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Bulletin 2216

U.S. Department of the Interior
U.S. Geological Survey

U.S. Department of the Interior
Gale A. Norton, Secretary

U.S. Geological Survey
Charles G. Groat, Director

U.S. Geological Survey, Reston, Virginia: 2003

U.S. Geological Survey Information Services
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Published in the Western Region, Menlo Park, California
Manuscript approved for publication, September 26, 2003
Text edited by Peter H. Stauffer
Production and design by Susan Mayfield

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By Jane A. Reid[1] and William R. Normark[2]

Abstract

Turbidity-current overflow from Cascadia Channel near its western exit from the Blanco Fracture Zone has formed the Tufts submarine fan, which extends more than 350 km south on the Pacific Plate to the Mendocino Fracture Zone. For this study, available 3.5-kHz high-resolution and airgun seismic-reflection data, long-range side-scan sonar images, and sediment core data are used to define the growth pattern of the fan. Tufts fan deposits have smoothed and filled in the linear ridge-and-valley relief over an area exceeding 23,000 km^2 on the west flank of the Gorda Ridge. The southernmost part of the fan is represented by a thick (as much as 500 m) sequence of turbidite deposits ponded along more than 100 km of the northern flank of the Mendocino Fracture Zone. Growth of the Tufts fan now permits turbidity-current overflow from Cascadia Channel to reach the Escanaba Trough, a deep rift valley along the southern axis of the Gorda Ridge.

Scientific drilling during both the Deep Sea Drilling Project (DSDP) and the Ocean Drilling Program (ODP) provided evidence that the 500-m-thick sediment fill of Escanaba Trough is dominantly sandy turbidites. Radiocarbon dating of the sediment at ODP Site 1037 showed that deposition of most of the upper 120 m of fill was coincident with Lake Missoula floods and that the provenance of the fill is from the eastern Columbia River drainage basin. The Lake Missoula flood discharge with its entrained sediment continued flowing downslope upon reaching the ocean as hyperpycnally generated turbidity currents. These huge turbidity currents followed the Cascadia Channel to reach the Pacific Plate, where overbank flow provided a significant volume of sediment on Tufts fan and in Escanaba Trough. Tufts fan and Tufts Abyssal Plain to the west probably received turbidite sediment from the Cascadia margin during much of the Pleistocene.

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Introduction

Most modern submarine fans receive sediment as a result of a direct connection to an adjacent submarine canyon or large river delta and thus are found immediately adjacent to continental areas (for example, Bouma and others, 1985). The Tufts fan, in contrast, has formed on the Pacific Plate some 400 km off the Oregon and northern California coast and is separated from the North American continent by the Gorda Ridge, a high-relief, oceanic spreading center (fig. 1). The Tufts fan receives sediment from the Cascadia deep-sea channel, which itself is atypical of submarine turbidite pathways. The Cascadia Channel reaches the Pacific Plate via a narrow trough in the Blanco Fracture Zone and continues west for more than 1,000 km (figs. 1, 2; see Hurley, 1964; Griggs and Kulm, 1970a; Embley, 1985; DeCharon, 1986).

The character of the sediment transported through and deposited in Cascadia Channel is generally known from samples obtained mostly on the eastern side of the oceanic ridge system (Duncan and others, 1970; Duncan and Kulm, 1970; Griggs and Kulm, 1970b, 1973). One study (Griggs and others, 1970) specifically suggested, however, that sediment from the late Pleistocene floods from glacial Lake Missoula reached the Pacific Plate through Cascadia Channel.

