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Channel–levee complexes, terminal deep-sea fan and sediment wave fields associated with the Toyama Deep-Sea Channel system in the Japan Sea

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Abstract

The Toyama Deep-Sea Channel (TDSC) in the Japan Sea is one of the most prominent deep-sea channels in rifted margins. This study revealed the course and morphology of the entire TDSC system for the first time, based on high-resolution and air-gun seismic reflection profiles, and sediment cores. The channel starts from Toyama Bay and extends for 750 km through the Toyama Trough, a Miocene rift, to the Miocene Yamato and Japan back-arc basins. The TDSC system is fed with sediment from the Northern Japan Alps, through tributary canyons on the narrow shelf, which are directly connected with rivers, even during sea-level highstands. Levee complexes border the channel in the Toyama Trough and Yamato Basin, and in the Japan Basin, the channel feeds the terminal Toyama Fan. Levees in the confines of the Toyama Trough are accompanied by an over-bank turbidite plain, whereas levees in the Yamato Basin are characterized by prominent sediment waves. Toyama Fan consists of a channel–levee complex with sediment waves in the upstream part and of lobes at the channel end.

The course and morphology of the channel–fan system are primarily controlled by basin morphology. Thick, sheet-like sediments, deposited from ponded turbidity currents, have accumulated in the narrow, elongate Toyama Trough, whereas extensive levees and the Toyama Fan have formed in the more open basins. Distribution of sediments and consequent morphology of the channel–levee complexes are also controlled by Coriolis and centrifugal forces. Preferential development of the levees on the right-hand side is attributed to Coriolis-force tilt effects in the Northern Hemisphere. Centrifugal forces at the meander loops or bends of the channel result in flow stripping, causing levees to build on the outer bends. The distribution, form and orientation of sediment waves are consistent with the extent and direction of inferred spill-over turbidity currents, and with consequent levee growth. Fluvial-like features such as meanders, terraces, levee slumps and a crevasse splay are developed along the TDSC. Unlike other submarine channels, sinuosity seems to be controlled by bedrock structures rather than by valley slopes. Channel avulsion has not been recorded in the TDSC system. Active clastic deposition on the uppermost lobe during the past 1 ka suggests recent active sediment transportation through the channel. Sediment transportation, however, may have ceased during the Holocene in the cut- and fill-tributaries developed in the Quaternary succession on the slope to the trough, where a relatively wide shelf separates canyons from rivers in the eastern margin of the drainage area.

Keywords: deep-sea sedimentation; channel geometry; levees; submarine fan; turbidites; Japan Sea

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1. Introduction

Deep-sea channels are long conduits which traverse the ocean floor and feed into the abyssal transport system (Carter, 1988). Such channels are classified as those within marginal rifts, and those within aborted ocean basins, margin-parallel channels and relict channels according to their tectonic setting (Carter, 1988). Our understanding of those within marginal rifts remains limited by a paucity of examples described in the literature. This paper describes a deep-sea channel within a marginal rift from the central Japan Sea.

The Toyama Deep-Sea Channel (TDSC), which extends for 750 km in the central Japan Sea, is one of the most prominent submarine channels in the West Pacific (Fig. 1). The length of the TDSC is comparable to the Nankai Deep-Sea Channel (700 km long) on the Pacific side of the Japan Arc (Taira and Niitsuma, 1986; Shimamura, 1989) (Fig. 1).

The TDSC starts from the Toyama Bay and extends northwards through the Toyama Trough and the Yamato Basin to the Japan Basin (Fig. 2). Iwabuchi (1968) first recognized the meandering channel with its prominent levees in the Toyama Trough and Yamato Basin. Ludwig et al. (1975) described this channel as a depositional–erosional feature and noticed asymmetric levees based on seismic reflection profiles. Turbiditic sediments interpreted as both levee and channel facies were recovered during drilling of the Yamato Basin in

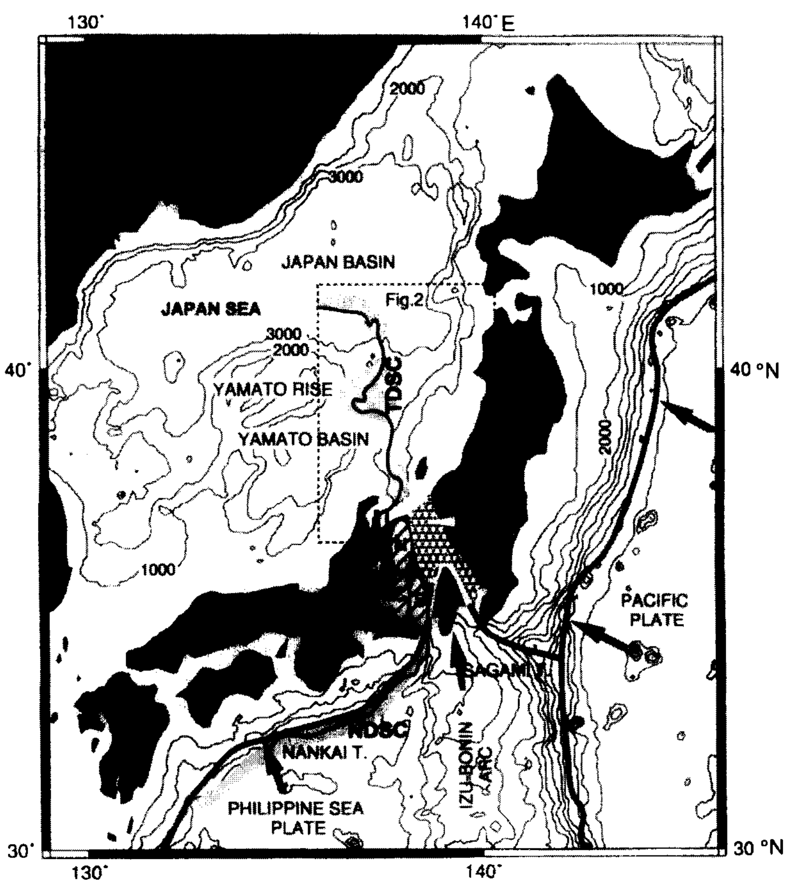

Fig. 1. Bathymetry and tectonic setting around the Japan Arc. *TDSC* = Toyama Deep-Sea Channel; *NDSC* = Nankai Deep-Sea Channel (Shimamura, 1989). Dotted area = turbidite distribution. *N*, *C* and *S* in the Japan Alps = Northern, Central and Southern Alps, respectively. Solid arrows = directions of plate motions. Bathymetric contours in metres.

