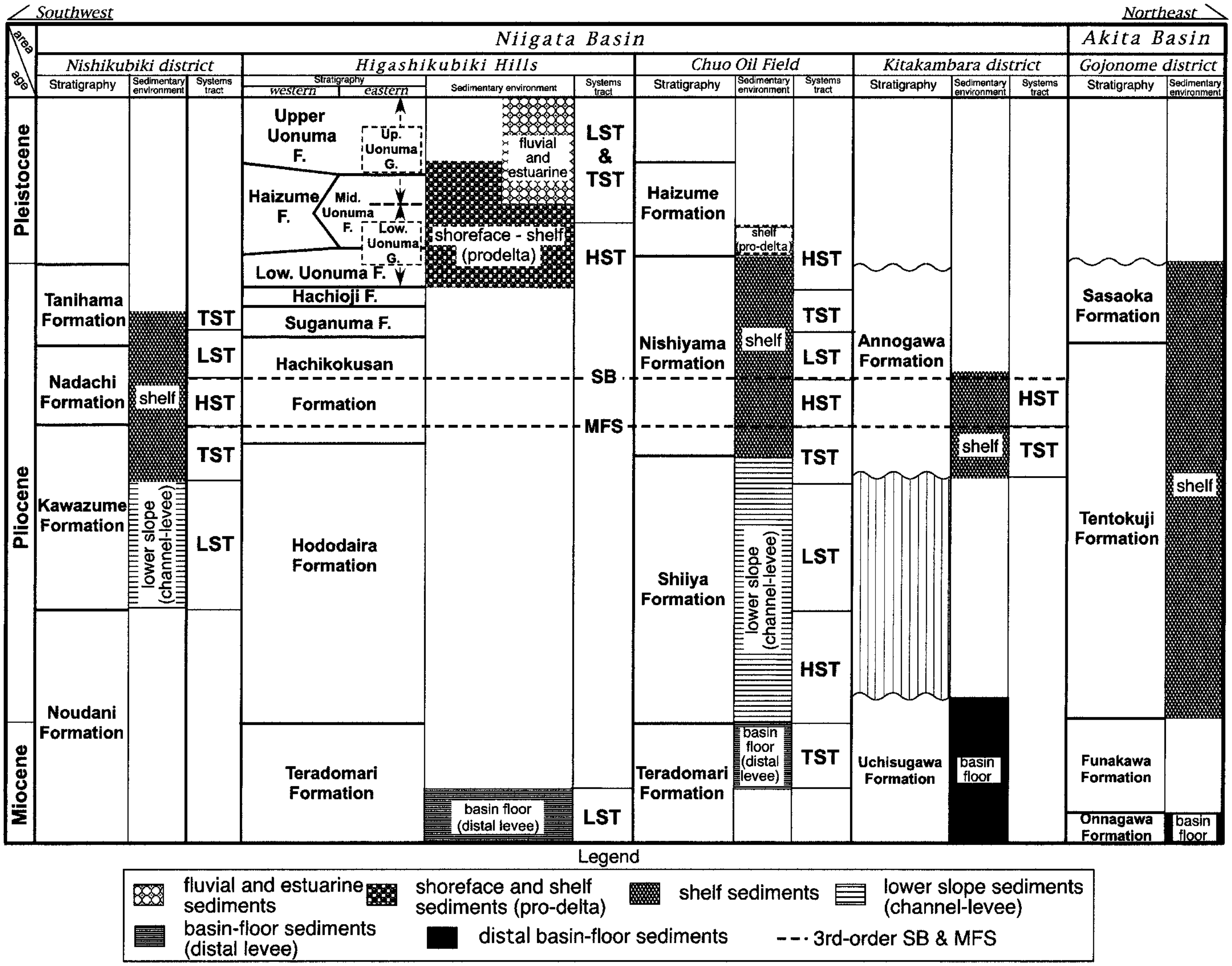


FIG. 2.—Stratigraphy and correlations between districts, and depositional systems in Upper Miocene to Lower Pleistocene intervals of the Niigata and Akita sedimentary basins (from Takano 1998; Omura 2000; Hoyanagi et al. 2000; and Takano et al. 2001). LST: lowstand systems tract, TST: transgressive systems tract, HST: highstand systems tract.

parts for organic-matter analysis. Twenty seven of the 290 samples were from cores collected from the Higashikubiki district.

Basin-Floor and Slope Deposits

Diatomaceous and calcareous siltstone samples (12 total) of basin-floor sediments were collected from the Uchisugawa Formation in the Kitakambara district and from the Onnagawa Formation in the Gojonome district (Fig. 2). We did not interpret the sequence stratigraphy of these Miocene pelagic sediments.

Thick-bedded turbidites in the lower Teradomari Formation constitute a lowstand systems tract of late Miocene age (Takano 2002; Hoyanagi et al. 2003). Twenty-seven samples were collected from these black turbidite mudstones (Et) in drill cores from the Higashikubiki Hills.

Thin sandstone, turbidite mudstone, and hemipelagic mudstone of the upper Teradomari Formation (Miocene) constitute a transgressive systems tract composed of submarine-fan sediments (Takano 2002). Five mudstone samples of distal levee sediments were collected from the upper Teradomari Formation in the Chuo Oil Field (Omura et al. 2001). Four of these are turbidite mudstone (Et) and one is hemipelagic mudstone (Eh).

Thick-bedded sandstone and turbidite mudstone (Et) in the lower part of the lower Pliocene Shiiya Formation constitute a highstand systems tract of submarine-fan sediments (Fig. 2; Takano 1998). We collected twenty-one samples of sandy levee and interchannel mudstone from the lower part of the Shiiya Formation.