Escanaba Trough, the turbidite-covered southernmost segment of the Gorda Ridge axial valley, lies 300 km to the south of Cascadia Channel and just north of the Mendocino Fracture Zone (fig. 1). Sediment recovered at Deep Sea Drilling Program (DSDP) Site 35 within Escanaba Trough indicated that the upper few hundred meters of this sediment fill probably came from the Columbia River drainage area (Shipboard Scientific Party, 1970; Vallier, 1970; Vallier and others, 1973; Zuffa and others, 1997). Later drilling during Ocean Drilling Program (ODP) Leg 169 provided a continuously cored section to basaltic basement at more than 500 m subbottom (Shipboard Scientific Party, 1998). Zuffa and others (2000) determined that the bulk of the fill of Escanaba Trough recovered at ODP Site 1037 is from the Columbia River and not the adjacent California margin (fig. 1). Zuffa and others (2000) suggested that the Lake Missoula floods generated turbidity currents as a result of hyperpycnal flow upon reaching the ocean because of the tremendous amount of sediment carried in the floods (see Mulder and Syvitski, 1995). These workers further suggested that the sediment must have reached Escanaba Trough from the Pacific Plate because an enormous submarine slide that occurred about 110 ka, the Heceta slide, blocked southward transport of sediment along the base of the continental slope south of central Oregon (fig. 1; Goldfinger and others, 2000).

Evidence for the latest Pleistocene (that is, glacial Lake Missoula) catastrophic floods in the northwestern United States and southwestern Canada is abundant (see, for example, Bretz and others, 1956; Atwater, 1986; Baker, 1973; Baker and Bunker, 1985; Shaw and others, 1999; Waitt, 1980, 1985). On the other hand, the fate of these flood discharges after reaching the mouth of the Columbia River has remained largely undefined. The purpose of this study is to review the development of the informally named Tufts fan and evaluate the role of that fan in providing a Pacific Plate pathway for the glacial Lake Missoula flood deposits that reached Escanaba Trough.

Data

The Tufts fan study is primarily based on archive data obtained during the 1980s as part of the U.S. Geological Survey (USGS) sea-floor hydrothermal mineral project and surveys of the U.S. Exclusive Economic Zone (EEZ). Much of the fan area was surveyed to the limit of the 200-nautical-mile (370 km) EEZ during the GLORIA (Geological Long Range Inclined ASDIC) surveys of 1984 (EEZSCAN 84 Scientific Staff, 1986). In addition to the GLORIA side-looking sonar image of the sea floor, the surveys also obtained airgun seismic-reflection profiles and high-resolution 3.5-kHz profiles along regularly spaced, east-west tracklines (fig. 2*A*). A multichannel seismic-reflection survey of the southern Juan de Fuca and southern Gorda Ridges also obtained 3.5-kHz seismic-reflection profiles. Vessel transits to and from the southern Juan de Fuca Ridge in support of the USGS hydrothermal mineral program obtained only 3.5 kHz profiles. These tracklines form a narrow fan-shaped spread with the apex just north of the study area for this paper (fig. 2*A*); the higher speed during these transit legs resulted in large vertical exaggeration in these profiles.

More than 4,000 line kilometers of seismic-reflection data from nine expeditions conducted between 1980 and 1985 were available for this study, with position control for all cruises based on transit satellite data. A limited number of sediment-core samples from around the area of Tufts fan were obtained during earlier studies by Oregon State University researchers, and these confirm widespread deposition of terrigenous sediment of latest Pleistocene age on the west flank of the Gorda Ridge (fig. 2*A*). The significance for understanding the development of Tufts fan is provided by USGS-collected, unpublished deep-tow 4.5-kHz profiles acquired in support of ODP Leg 169 and subsequent drilling at Site 1037 in the Escanaba Trough (Shipboard Scientific Party, 1998). The continuously cored sequence obtained at this site was used to provide ground truth for interpretation of the high-resolution seismic-reflection data (Zuffa and others, 2000). A key sequence of 11 turbidite beds sampled in the upper 63 m of the hole is found throughout Escanaba Trough in water depths greater than 3100 m (figs. 1,3; table 1; Zuffa and others, 2000; Normark and Serra, 2001).

Escanaba Trough is a dead end for all turbidity currents that flow into it; as a result, all of the sediment in suspension within the turbidity-current flows is deposited, resulting in thick beds that show the same relative spacing of reflectors throughout the Trough. The thickness of any given turbidite bed in Escanaba Trough is a function of the water depth at the time of deposition (Normark and others, 1997; Normark and Serra, 2001). This relationship reflects the decreasing volume of suspended sediment with increasing height above the base of the flow. Except where the turbidity currents are trapped in closed basins such as Escanaba Trough, their appearance on high-resolution seismic-reflection records (the acoustic facies) is common to modern deep-sea fans everywhere. The difference in acoustic character between deposits resulting from trapped flow and those left during the passage of a turbidity current can be used to understand the growth pattern of Tufts fan.