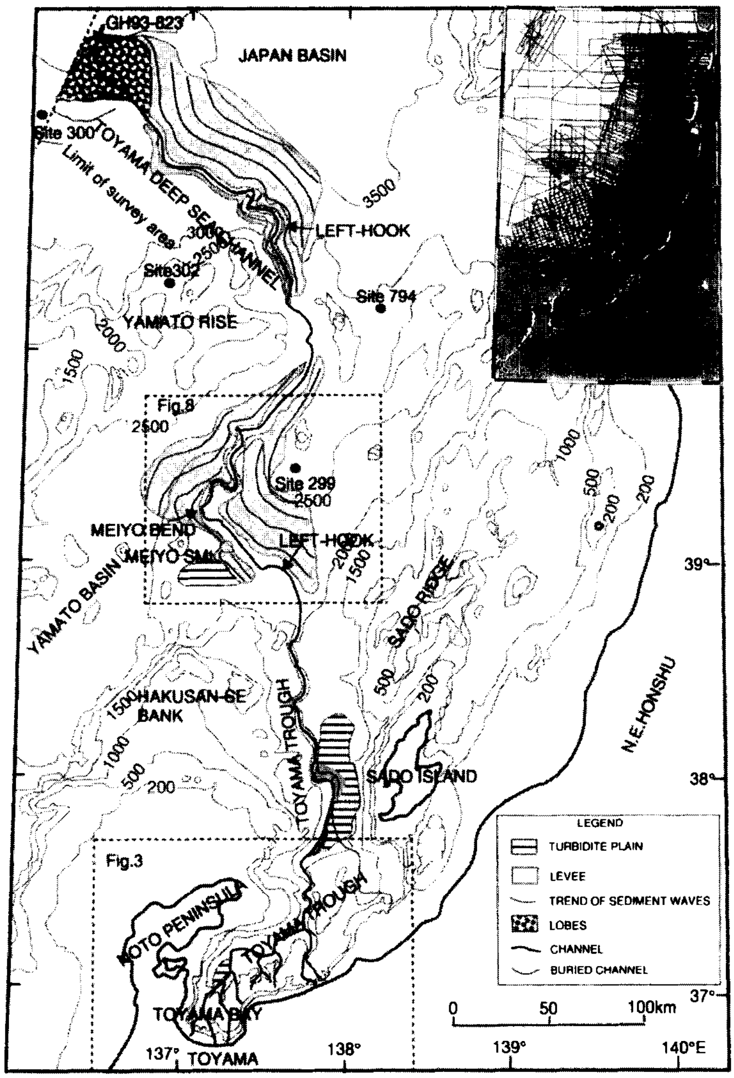

Fig. 2. Bathymetry of the southeastern Japan Sea and distribution of sediments along the TDSC. Bathymetric contours in metres. Positions of gravity core GH93-823, DSDP Sites 299, 300, 302 and ODP Site 794 are shown by solid circles. Inset shows track lines of seismic profiles.

DSDP Leg 31 (Karig et al., 1975). Based on analysis of the DSDP Site 299 cores (Fig. 2), Klein (1985) reported that the frequency of turbidites in the Yamato Basin has increased with the increased uplift rate of the Japan Alps since the Late Miocene or Pliocene. Whereas the entire course and physiography of the TDSC system have never been described synoptically by previous workers, this paper records, for the first time, the course and the morphology of the entire TDSC system based on available 3.5-kHz and air-gun reflection profiles, and sediment cores.

2. Geologic setting

The Japan Sea is a composite back-arc basin formed in the Early Miocene by continental rifting, accompanied by clockwise and counter-clockwise rotations of northeast and southwest Japan, respectively (Otofuji et al., 1985). The Japan Sea is divided by the continental fragment of the Yamato Rise (Tamaki, 1988) into two large basins, namely the Japan Basin in the north and the Yamato Basin in the south (Fig. 1). Many small-scale rifts (cf. Sado Ridge; Fig. 2) were formed along the eastern margin of the Japan Sea during the rifting stage (Suzuki, 1989: Okamura et al., 1995b). The eastern margin of the Japan Sea has been deformed under E–W compression, accompanied by basin inversion since the Pliocene (Okamura et al., 1995b). In contrast to the deformed marginal rifts, the Japan and Yamato basins have only subsided slightly since the Middle Miocene as shown by the subsidence curve obtained from ODP Site 794 (Fig. 2) at the junction of the Japan and Yamato basins (Ingle, 1992).

The Toyama Trough, between Sado Island and Noto Peninsula, is a N–S-trending, Early Miocene, large-scale rift system about 200 km long and 20–50 km wide (Okamura et al., 1995b), lying oblique to the Japan Arc and Sado Ridge (Fig. 2). The trough is accompanied by many reverse faults and folds trending both N–S and NE–SW (Okamura et al., 1994, 1995a; Ishida, 1996). Sediment thickness reaches 2.5–4.5 s (two-way travel time) in the Toyama Trough (Suzuki, 1989), but varies from 0.5 to 1.5 s in the Yamato Basin and from 1 to 2.2 s in the Japan Basin (Ludwig et al., 1975; Tamaki, 1988). Most parts of the Toyama Trough and Toyama Bay show low Bouguer anomalies consistent with thick sedimentary deposits (Komazawa et al., 1992; Okamura et al., 1995a). The southern landward extension of the Toyama Trough is the Fossa Magna of Early Miocene age, another large rift system in central Japan (Kato, 1992) (Fig. 1). Central Japan is an arc–arc collision zone between the Honshu and the Izu–Bonin arcs (Fig. 1) (Matsuda, 1978), with consequent rapid uplift of the Japan Alps, especially during the Quaternary (Research Group for Quaternary Tectonic Map, 1968; Sugi et al., 1983). The Japan Alps consists of the Northern, the Central and the Southern Alps, each of which rises 3000 m above sea-level (Fig. 1). During the Quaternary, an increase in Alpine uplift has resulted in high sediment delivery (Yoshikawa, 1974) and consequent increase in the rate of sediment supply to the TDSC system (Klein, 1985).

3. Data sets

The seismic reflection tracklines of the profiles used in this study are shown in Fig. 2 together with the locations of the key gravity core GH93-823, DSDP Leg 31 Sites and ODP Site 794. These tracklines almost cover the entire reach of the channel, although the lower fan in the Japan Basin is not covered by the available survey. Channel position and limits of the fan (Fig. 2) are based on 3.5-kHz and single-channel, two 120-inch^3 air-gun seismic-reflection profiles together with bathymetric data. Navigation was conducted by GPS. These data were obtained by the Geological Survey of Japan during the GH78-2, 88-2, 88-4, 89-2, 89-4, 90, 91, 92, 93 cruises of the R/V *Hakurei Maru*.

4. Channel course and morphology

Rivers draining the Northern Alps carry sediment for several tens of kilometres to the coast (Fig. 3). These rivers form alluvial fans and fan deltas at the foot of the mountains and construct the narrow Toyama coastal plain that is about 50 km long and 20 km wide (Fig. 3). The southern landward margins of the Toyama Bay and Toyama Trough are steep (>15°), high (up to 1000 m relief), and are fringed by a very narrow (<4 km wide) shelf or have no shelf. The marginal slopes are incised by many canyons that head toward the rivers and reach their mouths (Fig. 3). A 3.5-kHz seismic profile across the shelf (Fig. 4A) shows that the incised canyons are highly reflective, suggesting recent sediment transport through the canyons. An exception is the eastern margin of the drainage area where a relatively wide shelf (16–20 km wide) separates the rivers and canyons (Fig. 3). The canyons coalesce into the TDSC incised into the floor of southern Toyama Trough (Fig. 3).