Thick sandstone and turbidite mudstone in the upper part of the Pliocene Shiiya Formation represent a lowstand systems tract composed of submarine-fan sediments (Fig. 2; Takano 1998). We collected twenty-three samples of sandy-levee and interchannel mudstone from the upper part of the Shiiya Formation.

Sandstone and turbidite mudstone of the uppermost part of the Pliocene Shiiya Formation constitute a transgressive systems tract of submarine-fan sediments (Fig. 2; Takano 1998). Eight samples of sandy levee and interchannel mudstone were collected from the uppermost part of the Shiiya Formation.

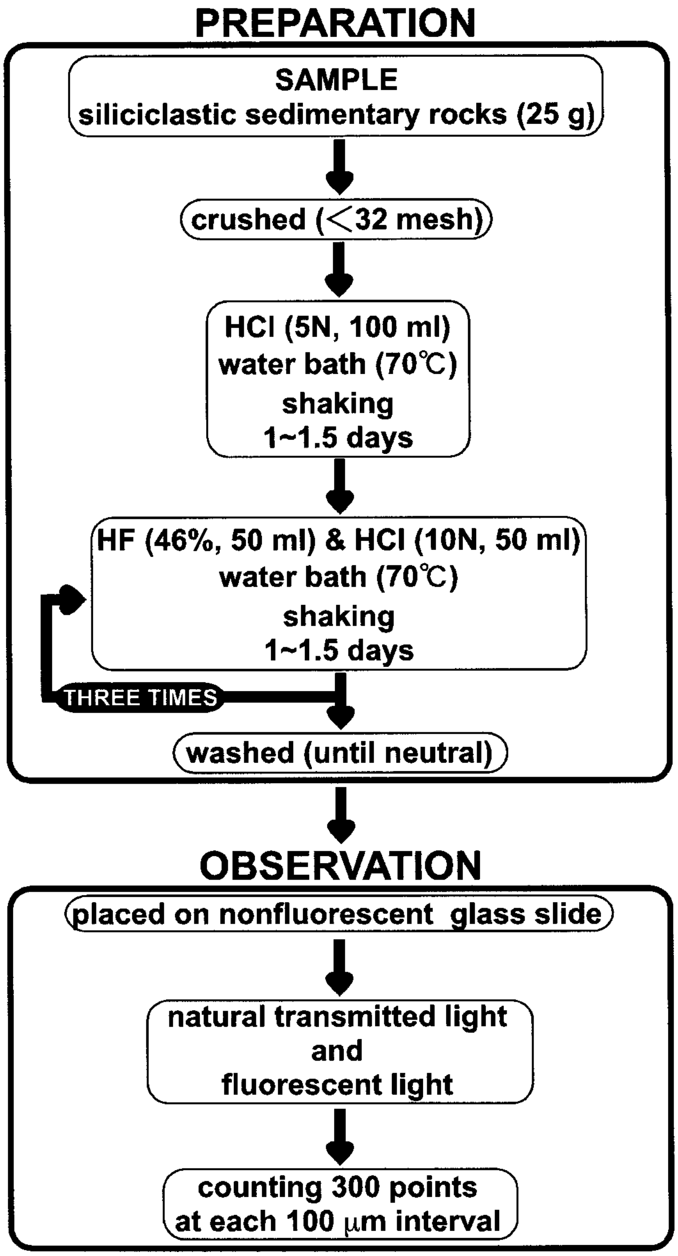


FIG. 3.—Work flow for fluorescent visual-kerogen analysis (after Hirai 1980; Sawada and Akiyama 1994).

Shelf and Fluvial Deposits

The shelf sediments consist of upward-coarsening and upward-fining facies, for which a third-order depositional sequence has been established by Takano (1998). The sequence boundaries and maximum-flooding surface, established in the Niigata sedimentary basin, bound the transgressive, highstand, and lowstand systems tracts (Takano 1998; Omura 2000). One hundred and twenty-six shelf mudstone and sandy mudstone samples were collected from the Nishiyama Formation in the Chuo Oil Field, the uppermost Kawazume, the Nadachi, and the lower part of the Tanihama formations in the Nishikubiki district, as well as in the Annogawa Formation in the Kitakambara district (see Fig. 2 and Appendix 1 for details).

A repeated succession of upward-shallowing facies, from wave-dominated shelf to shoreface, constitute prodeltaic sediments in a highstand systems tract of the latest Pliocene to early Pleistocene (Fig. 2; Hoyanagi et al. 2000). Twenty-eight samples of sandy mudstone and siltstone in the prodelta were collected from the lower part of the Uonuma Group and the Haizume Formation in the Higashikubiki Hills, and the Chuo Oil Field (Omura et al. 2001). Five very fine sandstone and fine sandstone samples of shoreface sediments on the prodelta were collected from the lower part of the Uonuma Group and the Haizume Formation in the Higashikubiki Hills (Omura et al. 2000).

Estuarine sediments in the Higashikubiki Hills constitute an early Pleistocene fourth-order transgressive systems tract (Fig. 2; Hoyanagi et al. 2000). Twenty siltstone and sandy siltstone samples of estuary-mouth and central-basin sediments were collected from the upper part of the Uonuma Group in the Higashikubiki Hills (Omura et al. 2000).

Fluvial sediments in the Higashikubiki Hills constitute an early Pleistocene fourth-order lowstand systems tract (Fig. 2; Hoyanagi et al. 2000). Six siltstone samples of fluvial flood-plain and channel sediments were collected from the upper part of the Uonuma Group in the Higashikubiki Hills (Omura et al. 2000).