Cascadia Channel and Tufts Submarine Fan

Tufts submarine fan is a relatively small deposit that has formed as a consequence of the transport of a tremendous volume of sediment to the Pacific Plate via the Cascadia Channel. Hurley (1960) recognized the importance of Cascadia Channel, but surprisingly little has been done since his pioneering work to map the extensive terrigenous deposits in the northeast Pacific Ocean (see review of Stevenson and Embley, 1987). The relation between Cascadia Channel, Tufts fan, and the glacial Lake Missoula floods is examined in this section.

Cascadia Channel

Cascadia Channel extends from offshore of the Willapa Canyon near the mouth of the Columbia River (fig. 1). Hurley (1964) showed that the channel extends about 2,300 km from the base of the continental slope. Later work, however, has generally been limited to the proximal 700 km of the channel, that is, to the area upstream from where the channel exits the Blanco Fracture Zone (BFZ) (Griggs and Kulm, 1970a, b; 1973; Embley, 1985). As Cascadia Channel bends to the south toward its interception with the BFZ, the channel forms the western margin of the Astoria Fan, acting as a drainage channel for flows that move across the fan (fig. 1). Cascadia Channel is deeply eroded where it approaches the BFZ (fig. 4*A*). Available crossings of the channel show that it is 200–300 m deep throughout the study area, except in the BFZ, where it is only slightly less deep (Embley, 1985; fig. 4*B*). Embley (1985) obtained multibeam sounding data that showed that the

Cascadia Channel makes abrupt, nearly 90° bends not only where it enters and exits the BFZ, but also where it steps from the northern to the southern side of the fracture-zone trough (figs. 1, 2).

The seismic-reflection profiles of figure 4 show that both north and south of the BFZ, the Cascadia Channel is eroded into stratified, generally flat-lying deposits that have an acoustic character typical of turbidite deposition. The right-hand margin of the channel is higher than the left on all crossings; however, distinct levee relief is exhibited in only a few places, for example in figs 4*B*, *D*. Elsewhere, overflow near the channel has been of sufficient volume to smooth the underlying relief of the sea floor, ponding between volcanic hills and ridges (fig. 4*A*, west side). All of the available seismic-reflection profiles show that the upper part of the stratified sediment along the margins on both sides of the Cascadia Channel has smoothed pre-existing topography, whether of autocyclic origin or pre-existing basement topography (figs 4, 5*A*, *B*, 6*A*, *C*).

Where Cascadia Channel has sharp bends, the upper part of a turbidity current that exceeds the channel depth will continue to flow uninhibited by the bend. This process is known as flow stripping, because the upper part of the turbidity current is separated from the flow remaining in the channel (Piper and Normark, 1983), and is a special case of overbank deposition around turbidite channels. Tufts fan receives flow-stripped sediment in the area immediately south of the sharp, westward bend in the channel that is downstream from its exit from BFZ. In this area, there is a low, convex-upward profile of the fan surface (figs 5*A*, *B*). Slightly farther west, deposits of normal overbank flow that also feeds Tufts fan have generally smooth, flat-lying appearance (see, for example, fig. 4*C*).

Upstream from Tufts fan, where the Cascadia Channel turns south to exit the BFZ, westward-directed flow stripping removed substantial volumes of sediment from the flows, even though the channel has nearly 300 m of relief along its right-hand margin. In total, this westward-directed flow-stripping action deposited as much as 500 m of turbidites in a deep, 100-km-long trough on the southwest side of the BFZ (fig. 6*A*) and filled other smaller basins in the rugged topography between the channel and BFZ. Both the airgun and 3.5-kHz high-resolution profiles across these basins filled by flow-stripped deposits show that sea-floor relief produced by tectonic deformation has been nearly eliminated by the ponded deposits (figs 6*A*, *B*). The present sea-floor water depths of these overbank turbidite deposits north and west of Cascadia Channel generally are between 3,150 and 3,275 m. The upper surfaces of the larger turbidity currents, where recorded in Escanaba Trough, are generally between 3,125 and 3,194 m water depth (table 1); thus, the ponded turbidites north of the channel appear well within the depth range of the flows that reached Escanaba Trough.