The TDSC exhibits both erosional and depositional–erosional features. Channel profiles in the

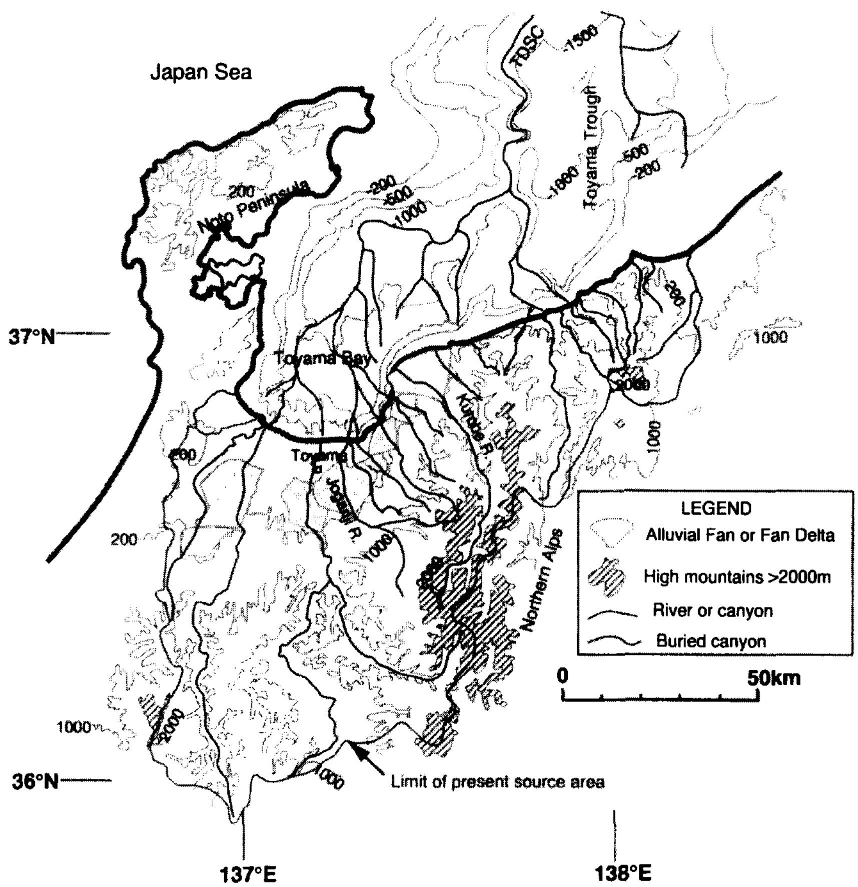

Fig. 3. Topographic map of the source area of the TDSC showing bathymetry of the Toyama Bay and the Toyama Trough. Contours in metres. Most of the rivers are directly connected with submarine canyons, while buried canyons at the eastern margin of the Toyama Trough are intercepted at present by shelf deposition.

basins and troughs are either U-shaped or V-shaped with reliefs of 150 to 300 m (Fig. 4). The channel has a sharp V-shaped profile at three places, where it crosses structural highs, east of the Noto Peninsula (Fig. 4B), at the northern end of the Toyama Trough (Fig. 4D), and at the eastern flank of the Yamato Rise (Fig. 4G). Channel relief attains 600 m in these areas and no distinct levees are formed on either bank of the channel. Longitudinal profiles of channel and levee depth (Fig. 5) show that the channel is more incised at the two structural highs at the southern and the northern end of the Toyama Trough than in other reaches. Longitudinal profiles of the gradient (Fig. 5) reveal a slightly higher gradient (0.005–0.01) in the southern Toyama Trough and at the eastern flank of the Yamato Rise than in other parts of the channel (<0.005).

Where the TDSC enters the central Toyama Trough, the Yamato Basin and the Japan Basin, either channel–levee complexes or a terminal deep-sea fan are formed (Fig. 2). Distinct levees, built by overspilling turbidity currents (Nakajima et al., 1996), have developed on both sides of the channel in the Yamato and Japan basins but only on the right banks in the central Toyama Trough. The profiles across major basins show asymmetric channel cross-sections, with the right levee (looking down channel) being higher (up to 90 m) than the left levee (Figs. 4 and 5). The profile (Fig. 4F) along the major 90° clockwise 'Meiyo Bend', named after a nearby seamount in the Yamato

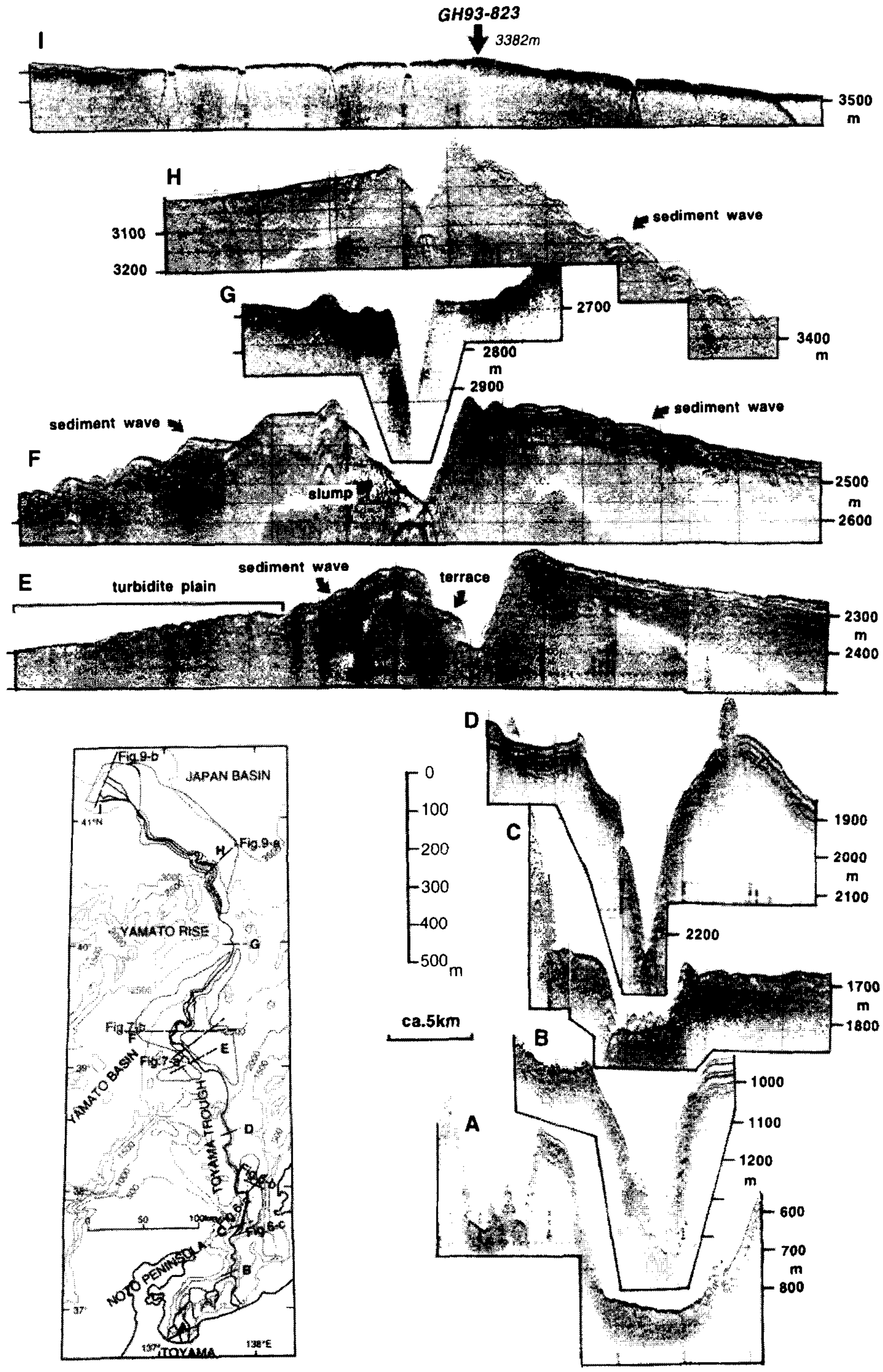

Fig. 4. Selected 3.5-kHz profiles across the TDSC. For location see index map. The log of key gravity core GH93-823 in (I) is shown in Fig. 9b.