CLASSIFICATION OF VISUAL KEROGEN AND TERNARY DIAGRAM

Kerogen (insoluble organic matter in sedimentary rocks) has been classified in several ways (Tyson 1995). Herein we use an approach similar to those of Staplin (1969), Tissot and Welte (1984), and Boulter and Riddick (1986). In order to compare the composition of kerogen in a variety of sedimentary environments, we used the classification systems of Sawada and Akiyama (1994) and Tissot and Welte (1984). The morphological and fluorescent characteristics of kerogen, including vitrinite, sporinite, cutinite, resinite, sclerotinite, and alginite, are shown in Table 1 and Figure 4. Amorphous organic matter (AOM) has been subdivided into FA (fluorescent amorphous organic matter), WFA (weakly fluorescent amorphous organic matter), and NFA (nonfluorescent amorphous organic matter) on the basis of fluorescence under a reflected-light fluorescent microscope (Sawada and Akiyama 1994).

We use the kerogen ternary plot proposed by Shimazaki (1986), for which he separated kerogen into woody–coaly organic matter, herbaceous organic matter with pollen and spores, and AOM with alginite (marine organic-walled microfossils). Woody–coaly organic matter contains vitrinite and sclerotinite. Herbaceous organic matter with pollen and spores contains sporinite, cutinite, and resinite. The AOM with alginite is classified into FA + NFA, WFA, and alginite, for samples that contain these components in abundance.

RESULTS

Composition of Kerogen by Sedimentary Environment

The distribution pattern for the composition of kerogen in the fluvial and estuarine sediments is concentrated between the apexes for herbaceous organic matter with pollen and spores and woody–coaly organic matter (Fig. 5A). This distribution pattern is also close to the base of the ternary diagram, because the fluvial and estuarine sediments contain a very small amount of AOM + alginite.

The prodeltaic sediments contain a small amount of herbaceous organic matter with pollen and spores, and high proportions of woody–coaly organic matter (Fig. 5A), plus a small amount of AOM + alginite.

The shelf sediments have very low content of herbaceous organic matter with pollen and spores, and large amounts of woody–coaly organic matter and AOM + alginite (Fig. 5A). The distribution pattern for the composition of kerogen in the shelf sediments extends between the woody–coaly organic matter and AOM + alginite apexes, from 50% woody–coaly organic matter to more than 90% AOM + alginite. Almost all the AOM in shelf sediments consist of NFA + FA in the sub-ternary diagram, with no WFA and alginite (Fig. 5B).

TABLE 1.—*Classification of sedimentary organic matter using fluorescent visual kerogen analysis.*

Group	Constituent	Characteristics		Origin
		Transmitted Light	Fluorescent Light	
woody–coaly organic matter	vitrinite	translucent, brown semiopaque and black opaque, square- and blade-shape	no fluorescence	higher-plant debris
	sclerotinite	translucent, brown and pole-shaped with joints	no fluorescence	hyphae
herbaceous organic matter with pollen and spores	sporinite	translucent, brown, pollen and spore-shaped	strong fluorescence yellow to white color	pollen; spores
	cutinite	translucent, plant tissue structures	moderate fluorescence yellow to light grey color	cuticle; leaves
	resinite		strong fluorescence orange color	resin
amorphous organic matter	FA (Fluorescent amorphous organic matter)	structureless	strong fluorescence yellow to white color	sporinite; cutinite
	NFA (Nonfluorescent amorphous organic matter)	structureless	no fluorescence black color	vitrinite and other terrigenous organic matter
	WFA (Weakly fluorescent amorphous organic matter)	structureless	weak fluorescence dark orange to light brown color	marine plankton
aquatic organic microfossils	alginite	translucent, dinoflagellates- and acritarchs-shaped	strong fluorescence yellow to white color	algae; marine plankton

Modified from Tissot and Welte (1984), Senftle et al. (1993), and Sawada and Akiyama (1994).

The turbidites of slope and basin-floor submarine-fan sediments seen in outcrop have low amounts of herbaceous organic matter with pollen and spores, and have large amounts of woody–coaly organic matter and AOM + alginite. The distribution pattern of the modal composition for kerogen in turbidites also extends between the woody–coaly organic matter and AOM + alginite apexes, similar to the pattern seen in shelf sediments (Fig. 5A). The distribution pattern for the modal composition of kerogen in turbidites is different for turbidite mudstone (Et) and hemipelagic mudstone (Eh) on the sub-ternary diagram (Fig. 5B). The AOM in the turbidite mudstone (Et) of a slope and basin-floor submarine fan is mainly composed of NFA + FA, whereas AOM in hemipelagic mudstone (Eh) consists of WFA (Fig. 5B).

The distribution pattern for the modal composition of kerogen of 27 basin-floor turbidite samples taken from cores is the same as for outcrops (Fig. 5A). Almost all the AOM in basin-floor turbidites in cores consists of NFA + FA (Fig. 5B).

The kerogen in distal basin-floor sediments is consists mainly of AOM. The AOM + alginite component of the distal basin-floor sediments is highest in a range of sediments (Fig. 5A). Almost all AOM in the distal basin-floor sediments is WFA (Fig. 5B).

Composition of Kerogen by Systems Tract

The composition of kerogen for each systems tract of the slope and basin floor is plotted in Figure 6. The proportion of herbaceous organic matter with pollen and spores in the submarine fan of the transgressive systems tract ranges from zero to a few percent. The proportion of woody–coaly organic matter is also low, at 20%, compared to abundant 80% for AOM + alginite (Fig. 6A). In comparison, submarine-fan sediments in the highstand systems tract have relatively high proportions of herbaceous organic matter with pollen and spores and woody–coaly organic matter (Fig. 6B).