To understand the extent of deposition from the turbidity currents that were generated by the larger floods from glacial Lake Missoula, the figures presenting reflection profiles show the range in depths to the tops of the turbidity currents that reached Escanaba Trough (for example, fig. 4; table 1). North of the BFZ, the turbidity currents from the floods probably flowed across much of Astoria Fan and overflowed Cascadia Channel to smooth the sea floor west of the channel (fig. 4*A*). Once the currents descended into the BFZ, however, the flows became confined until reaching the area of Tufts fan and the elongate basins adjacent to the main trend of the BFZ.

Deposition within Cascadia Channel is typical of many modern turbidite systems, showing a change to more clay-rich sediment during the Holocene (Griggs and Kulm, 1970b, 1973). Nelson and others (1988) were able to use the presence of Mazama ash, dated at 7.7 ka, in several sandy turbidite beds within the sequence in Cascadia Channel to demonstrate that the channel was active well into the mid Holocene. There is a marked change in sediment grain size, however, between the late Pleistocene and Holocene deposits in Cascadia Channel. Griggs and others (1970) described coarse-grained (to gravel size) sediment from three localities within the proximal 750 km of Cascadia Channel. One sample, core C3, was from the channel on the south side of the BFZ (table 2 and fig. 2*A*). Griggs and others (1970) showed that the lithology of pebbles in these gravel beds is consistent with rock types known from the drainage basin of the Columbia River and its tributaries. Conclusive ages for the gravel layers were not available, but the authors speculated that the deposits were brought to the ocean by late Pleistocene glacial floods.

Other core samples on the north side of Cascadia Channel document that terrigenous-sediment deposition occurred in the same time frame as the Lake Missoula floods. Core C1 (table 2 and fig. 2*A*) recovered 9.75 m of inferred late Pleistocene terrigenous sediment at 3,232-m water depth in the area of flow-stripped deposition that lies 50 km west of the exit of Cascadia Channel from BFZ (Duncan and others, 1970). Carbon-14 analyses gave an age of 15.9 ka at 2.3-m depth in this core. At 5.8 m depth in the core, the age was 27.2 ka, suggesting deposition of terrigenous sediment earlier than the the Lake Missoula floods. Core C2 (table 2 and fig. 2*A*), which is from Cascadia Channel on the Pacific Plate about 20 km west of the channel-floor core described by Griggs and others (1970), shows that turbidite deposition was common until just after 9.6 ka; this is consistent with the age of the youngest turbidite cored at ODP Site 1037 in Escanaba Trough (Duncan and others, 1970; Brunner and others, 1999).

Tufts Fan

Tufts fan is defined herein as the turbidite system that extends southwards from Cascadia Channel immediately downstream of its exit from the BFZ (fig. 2). Its name is taken from the adjacent Tufts Abyssal Plain, a name which has been used to cover all of the terrigenous-sediment-covered area west of the Gorda Ridge (Hurley, 1960).

The Tufts fan is fed by overbank flow where the Cascadia Channel turns abruptly west after reaching the Pacific Plate (figs. 2, 5). The southern wall of the Cascadia Channel is about 150 m above its thalweg at this bend (fig. 4*C*), with the water depth along this southern overbank area at between

3,260 and 3,300 m. Thus, as shown by the depth to the tops of the turbidity currents that reached Escanaba Trough (table 1), the larger turbidity currents moving through Cascadia Channel could overflow along a 40-km-long reach of the channel.