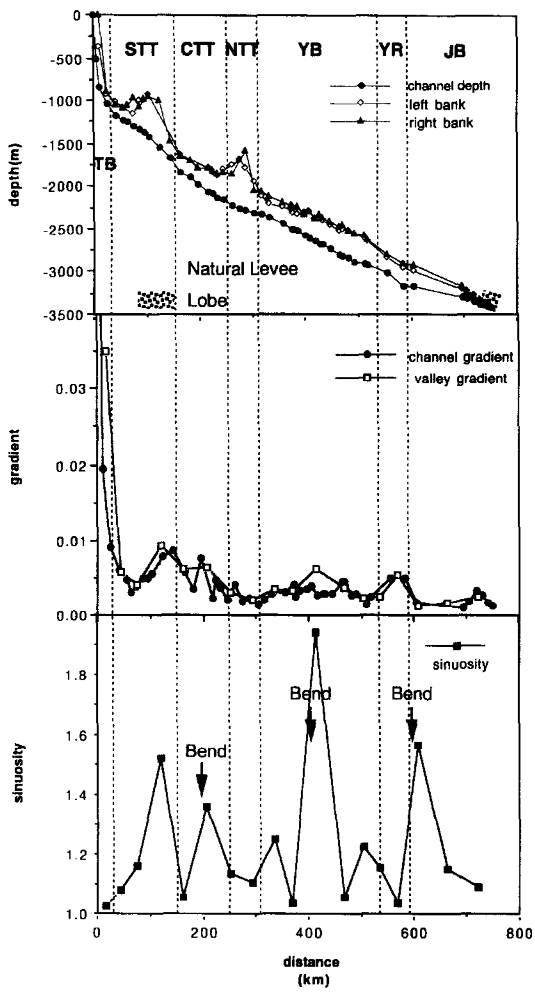

Fig. 5. Down-channel plots of a channel depth, levee depth, channel gradient, valley gradient and a sinuosity of the channel axis. Down-channel distances measured from the canyon head at the Joganji River mouth (Fig. 3). The valley gradient is the average gradient measured along the straight reaches of the channel, each of which is about 40 km long. Result based on 3.5-kHz profiles of the tracklines shown in Fig. 2. *TB*=Toyama Bay, *STT*=Southern Toyama Trough, *CTT*=Central Toyama Trough, *NTT*=Northern Toyama Trough, *YB*=Yamato Basin, *YR*=Yamato Rise, *JB*=Japan Basin.

Basin (Fig. 2) is, however, almost symmetric. The channel displays left hooks where it enters into the Yamato and Japan basins (Fig. 2). Channel sinuosity (Fig. 5) appears to increase at the three abrupt channel bends and in their lower reaches. Sinuosity also increases at the southern part of the Toyama Trough, where the TDSC crosses the uplift zone between Sado Island and the Noto Peninsula (Kato et al., 1990) (Fig. 3). The channel splits into smaller distributary channels that feed a series of lobes in the central Japan Basin (Figs. 2 and 4I).

5. Channel–levee complexes and the Toyama Fan

5.1. Toyama Trough

The channel–levee complexes in the central Toyama Trough are accompanied by a flat overbank turbidite plain beyond the right-hand levee. The levee itself is small with sediment waves on the right bank (Fig. 4c, Fig. 6a, c). The acoustic facies in 3.5-kHz profiles of the turbidite plain (Fig. 4c) is characterized by relatively strong bottom returns with intermittent sub-bottom reflectors. This acoustic facies is comparable with the echo type IIA of Damuth (1980). Cores recovered from the turbidite plain show many intercalated turbiditic fine-sand layers (Nakajima et al., 1995), suggesting spill-over of turbidity currents from the channel. Seismic reflection profiles (Fig. 6b) of the turbidite plain exhibit continuous and sheet-like internal reflectors.

The levee and sediment waves are especially conspicuous on the right-hand bank of the abrupt counter-clockwise bend of the TDSC, west of Sado Island (Figs. 2 and 6a). Seismic reflection profiles crossing the channel to the north of the bend exhibit a N–S-trending anticline which deflects the channel course, and causes the bend. The acoustically reflective turbidite plain extends northward from this bend (Fig. 2) (Nakajima et al., 1995).

In the profile transverse to the trough, the lower stratified layers dip slightly to the east and are truncated by an active reverse fault at the eastern margin of the trough (Fig. 6b). This profile indicates that the trough is flattened by infilling by younger sediments. It also suggests that the trough is tilting to the east and subsiding due to movement along the reverse fault (Okamura et al., 1995a).

In addition to the TDSC, buried canyons transverse to the upstream part of the turbidite plain are also observed in the air-gun reflection profiles (Fig. 6c). The canyons repeatedly cut and