The proportions of kerogen in the lowstand turbidite exhibit two distribution patterns in the ternary diagram (Fig. 6C), one with relatively abundant woody–coaly organic matter and one with relatively abundant AOM + alginite.

TOC

The total organic carbon (TOC) content of the distal Miocene basin-floor sediments in the Kitakambara and the Gojonome district ranges from 1.05 to 1.85 wt %. In comparison, values for the Pliocene shelf sediments in the Nishikubiki, Kitakambara, and Gojonome districts range from 0.34 to 1.14 wt %, and values for the Pleistocene fluvial, estuarine, and prodeltaic sediments in the Higashikubiki district range from 0.11 to 0.68 wt %. Appendix 1 contains the details (see Acknowledgments).

δ^{13}C Values of Kerogen

Kerogen samples with high proportions of WFA were selected from the basin-floor sediments in the Uchisugawa Formation (Us-01, 03, 08, and 09) of the Kitakambara district and the Onnagawa Formation (On-01) of the Gojonome district. These samples contain more than 88.3% WFA, and their kerogen exhibits δ^{13}C values between −20.0 and −23.6‰ (Fig. 7).

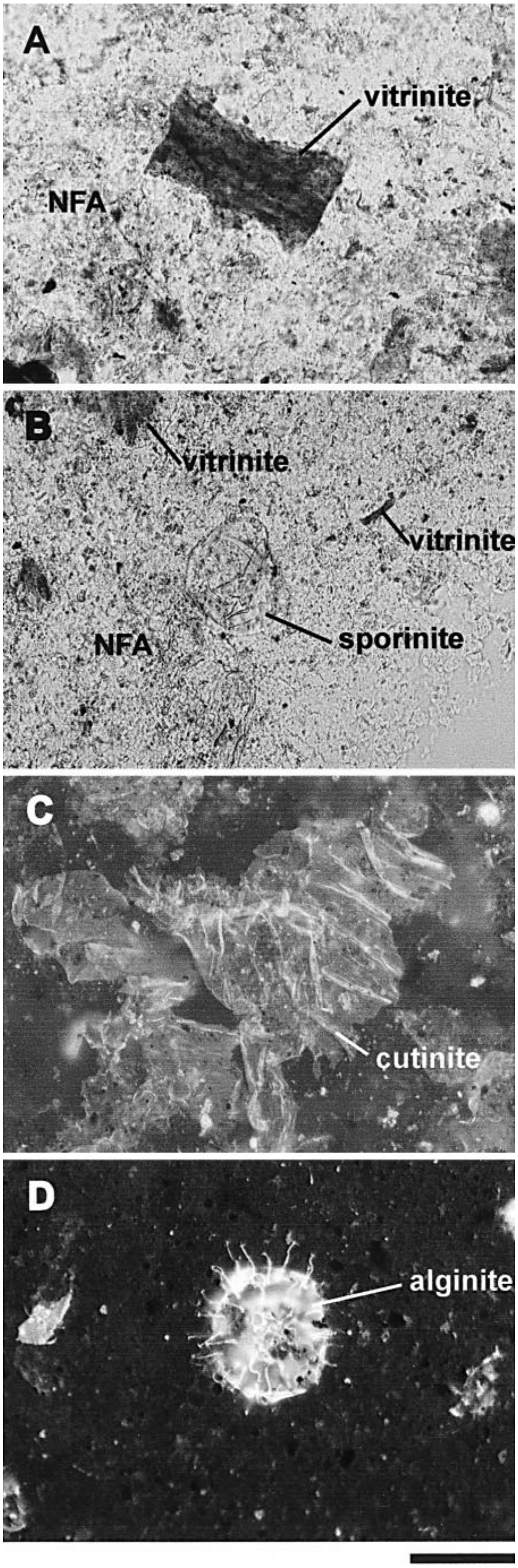
Kerogen samples with high proportions of NFA were selected from the outer-shelf sediments of the uppermost Kawazume (Ka-05), the Nadachi (Na-10 and 21) formations in the Nishikubiki district, the Annogawa Formation (An-01, 11 and 22) in the Kitakambara district, and the Sasaoka (Ss-01) and the Tentokuji (Tt-05) formations in the Gojonome district. These units contain more than 81.0% NFA. Their kerogen has δ^{13}C values between −24.6 and −27.3‰ (Fig. 7). Kerogen samples with high proportions of vitrinite from the shoreface of prodeltaic (Iu-03), flood-plain (Iu-11), and estuarine central basin (Iu-20) sediments of the Uonuma Group in the Higashikubiki Hills contain 46.0 to 84.7% vitrinite and have δ^{13}C values between −24.6 and −28.6‰ (Fig. 7).

Although the δ^{13}C values of kerogen may vary with thermal alteration, they have not done so if vitrinite reflectance is less than 0.8 (Omokawa 1985). Vitrinite reflectance of the Nishiyama to Teradomari formations is 0.59 to 0.65 in the Niigata Basin (Omokawa 1985), and values for the Onnagawa Formation are less than 0.45 (Sawada and Akiyama 1994). Therefore, δ^{13}C values of kerogen in the Niigata and Akita basins were not thermally altered.

DISCUSSION

Weathering Effects

The AOM in the turbidite mudstones (Et), which were collected from both cores and outcrops, consist entirely of NFA. This phenomenon suggests that the WFA did not lose its fluorescence and did not become NFA because of subaerial weathering. The grain size of samples affects these results; nearly all samples used for the analyses are muddy sediment lacking medium- to coarse-grained sand particles. Weathering does not affect the inner portion of muddy sediments, because both porosity and perme-



ability are low, so we used outcrop samples for organic-matter analyses after removing the outer portions.