The elongate shape of Tufts fan is a result of allocyclic control by bedrock topography on the flow of turbidity currents building the system. The linear ridge-and-valley topography of the flank of Gorda Ridge is clearly shown where the tops of the ridges have not yet been buried by fan sediment (fig. 2*B*). Tufts fan does not exhibit a simple apex because it does not have a point source, such as a submarine canyon, for sediment building the fan. Rather, the overflow from Cascadia Channel occurs along a reach of as much as 50 km, depending on the thickness of the flow after it exits from the Blanco Fracture Zone (figs 1, 2*B*). Thus, upper Tufts fan is primarily an overbank (levee) deposit for Cascadia Channel and shows a typical autocyclic morphology indicative of both overbank and upper fan elements.

The eastern edge of the fan generally trends north–south and is characterized by turbidite deposition onlapping and ponding between basement ridges on the flank of the Gorda Ridge. The western edge of the fan is bounded by prominent north-south-trending ridges, except between about 42° and 42°45' N latitude, where bathymetric data are insufficient to resolve the fan boundary (fig. 2*A*).

As noted above, Tufts fan is fed by both flow-stripping and normal overbank deposition. As a result, the upper fan does not show typical turbidite channel/levee relief that is found on submarine fans fed by canyons or deltas. An area of convex-upward morphology is the equivalent of an upper fan environment for Tufts fan, with the total turbidite sediment thickness typically 200 to 300 m in this area (fig. 5*A*). A broad, low-relief, southward-directed feeder channel nearly due south of Cascadia Channel's exit from the BFZ is evident on both deep- and shallow-penetrating seismic lines (fig. 5*B*, *C*). This channel on the upper fan shows well-developed sediment waves on the western (right-hand, looking downstream) levee that are at a scale typical for overbank deposition on the upper part of many submarine fans (Wynn and Stow, 2002; Normark and others, 2002). Much of the broad, convex-upward relief on the Tufts fan is the result of the formation of the western levee of the channel. The eastern levee, in contrast, is narrower and its form might in part reflect allocyclic control on deposition. The upper fan area east of the channel levee feature is generally flat as a result of ponding in a basin south of a high ridge of the BFZ (figs. 2B 6*C*, *D*). The western upper fan is gently sloping with little local relief (see, for example, fig. 4*C*). This low relief probably reflects the ponding of flows caused by the north-south trending ridges that form the western margin of the upper fan (fig. 2*B*).

From the southern edge of the upper fan at about 43° 15' N to the Mendocino Fracture Zone (MFZ), 300 km farther south, the turbidite deposits are ponded between the numerous basement ridges and hills on the flank of Gorda Ridge (figs. 2, 7-11). Numerous small channels on the surface of the fan similar to those found on lobe areas of sandy submarine fans (fig. 7*A*, *B*; Piper and Normark, 2001) mark the northern portion of the middle fan. These small channel features are limited to the area between the smooth convex-upward morphology of the upper fan and about 42°45' N latitude (fig. 9). Several scour features or moats are evident around small ridges and hills, where acceleration occurs as the flows impinge upon the topographic restriction. Flows were probably confined between north-south ridges, which were progressively buried by successive large turbidity currents. The channelized/scoured lobe area (middle fan) of Tufts fan shows typical turbidite character in 3.5-kHz profiles, with relatively high-amplitude, continuous, and subparallel reflectors (figs. 7*A*, *B*, 9).

The GLORIA sidescan-sonar backscatter image of figure 9 shows the transition from the channelized middle-fan area to the sloping lower-fan element where low-relief lobes are found. The ridges that form the eastern and western margins of the fan show as light (high backscatter) returns in the GLORIA image. Channel and depositional-lobe elements are observed locally but are relatively subtle features in this image compared with GLORIA images from the distal Mississippi Fan (see figs. 5-10*A* in Twichell and others, 1996). The backscatter image of Tufts middle fan shows no prominent continuous channels that might serve as major conduits for turbidity currents flowing south. This lack of surficial channel features is consistent with deposition over the entire fan surface from the largest flows resulting from glacial Lake Missoula floods. The depth of the upper surface of these flows indicates that the entire fan surface shown in figure 9 was covered by the flows.