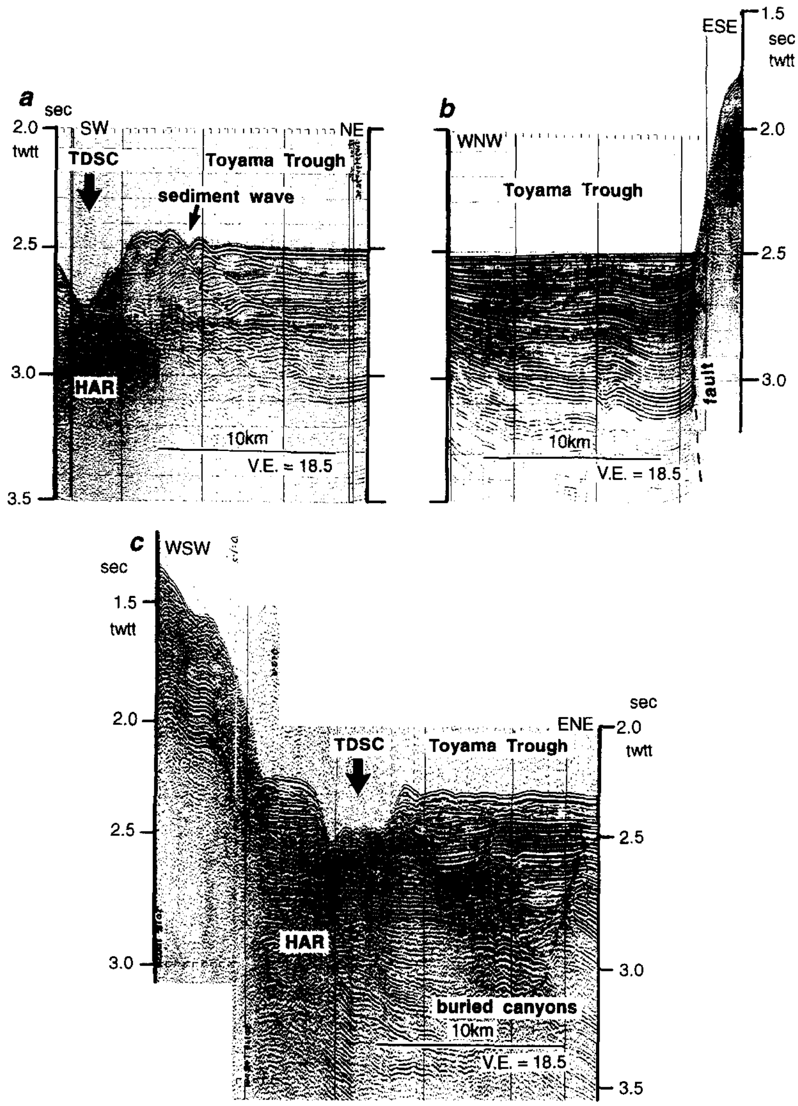

Fig. 6. Single-channel air-gun profiles across the central Toyama Trough (see index map in Fig. 4). (a) Cross-channel profile at the abrupt counter-clockwise bend in the central Toyama Trough, showing small levee with sediment waves overlain by thick sheet-like deposits. (b) Sheet-like layers which slightly dip to the east and are truncated by a reverse fault at the eastern margin of the central Toyama Trough. (c) Profile across the southern Toyama Trough. High-amplitude reflectors (*HAR*) below the TDSC show channel aggradation and migration toward the east. Buried canyons are conspicuous along the eastern side of the TDSC. Note that reflections are less continuous near the buried canyons.

filled in the upper sequence of the trough at several stratigraphic levels and shifted laterally. These canyons continue from the shelf-margin slopes, off the eastern drainage area, through the southeastern part to the central Toyama Trough (Okamura et al., 1994) to eventually coalesce with the TDSC (Figs. 2 and 3). A seismic-reflection profile crossing the TDSC at the junction of the canyons exhibits that the canyons and high-amplitude reflectors (HAR) below the TDSC overlap each other at several stratigraphic levels. Canyon-fill sediments on slopes are usually represented by weak, intermittent reflectors in reflection profiles (Okamura et al., 1994), whereas reflections are continuous in the trough (Fig. 6c). The uppermost canyon on the slope is filled by thick sediments of up to 150 m (Okamura et al., 1994). In contrast, the aggradational HAR below the TDSC (Fig. 6c) suggest that the main channel of the TDSC has been active without any channel abandonment.

5.2. Yamato Basin

The TDSC system in the Yamato Basin is characterized by a large-scale channel–levee complex, accompanied by sediment waves on levee backslopes (Fig. 7). Sediment waves are particularly conspicuous on the right banks, where the TDSC enters the Yamato Basin (Figs. 4e and 7a). However, migrating waves are also conspicuous on the left bank in the Yamato Basin at the Meiyo bend (Figs. 7b and 8). This bend may be a consequence of flow deflection by a seamount (Figs. 7b and 8).

Sediment waves have wavelengths ranging from 0.5 to 3 km and amplitudes ranging from several to 70 m (Fig. 8). The waves migrated upslope in the seismic reflection profiles (Fig. 7), which suggests that sedimentation is more rapid on the upslope limb of the waves than on the downslope limb. They tend to decrease in spacing and amplitude downslope on levee backslopes (Figs. 7 and 8). Wave amplitudes on the outer corners of channel bends are higher than those on the inner corners (Figs. 4f, 6a and 7b). Wave crest lines appear sinuous, but are generally aligned parallel or subparallel to the depth contour lines (Fig. 8). They are, therefore, sub-parallel to the channel in

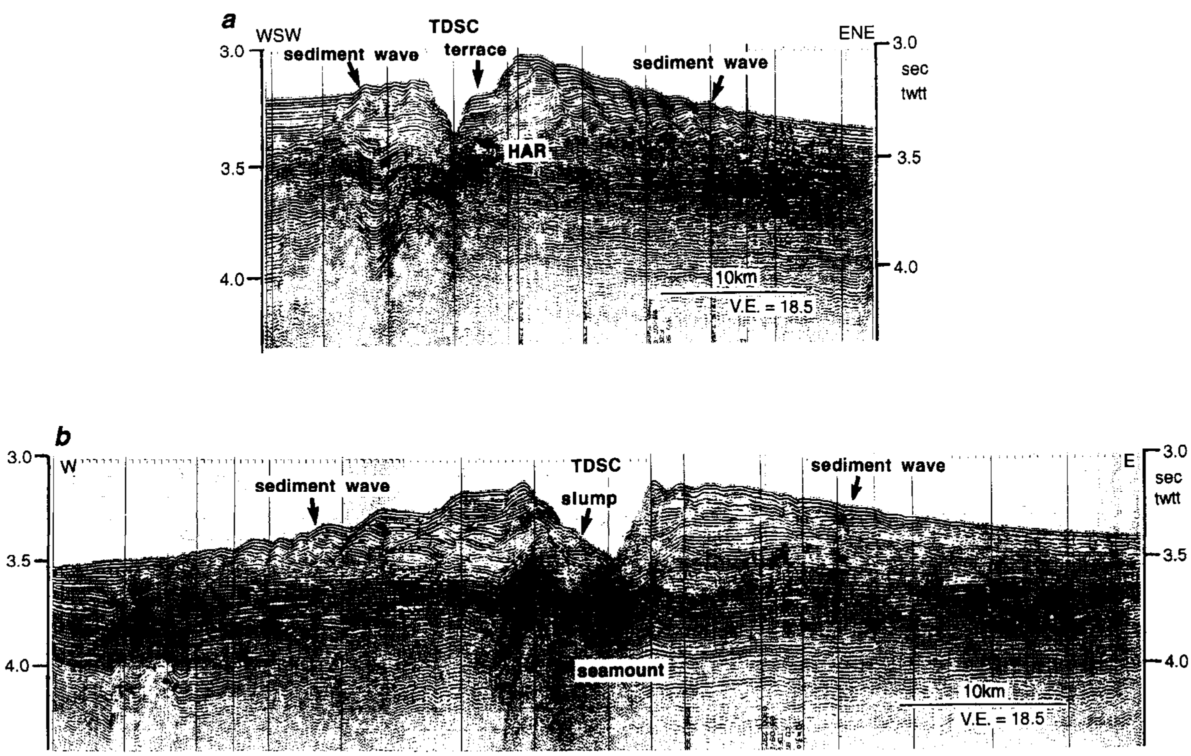

Fig. 7. Single-channel air-gun profiles across the channel in the Yamato Basin (location see Fig. 8). (a) Profile across the TDSC downstream of the left hook point in the Yamato Basin. Note that the right-hand levee is higher and broader than the left-hand levee. Sediment waves are also conspicuous on the right-hand levee. (b) Profile across the TDSC at the Meiyo Bend. Note the submerged seamount below the channel floor. Levees are prominent on both sides of the channel. Sediment waves are higher and show more intense upslope migration on the left-hand levee than on the right-hand levee. An inner levee slump has occurred at the left-hand levee.