Interpretation of Kerogen Patterns

The distribution pattern of visible kerogen in fluvial and estuarine sediments (Fig. 5) may reflect the fact that the kerogen in such environments consists mainly of terrigenous organic matter with very little marine organic matter. Because pollen and spores are deposited mainly at the mouth of rivers and estuaries (Kurita et al. 1997; Omura et al. 2000), fluvial and estuarine sediments have high proportions of not only woody–coaly organic matter but also herbaceous organic matter with pollen and spores.

Prodeltaic sediments are relatively poor in herbaceous organic matter with pollen and spores, compared to fluvial and estuarine sediments. It is thought that pollen and spores are mainly trapped in an estuary, with a much smaller amount transported to the prodelta. Proportions of woody–coaly organic matter in terrigenous organic matter, which is derived from rivers, increase, whereas the proportions of herbaceous organic matter with pollen and spores decrease. We distinguish prodeltaic sediments from fluvial and estuarine sediments, because the former has a higher proportion of AOM + alginite than the latter.

The content of herbaceous organic matter with pollen and spores in shelf and submarine-fan sediments deposited on the slope and basin floor is lower than in prodeltaic sediments. Even though pollen and spores are transported by the wind as well as by rivers, the supply of pollen and spores decreases away from land. The submarine-fan sediments on the slope and basin floor differ from prodeltaic sediments by having relatively abundant AOM + alginite and sparse woody–coaly organic matter. We infer that this has resulted from a seaward decrease in the supply of coarse-grained terrigenous organic matter. The composition of submarine-fan sediments on the slope and basin floor is similar to that of shelf sediments, as seen in the ternary diagram, even though the former are relatively far from shore. This implies that the coarse-grained terrigenous organic matter was supplied to offshore environments by turbidity currents. This in turn suggests that slope-collapse-generated turbidity currents transported organic matter from the shelf to basin floor.

Almost all the AOM + alginite in shelf, submarine-fan, and basin-floor sediments consist of AOM. Shimazaki (1986) and Sato (1980) also suggested that amorphous organic matter increases with increasing water depth and foraminiferal diversity. WFA, NFA, and FA are thought to consist of marine plankton, terrigenous organic matter, and herbaceous organic matter (including pollen and spores), respectively (Sawada and Akiyama 1994). However, Omura et al. (2000) and Omura et al. (2001) have suggested that land-derived amorphous organic matter also increases seaward. Prodeltaic sediments can be separated from shelf and submarine-fan sediments, because the AOM, whatever its origin, is combined with alginite on the ternary diagram. Therefore, AOM with alginite indicates an offshore environment in the main ternary diagram, independent of AOM's origin.

Basin-floor sediments differ from shelf and submarine-fan sediments, in that almost all their organic matter consists of AOM without terrigenous organic matter. This condition results from the absence of terrigenous organic matter on the distal basin floor, which is not influenced by turbidity currents.

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FIG. 4.—Organic matter under reflected-light fluorescence microscopy (Olympus BX50) with tungsten light (A and B) and ultraviolet light (C and D). Scale bar is 50 μm. **A)** Vitrinite and NFA in shelf sediment of the Uonuma Group. **B)** Sporinite, vitrinite, and NFA in estuarine sediments of the Uonuma Group. **C)** Cutinite in estuarine sediment of the Uonuma Group. **D)** Alginite in basin-floor sediment of the Uchisugawa Formation.