More prominent in the backscatter image of figure 9 are the deeper, isolated pockets of ponded sediment along the eastern margin of Tufts fan that show an acoustic character similar to the latest Pleistocene deposits in Escanaba Trough (fig. 10). Where the seismic-reflection profiles and 3.5-kHz profiles cross an isolated pocket of sediment characterized by widely spaced, parallel reflections (fig. 8; compare acoustic character with fig. 3), the backscatter image shows the lowest strength (black) returns (figs. 2*B*, 9, 10). In all cases, these deeper, local basin-fills are separated from Tufts fan by one or more ridges (figs 2*B*, 8). These local basins most likely filled by the deposits stripped from the upper part of flows that have overtopped the ridge crests while the main body of the flows continued to the south.

The lower-fan and basin-plain elements, which make up much of Tufts fan, are broken into north-south-trending turbidity-current pathways separated by the partially buried (north-south-trending) ridges on the Gorda Ridge flank (figs. 2*A*, 10). These two fan elements are between 3,275 and 3,350 m water depth, which is deeper than the observed flow-stripped deposits north of the Cascadia Channel. On the gently sloping lower fan and basin plain, onlap of the subparallel reflections on the tops of basement ridges is commonly observed (fig. 7*D*). The reflection character of the lower fan and of the distal eastern margin of the upper fan approaches that of the isolated, local basin fills described above (compare figs. 6*D* and 7*D* with fig. 8).

Where the Tufts fan impinges upon the high relief of the MFZ, more than 500 m of mostly turbidite sediment fills a trough at the base of the ridge (figs. 10, 11). Thick sediment fill between the south end of the high ridges on the west flank of the Gorda Ridge and the MFZ continues eastward to the edge of Escanaba Trough (fig. 12*A*). Turbidity currents can enter Escanaba Trough only through a fairly narrow gap between the Gorda Ridge and MFZ (fig. 2), where the sill is currently at about 3,250-m water depth. Onlap of reflectors from the west indicates that this sill originally acted as a dam for currents moving from Tufts fan to the east along the MFZ (fig. 12*A*). Thus, the turbidite fill of Escanaba Trough is essentially flow-stripped sediment from the thicker Cascadia-channel flows that reached the MFZ. North of the MFZ, pockets of low backscatter confirm ponding in the valleys between prominent ridges on the flank of the Gorda Ridge (figs. 10, 11*A*, *B*). The profile in figure 11*C* crosses from the southern end of a prominent ridge southward to the base of the MFZ and shows there is no channel acting as a conduit for sediment flowing toward Escanaba Trough. The uppermost 50-100 m of sediment is flat-lying and smoothes underlying topographic relief along much of the crossing, except over a buried high in the middle of the profile. East of figure 11*C*, the buried ridge crops out, forming a bedrock island surrounded by sediment-smoothed sea floor (fig. 10). Figure 10 also shows, north of this island, gently arcuate backscatter returns that might result from sediment waves formed as the turbidity currents flowed eastward around the island toward Escanaba Trough. These waveforms are subparallel to the probable flow direction and might be analogous with those common to sediment drifts (see review in Wynn and Stow, 2002). The ponded turbidite sequences along the MFZ and between ridges on the western flank of Gorda Ridge are part of the ponded basin-plain element for Tufts fan.

The upper 120 m of turbidites in Escanaba Trough that are the result of the glacial Lake Missoula floods formed from the largest flood events that have been recorded on land—those that produced turbidity currents thick enough to maintain flow across the ponded basin-plain element described above. Zuffa and others (2000) argued that the turbidite fill of Escanaba Trough could not have come from the east. Their argument was based on a study by Goldfinger and others(2000), who showed that the Astoria Channel, which extends from Astoria Canyon near the mouth of the Columbia River southward along the base of the continental slope, was blocked along the southern Oregon margin by the immense Heceta landslide about 110 ka. In addition, Wolf and others (1999) showed that the Astoria Channel south of the Heceta slide is filled with muddy sediment and has not been an active sediment-transport conduit. Using the thickness of sediment fill in Astoria Channel off northern California (approximately 15 m, Wolf and others, 1999), the evidence from the nearby Ocean Drilling Program (ODP) Site 1020 (Shipboard Scientific Party, 1997) shows that the channel probably has been inactive for more than 100 ka. An airgun profile across the mouth of Escanaba Trough (fig. 12*A*) shows that the turbidite fill of Escanaba Trough pinches out to the east on the southern end of one of the high mountains of Gorda Ridge. Available 3.5-kHz profiles also show that the latest Pleistocene sediment of Escanaba Trough onlaps and pinches out along the eastern margin of the trough (figs. 12*B*, *C*). Thus, the latest Pleistocene deposits in Escanaba Trough were deposited from the tops of southward-flowing turbidity currents that crossed Tufts fan, were deflected by the relief of the MFZ, and then flowed eastward until intercepted by the deep rift valley of Escanaba Trough.