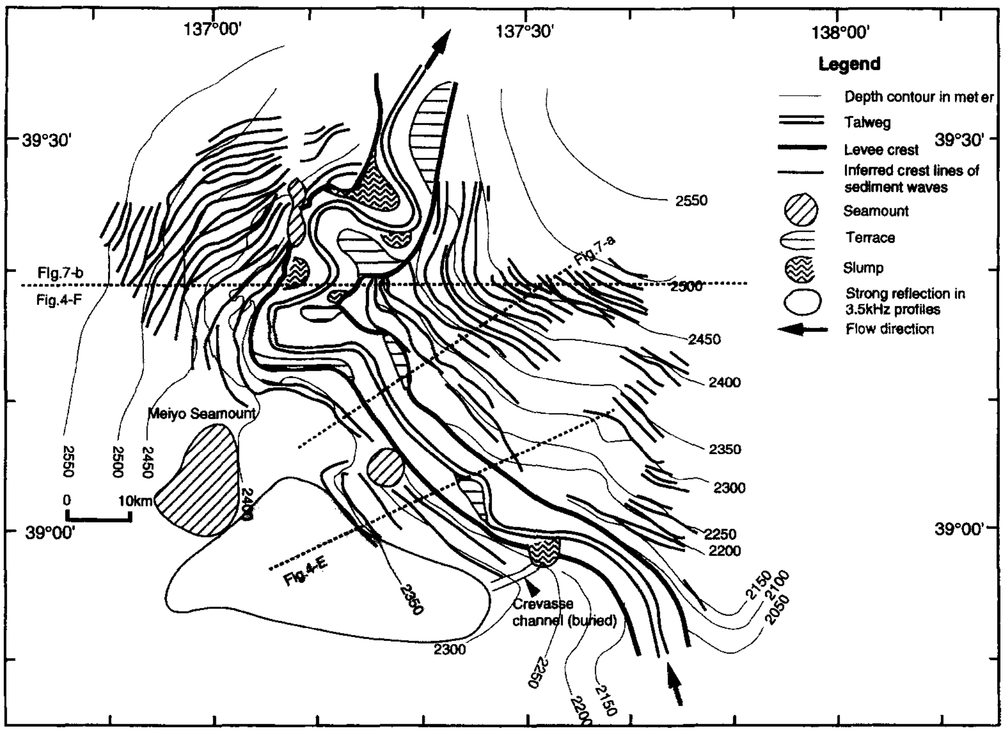

Fig. 8. Detailed map of the channel–levee complex in the Yamato Basin adjacent to the Meiyo Bend, showing characteristic topography of the channel–levee complex and orientation of sediment waves. This map is based on interpretations of the 3.5-kHz seismic profiles.

most cases. Those on the left bank at the Meiyo bend, however, display a convex pattern toward the northwest (almost perpendicular to the channel in the upstream direction) (Fig. 8).

Fluvial-like features, such as terraces and levee slumps, are observed within meander loops of the channel (Figs. 4, 7 and 8). Terraces are usually observed at the inner corners of meander loops (Fig. 8), terrace surfaces being flat or gentle and highly reflective in 3.5-kHz profiles (Fig. 4e). An air-gun profile (Fig. 7a) transverse to the terrace shows continuous, stratified internal reflectors, which pass without interruption into reflectors in the levee and the sediment wave field. High-amplitude reflectors lie at the base of the terrace in the profile. Levee slumps show highly reflective and hyperbolic patterns in the 3.5-kHz profile (Fig. 4f). An air-gun profile across the slump deposit shows inclined internal reflectors which abut against the channel wall and are oblique to the reflectors in the levee (Fig. 7b).

A turbidite plain, with strong bottom returns in 3.5-kHz profiles, is located on the basin plain beyond the left levee close to the left hook point in the Yamato Basin (Figs. 2, 4e and 8). The surface of the turbidite plain shows either smooth or hummocky relief in the 3.5-kHz profile (Fig. 4e). Cores from this turbidite plain are characterized by thicker and coarser turbidite layers than cores from the levee (Nakajima, 1997). Downstream of the left hook point, slumping of the upper part of the left levee and consequent breaching of the upper levee are apparent (Fig. 8). A buried channel connects the breaching point of the levee with the flat turbidite plain (Fig. 8).

5.3. Toyama Fan

The TDSC ends in the southern part of the Japan Basin with the Toyama Fan. Asymmetric large-scale levees with conspicuous sediment waves

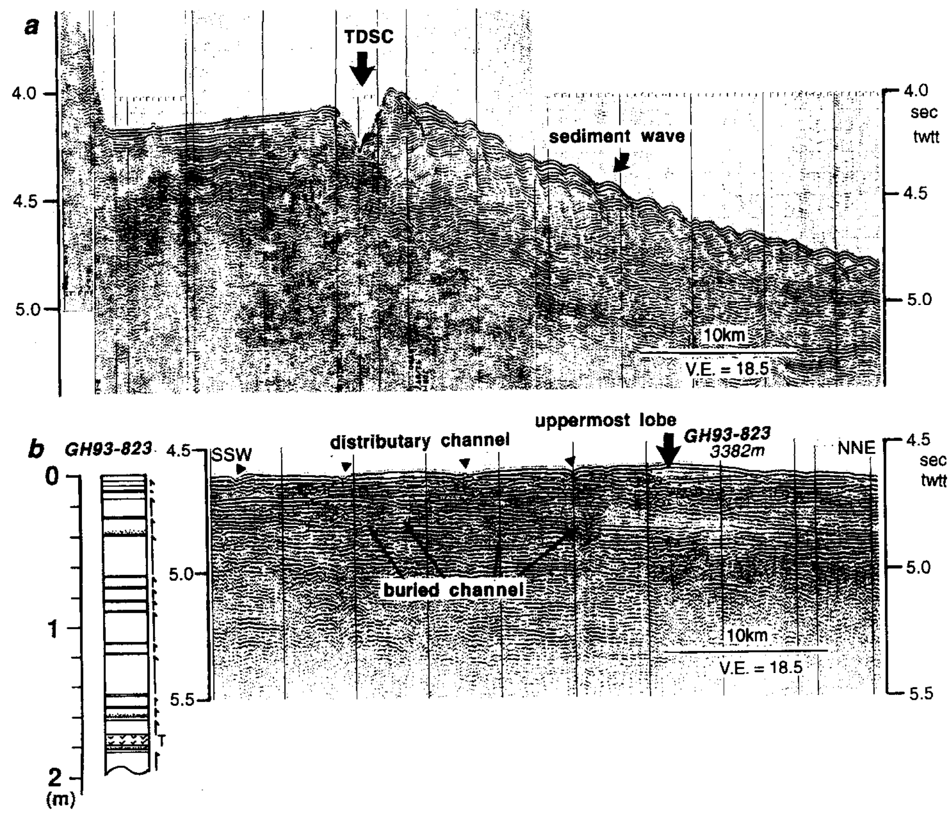

Fig. 9. Single-channel air-gun profiles across the Toyama Fan in the Japan Basin (for location see index map in Fig. 4). (a) Profile across the upstream part of the fan, showing asymmetric large-scale levees with conspicuous sediment waves on the right-hand levee. (b) Profile across the lobes together with the location and log of core GH93-823. Note that shallow distributary channels occur on the uppermost lobe, while buried distributary channels occur on the abandoned lobes. *T* in log of the core represents B-Tm tephra with an age of 1 ka (Machida and Arai, 1992). Arrows in log of the core represent silt turbidite layers.