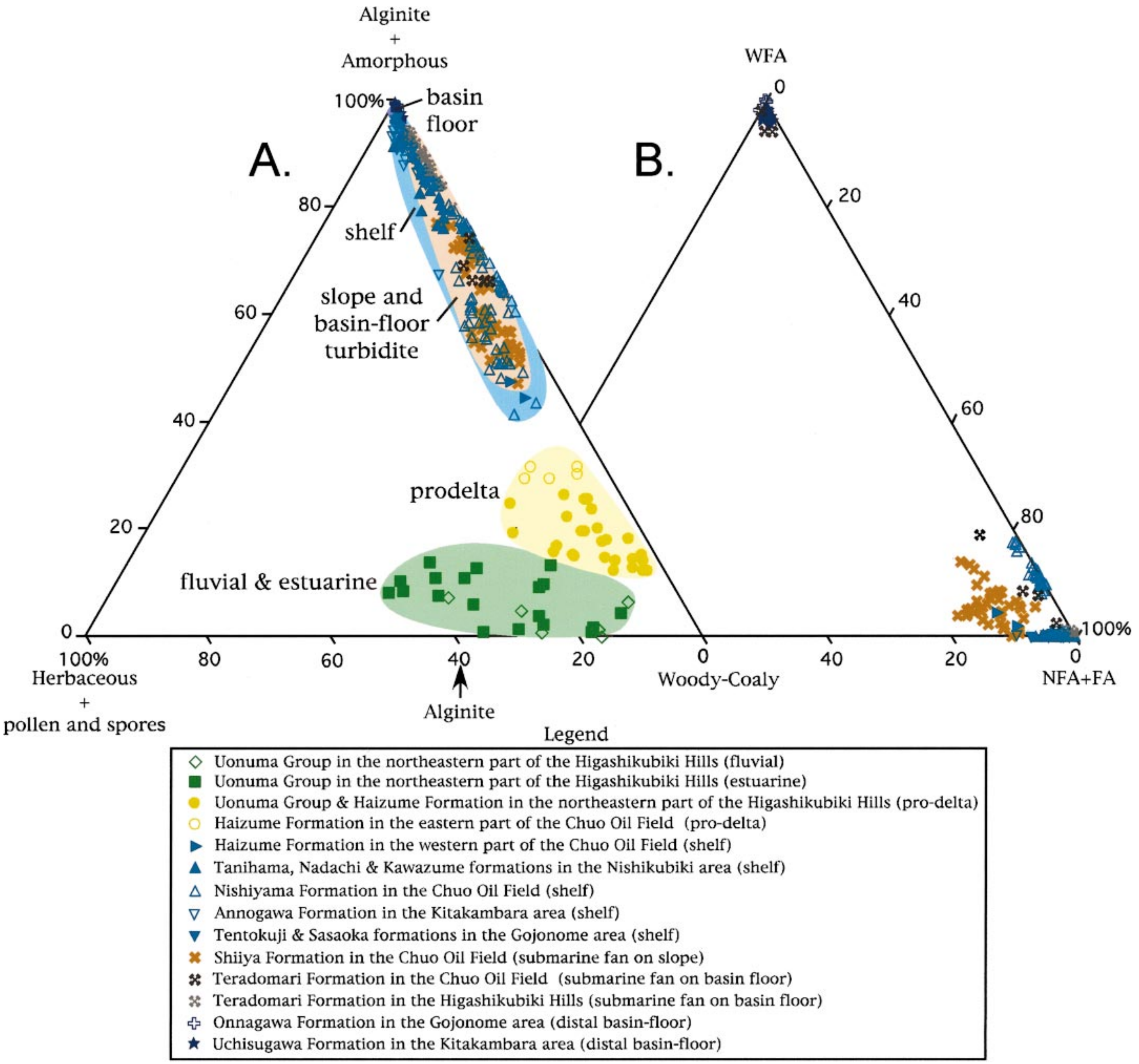

FIG. 5.—**A)** Ternary diagram of organic-matter classification in fluvial, estuarine, prodeltaic, shelf, submarine-fan and basin-floor sediments. **B)** Amorphous organic matter and marine organic-walled microfossils in a sub-ternary diagram classified as FA + NFA, WFA, and alginite.

Environmental Significance of the Ternary Diagram

The significance of the apexes in the ternary diagram can be deduced from the relationships discussed above. The apex with herbaceous organic matter with pollen and spores indicates environments near a river mouth. The apex with woody–coaly organic matter indicates environments where coarse-grained terrigenous organic matter is abundantly supplied by a delta or turbidity currents. The apex with AOM + alginite indicates offshore environments.

The sub-ternary diagram with apexes for alginite, WFA, and NFA + FA distinguished shelf, submarine fan, and distal basin-floor sediments because these sediments contain abundant AOM. The AOM in shelf sediments and turbidite mudstone consists mainly of NFA + FA, whereas the AOM in hemipelagic mudstone and distal basin-floor sediments consists mainly of WFA. These occurrences suggest that the proportions of NFA + FA are high in environments with an abundant supply of terrigenous organic matter, such as the shelf and basin-floor fan, and that the proportion of WFA is high in environments that lack a supply of terrigenous organic matter, such as the depositional interval between turbidity currents, or the distal basin floor. As a consequence, the NFA and FA are inferred to originate from terrigenous organic matter, and the WFA from marine organic matter. The sub-ternary diagram can be used for the origin of the AOM, although AOM + alginite indicates an offshore environment in the main ternary diagram, in spite of the AOM's origin.