are developed in the upstream part of the fan (Figs 2, 4h and 9a), whereas the downstream part north of 41°N is composed of lobes (Figs. 2, 4i and 9b). The channel obviously decreases in depth down-channel from a point at about 41°N (Fig. 5) and branches into several shallow (up to 20 m deep) distributary channels on the uppermost lobe (Fig. 2). The surface of the uppermost lobe is almost flat or slightly convex upwards (Fig. 4i, Fig. 9b). In 3.5-kHz profiles, the surface of the uppermost lobe is characterized by indistinct, prolonged bottom echoes with no sub-bottom reflectors (echo type IIB of Damuth (1980)) (Fig. 4i). Lobes are composed of a stack of lenticular sedimentary bodies with shallow channels representing abandoned former lobes with buried distributary channels (Fig. 9b). The uppermost lobe is thickest at the northeastern margin of the lobe where no branch channel incises the lobe surface (Fig. 9b). The key core GH93-823 recovered from the thickest part of the uppermost lobe has fourteen turbidite layers intercalated with hemipelagic mud above the B-Tm tephra layer (Machida and Arai, 1992) with an age of 1 ka (Fig. 9b). These turbidites are silt turbidites with their median grain sizes ranging from 5.5 to 30.6 μm, while those in hemipelagic intervals range from 5.5 to 6.6 μm. Another core besides a distributary channel, however, intercalates medium sand layers of up to 20 cm thick (Nakajima, 1997). Shallow distributary channels disappear at the northwest end of the survey area (Fig. 2).

6. Discussion

6.1. Basin morphology as a primary control on TDSC morphology

Basin morphology primarily controls the course and morphology of the TDSC, and sediment distribution. The TDSC follows basin lows and forms channel–levee complexes and a deep-sea fan, which are separated by intrabasin highs (e.g. Yamato Rise).

The difference of morphostructures between the Toyama Trough and the two basins has strongly affected the channel morphology. The narrow, elongate Toyama Trough allowed accumulation of thick sediments (Suzuki, 1989) supplied by the channel. Subsidence of the trough may have also favoured accumulation. Consequent features of sediments include an aggradational channel, poorly developed levees and sheet-like thick sediments due to ponding or reflection of turbidity currents within the narrow, elongate trough (Fig. 6) (cf. Normark and Piper, 1991). In contrast, large-scale channel–levee complexes have been built up in the more open Yamato and Japan basins with less aggradational channels (Figs. 7 and 9). These settings and features of the TDSC system are similar to those of the rifted-margin channel systems such as the Valencia Valley–Fan (Maldonado et al., 1985; O'Connell et al., 1985) and the Bounty Channel system (Carter and Carter, 1987, 1996). The TDSC system as well as these rifted-margin channel systems have abyssal fans, detached from the continental slope through the narrow, elongate troughs. It displays, however, a more complex channel system than the Valencia and the Bounty Channel systems whose fans are proximal to the trough-mouths. The TDSC traverses about 450 km after it exits from the Toyama Trough. In the Yamato and Japan basins the TDSC is accompanied by elongate channel–levee complexes and a terminal deep-sea fan, respectively, which are separated by complex structures of the composite back-arc basin.

Channel morphology itself also changes as it transits a string of basins and intrabasin highs. The channel exhibits leveed, aggradational features as it crosses basins, whereas it exhibits V-shaped erosional features as it crosses intrabasin highs. A similar example from the northwest slope of the Gulf of Mexico was reported by Satterfield and Behrens (1990). They classified a late Quaternary canyon and channel system into two types of units: (1) leveed, aggradational, intrabasinal channels, and (2) erosional interbasinal canyons. The TDSC is a larger example of such channels because it traverses back-arc basins as well as a rifted trough, whereas the canyon and channel system on the northwest Gulf of Mexico continental slope is restricted to slope basins.

6.2. Effects of Coriolis and centrifugal forces

Both Coriolis and centrifugal forces also influence channel and levee morphologies. As formerly noted by Ludwig et al. (1975), the right-hand bank levees are usually higher and broader than the left-hand bank levees (Figs. 4 and 5), this being the well-known Coriolis-force effect in the Northern Hemisphere (Menard, 1955; Komar, 1969). In contrast, the almost symmetric levee development at the Meiyo Bend probably results from the balance between the Coriolis and centrifugal forces (Komar, 1969). Flow stripping (Piper and Normark, 1983) due to increased centrifugal force at the channel bends is responsible for the preferential distribution of the spill-over turbidites at the outer corners of bends. Structure may, however, also influence the size of adjacent levees (Carter and Carter, 1988). A seamount at the Meiyo Bend (Figa. 7b and 8) may also attribute to a relatively higher levee at the outer corner of the bend. Sediment type may also influence the size of levees. In the central Toyama Trough, the channel is closer to the source and appears less incised than in the Yamato and Japan basins (Fig. 4c). These settings encourage overspill of coarser sediment in the trough, which results in smaller levees. Cores from the Toyama Trough certainly have intercalated fine-sand layers (Nakajima et al., 1995) which are coarser than silt turbidites from levees in the Yamato Basin (Nakajima et al., 1996).

Distribution, form and orientation of sediment waves on levees (Figs. 7 and 8) may have a close relationship with spill-over turbidity currents which are, in turn, influenced by the Coriolis and centrifugal forces. These waves are developed only on levee backslopes with a gradient of 0.007–0.025 (Nakajima, 1997) and migrate upslope (Fig. 7). Sediment cores recovered from wave fields on the Yamato Basin levees display numerous thin silt turbidites intercalated with hemipelagic mud (Nakajima et al., 1996). These facts suggest that these waves were formed by turbidity currents under supercritical flow conditions (Normark et al., 1980; Piper and Savoye, 1993). The distribution and orientation of sediment waves (Fig. 8) may therefore indicate the flow direction and extent of spill-over turbidity currents (Hagen et al., 1994). Widely distributed waves on the right bank levee, upstream of the Meiyo Bend, may reflect preferential spill-over of flow at the right bank due to combined effect of Coriolis and centrifugal forces. The waves on the left bank at the Meiyo Bend are oriented convex toward the northwest, which suggests flow stripping as a result of the centrifugal force. They display intense upslope migration on the left bank of the bend (Fig. 7b), which suggests rapid sedimentation on the upslope limb of the wave, this being a possible consequence of flow stripping.