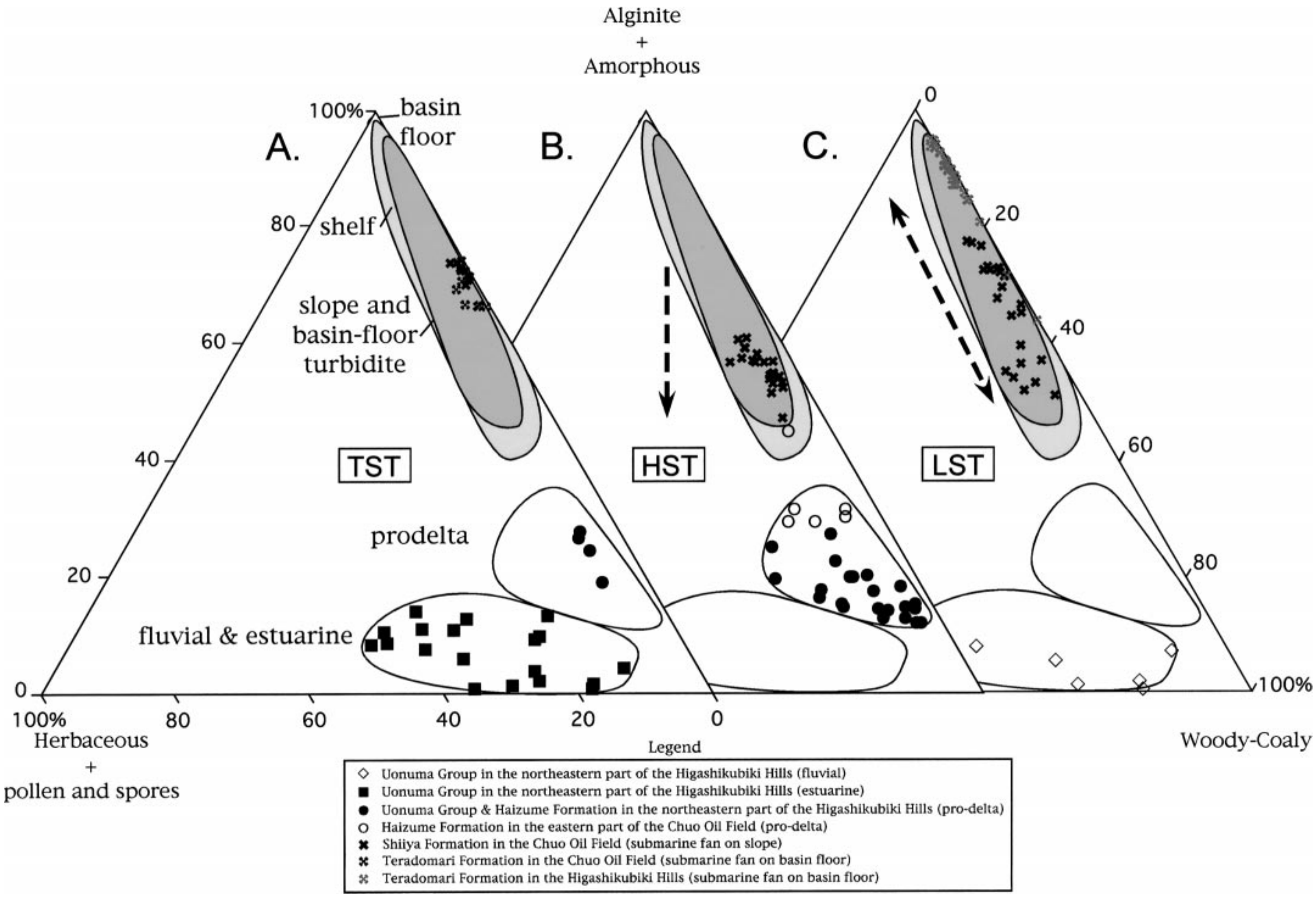

FIG. 6.—Ternary diagram showing organic-matter classification for sequence analysis in the Niigata backarc basin. **A)** Transgressive stage, **B)** highstand stage, and **C)** lowstand stage.

$\delta^{13}C$ Values and Origin of AOM

Terrestrial plants, except for C4 plants such as sugar and Indian canes (Deines 1980), are distinguished from marine plankton in the low- to middle-latitude ocean by their $\delta^{13}C$ values (Rau et al. 1982). Terrestrial and marine organic matter has $\delta^{13}C$ values between −25 and −28‰, and −19 and −23‰, respectively (Deines 1980; Rau et al. 1982; Jasper and Gagosian 1990). Kerogen samples with high proportions of NFA and high proportions of vitrinite exhibit $\delta^{13}C$ values typical of terrestrial organic matter, whereas kerogen with high proportions of WFA has values typical of marine organic matter (Fig. 7). The $\delta^{13}C$ values with high NFA values (78.6 to 93.3%) differ from samples with a high proportion (88.3 to 97.7%) of WFA organic matter. These lines of evidence strongly suggest for the Niigata and Akita sedimentary basins that the NFA originated from higher land plants, whereas the WFA originated from marine plankton.

We confirmed that the WFA originated as marine plankton on the basis of the $\delta^{13}C$ values in many Niigata basin WFA samples, whereas Sawada and Akiyama (1994) reached the same conclusion from stable carbon isotope analysis of WFA from the Onnagawa Formation. Sawada and Akiyama (1994) inferred that the NFA originated as terrestrial higher plants, on the basis of a single NFA sample from the Toarcian Shale at Yorkshire, England. In the present study, we infer that the NFA originated as terrestrial higher plants, on the basis of the $\delta^{13}C$ values of the shelf organic-matter samples, which consist mainly of NFA. This conclusion agrees with the composition of the samples of fluvial organic matter, which is mainly vitrinite. The NFA is thought to have formed from terrigenous organic matter in marine sediments, judging by examination of $\delta^{13}C$ values and the main ternary diagram for the modal composition of kerogen.

Watanabe and Akiyama (1998) suggested that the organic matter in turbidite mudstone and hemipelagic mudstone originated as terrigenous organic matter and marine plankton, respectively, on the basis of stable carbon isotope analysis of organic matter in the Teradomari Formation. The distribution pattern for the composition of kerogen in the main and subternary diagrams, and Watanabe and Akiyama's (1998) results indicate that the NFA consist of altered organic matter from terrestrial higher plants in marine sediments.

Sea-Level Changes

The effect of third-order relative sea-level changes on the composition of kerogen in submarine-fan turbidite deposits is shown in Figure 6. The differences in composition show strong systems-tract, and hence sea-level, control on kerogen compositions.

The submarine-fan sediments of the transgressive stage are poor in herbaceous organic matter with pollen and spores. Herbaceous organic matter with pollen and spores would have been trapped in a coastal estuary that developed during a transgressive stage, and little such organic matter would have been transported to the basin floor. Submarine-fan sediments of a transgressive systems tract are also poor in woody–coaly organic matter but rich in AOM + alginite. Because the supply of terrestrial materials

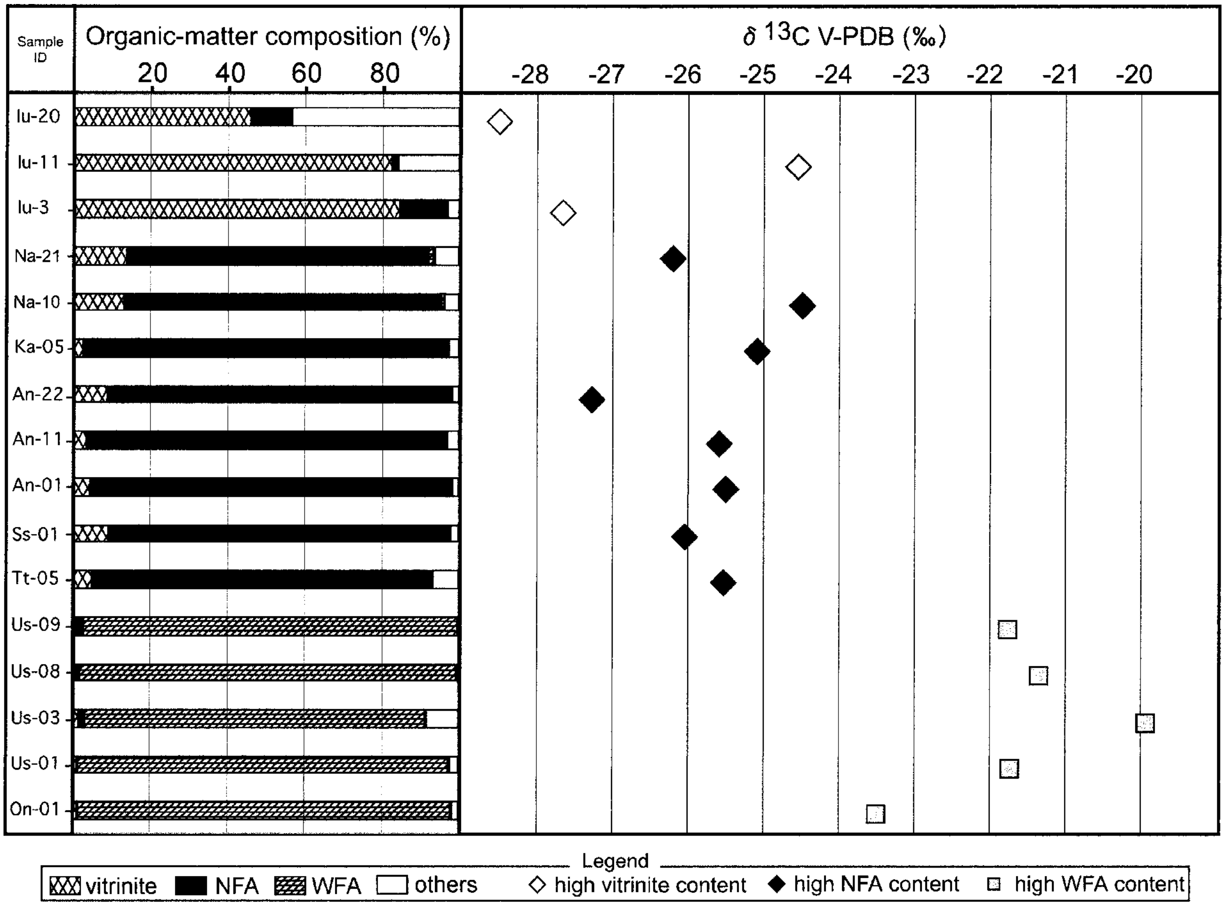

FIG. 7.—Relationship between organic matter and δ^{13}C values for total organic matter.

decreased with a rise in relative sea level, the AOM became relatively abundant in slope and basin-floor submarine-fan environments. A delta system also would have formed during a highstand stage. Because turbidity currents are frequently supplied from a prograding delta system, coarse-grained terrigenous organic matter increased in the prodelta and slope areas. During the transition from an estuary to a delta system, herbaceous organic matter with pollen and spores that had been trapped mainly in the estuary was transported directly to the prodelta and slope. As a result, the proportions of herbaceous organic matter with pollen and spores and woody–coaly organic matter in the highstand systems tract were higher than in the transgressive systems tract (Fig. 6). These facts suggest that a turbidite in a transgressive stage is distinct from a turbidite in a highstand stage, as seen in the ternary diagram.

On the other hand, the abundant woody–coaly organic matter in a lowstand turbidite suggests that large amounts of coarse-grained terrigenous organic matter were transported directly to the basin floor in feeder channels. The abundant AOM + alginite in lowstand turbidites may indicate resedimentation of shelf deposits by collapse of the shelf edge. Again, different depositional processes occur in different sea-level stages, thus kerogen contents vary in the turbidite deposits.

Application of Ternary Diagrams to Environmental and Sequence Analyses

In the present study, we have examined the composition of kerogen as a function of sedimentary environment and proposed ternary diagrams that clearly show kerogen variations in the sedimentary environments of mudstone. The apexes of the ternary diagrams reflect sedimentary processes. Our results for organic-matter composition in the ternary diagrams have been generated for backarc basins, but similar organic matter is found in a range of sedimentary basins, including fore-arc basins, interior basins, and continental-margin basins. The ternary diagrams we present should also infer sedimentary environments from cores and cuttings, which otherwise would be difficult or impossible to achieve. In addition, these ternary diagrams can be used to recognize maximum flooding surfaces in submarine-fan sediments, on the basis of differences in the composition of kerogen in transgressive, highstand, and lowstand deposits.

SUMMARY

Our ternary diagrams for woody–coaly organic matter, herbaceous organic matter with pollen and spores, and amorphous organic matter including marine organic-walled microfossils express differences in the composition of kerogen in a wide range of sediments. The characteristic properties of these environments reflect hydrodynamic behavior, distance from land, supply of terrigenous organic matter and depositional conditions. A sub-ternary diagram is useful for inferring the origin of the amorphous organic matter (AOM), and the results of such analysis have been confirmed by stable carbon isotope analysis. Relative sea-level changes affect sedimentary environmental changes, with corresponding changes in organic-matter type for fluvial to basin-floor sediments. As a result, ternary diagrams also express changes in the composition of kerogen during relative sea-level changes.

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