6.3. *Fluvial-like features*

The TDSC shows meanders like some other submarine channels as well as rivers. A plot of channel sinuosity vs. valley slope for other submarine channels shows that sinuosity increases with increasing valley slope in a manner similar to that observed in rivers (Flood and Damuth, 1987; Clark et al., 1992). Unlike other passive margin channels, the TDSC is deflected by structures such as seamounts in the Yamato Basin and anticlines in the Toyama Trough. Consequently, the channel sinuosity seems to be controlled by structures (bends) rather than by valley slopes although valley slope still plays a minor role in affecting sinuosity (Fig. 5). The Hikurangi Channel, east of New Zealand (Lewis, 1994), which is deflected by a seamount and a fan drift, is another example of such channels influenced by bedrock structures.

Terraces are common features in other meandering channels. The origin of terraces has been attributed to erosion (O'Connell et al., 1991), entrenchment by vertical tectonics (Hagen et al., 1994), varying volumes of turbidity currents (Klaucke and Hesse, 1996), modification of the floor of an abandoned channel (Soh et al., 1990) and the infilling of a small distributary channel (Carter and Carter, 1996). An air-gun profile (Fig. 7a) across a terrace in the TDSC, however, suggests a depositional origin. High-amplitude reflectors at the base of the terrace (Fig. 7a) indicate that (1) the terrace has been formed by aggradation of deposits on the former talweg as the talweg has migrated laterally, or (2) the channel floor has been wider when the HAR developed, followed by partial infilling of the channel as flow volumes decreased. Levee slumps are also common features in other meandering submarine canyons (Stubblefield et al., 1982; Liu et al., 1993; Hagen et al., 1994; Klaucke and Hesse, 1996). Levee slumps within the channel around the meander bends (Fig. 8) may result from cut-bank erosion (Hagen et al., 1994).

The turbidite plain beyond the left levee close to the left hook point in the Yamato Basin (Figs. 2, 4E and 8) is connected with the breaching point of the left levee by a buried channel. At this breaching point, turbidity currents may easily spill over the levee to form a crevasse splay (Lonsdale and Hollister, 1979; Hagen et al., 1994) (Fig. 8). The turbidite plain in the Yamato Basin is therefore interpreted as a crevasse splay sheet. True crevasses may be the beginning of channel avulsion (Lonsdale and Hollister, 1979). Channel avulsion is a common feature in meandering channels like the Amazon (Pirmez and Flood, 1995) and Mississippi channels (Weimer, 1991). The TDSC, however, does not show any channel avulsion based on air-gun profiles (Figs. 6, 7 and 9a). The highly stable channel system may be attributed to the fact that its channel floor lies below the base level of the surrounding floodplains (Fig. 7) (cf. Northwest Atlantic Mid-Ocean Channel; Hesse, 1989; Klaucke and Hesse, 1996).

6.4. *Recent active clastic transportation*

An active clastic deposition on the uppermost lobe during the last 1 ka clearly shows that the supply of coarse sediment and fan growth have not been restricted to sea-level lowstands as predicted in the models of Mutti (1985) and Posamentier et al. (1991). This may result from the active clastic supply into the TDSC system from the rivers through incised canyons on a very narrow shelf even during sea-level highstands. Continuous erosion and deposition by turbidity currents throughout lowstands and highstands of sea-level may result in the main channel being permanently active without any channel abandonment (Figs. 6, 7 and 9a). Based on the tephra age in core GH93-823, a turbidite was deposited, on average, once every 70 years on the uppermost lobe. Turbidity currents of such high frequency may have originated from hyperpycnal flows during floods or failures on fan delta frontal slopes as well as less frequent seismic triggering (Normark and Piper, 1991). Certainly average river sediment volume concentration during floods of the Joganji River (Fig. 3) was estimated at 0.01, based on reservoir deposits and total discharge during floods (Kanda, 1952). This value corresponds to a density of 1.03 which is nearly equal to seawater density. The density of the sediment-laden flow during peak discharges of major floods may, therefore, be sufficient to overcome the buoyancy effect of seawater and to ignite hyperpycnal flows. Evidence for sediment failures on a fan delta frontal slope at the Kurobe River mouth was also reported by Uda et al. (1989), based on topographic surveys.

In contrast to the main channel course, sediment transport has ceased in cut- and fill-canyons (buried tributaries of the TDSC) in the southeastern Toyama Trough. Similar cut- and fill-sequences are reported from the Pleistocene sections on continental slopes (Piper and Normark, 1989; Savoye et al., 1993) and are interpreted to result from erosion during the repeated lowstands of sea-level in the Quaternary. The relatively wide (16–20 km) shelf at the southeastern margin of the Toyama Trough may allow these canyons to be connected by rivers during lowstands and to be separated from rivers during highstands. The uppermost canyon can be traced to the shelf edge (ca. 150 m in depth) and heads toward a present river mouth (Fig. 3). The canyon, therefore, may have been connected with rivers during the maximum fall of the last lowstand. Assuming that the uppermost canyon was cut during the last lowstand, then the thick canyon-fill sediments up to 150 m thick reflect the rapid infill of the canyons after the last glacial maximum (ca. 18 ka BP) (Okamura et al., 1994). Canyon-fill sediments usually show weak, intermittent reflectors in air-gun reflection profiles on slopes (Okamura et al., 1994), which suggests that canyon-fill sediments consist of mass-flow deposits at least on slopes. The southeastern part of the Toyama Trough is uniformly draped by hemipelagic sediments at a sedimentation rate of 33–41 cm/ka during the Holocene (Katayama et al., 1994). The canyon-fill sediments are therefore likely mass-flow deposits derived from shelf margin slumps as a result of shoreface erosion during the transgression. These mass-flow deposits could probably remain in the canyons because turbidity currents of hyperpycnal flows origin, which will flush out the canyon floor, ceased as the sea-level rose.

7. Conclusions

The TDSC system is one of the most prominent deep-sea channel systems in rifted-margins (cf. the Valencia and Bounty Channel systems), whose course and morphology have been strongly controlled by basin morphology. The channel transports sediments from the active uplifting Japan Alps through the narrow, elongate Toyama Trough in the rifted-margin into the open, composite backarc Japan and Yamato basins.

Sediment distribution and fan morphology are controlled by the Coriolis force which promotes higher levees on the right side and by the centrifugal force which accentuates levee growth at the outer corner of the channel bend through flow stripping. The distribution, form and orientation of sediment waves are consistent with levee growth which is controlled by turbidity currents overspilling the channel. The distribution and characters of waves therefore can predict the amounts and directions of the spill-over flows.

Fluvial-like features such as meanders, terraces, levee slumps and crevasse splays are observable in the TDSC. Unlike other submarine channels, the sinuosity seems to be controlled by bedrock structures rather than by valley slopes. Channel avulsion has not been observed in the TDSC system probably because the channel floor lies below the base level of the surrounding floodplains.

Active deposition on the terminal lobe occurs because the narrow shelf in Toyama Bay allows clastic transport through the channel even during sea-level highstands. Transport, however, ceased during the Holocene in the cut- and fill-canyons developed in the Quaternary succession on the slope to the trough where the relatively wide shelf separates canyons from rivers in the eastern margin of the drainage area.

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