Only a few sediment cores are known from the general area of Tufts fan. Core C4 (table 2 and fig. 2*A*) is from near the northeast corner of the fan in water depths of 3,180 m. It recovered nearly 3 m of late Pleistocene sediment with a terrigenous component (Duncan, 1968). In the lower fan area, core C6 (table 1 and fig. 2*A*) has a near-surface layer that dates to about 15.5 ka (if we correct the raw age from Dowsett and Poore, 1999, by making a reservoir correction for the mixture of benthic and planktic forams that they used for the carbon-14 age).

Adjacent to the lower fan, two cores recovered sediment with silty terrigenous components. At 3,136-m water depth, core C7 (table 1 and fig. 2*A*) recovered terrigenous silty clay; carbon-14 dates at depths of 5-6 cm and 12-13 cm in the core were 15.38 ka and 15.82 ka, respectively (Ortiz and others, 1997). Farther west, core C8 (table 1 and fig. 2*A*) in 3,330-m water depth recovered sediment that was dated at 14.9 and 15.0 ka at depths of 14-15 cm and 20-21 cm, respectively (Ortiz and others, 1997). These dated intervals overlie terrigenous sediment in the interval between depths of 172 and 257 cm in the core.

These cores confirm that terrigenous sediment has been deposited on the western flank of Gorda Ridge (both within the fan area and to the west) between the lobe area of the fan and the thick, ponded sequence at the base of the MFZ. The age of the upper parts of these cores roughly coincides with the time of the Lake Missoula floods and other latest Pleistocene events in the northwestern United States and southwestern Canada.

Discussion

Age of Tufts Fan

There is no equivalent of an ODP sediment core that can be used to provide ground truth for estimating the age, periodicity of deposition, or character of sediment deposited on the Tufts fan. The available core data (table 2) support the conclusion that the last turbidites deposited on the fan are from the Lake Missoula floods. The deep erosion of Cascadia Channel into thick presumed turbidite deposits and the thicknesses of deposits (about 500 m) on the upper fan and in the area just north of the MFZ might indicate that turbidity currents have been active on the Pacific Plate during much of the Pleistocene.

The turbidity currents that were generated by glacial Lake Missoula and other latest Pleistocene flood events were able to reach the Escanaba Trough only because a pathway existed on the Pacific Plate as a result of previous, and fairly extensive, turbidite deposition. Creation of the Tufts fan involved substantially more sediment than the amount left by the latest Pleistocene flood pulses. Based on extrapolation of available age data on sediment from ODP Site 1037, it is unlikely that much, if any, of the sediment fill in Escanaba Trough can be older than 60 ka (using data from Brunner and others, 1999). The oldest date at Site 1037 is 32.2 ka at 317-m subbottom depth from a muddy interval that is underlain by about 185 m of turbidite sand and mud. Using the slowest rate provided by Brunner and others (1999)—7.6 m/k.y. for the relatively muddy interval between 262.25 and 316.90 m subbottom—gives an age of 56.5 ka for the basal turbidites. Sand beds are more common in the lower part of the hole, so the actual sedimentation rate would probably be greater. Thus, deposition of the turbidite section currently preserved in Escanaba Trough from flows moving across Tufts fan probably began only about 50 ka. It is possible that there are older turbidite deposits buried by volcanic flows and now uplifted as part of the terraces flanking the trough axis. Tilted and deformed sediment is common on the western side of the Escanaba Trough (fig. 12*A*), suggesting that active tectonism and uplift might have prevented earlier flows from reaching the axis from Tufts fan. Normark and Reid (in press) estimated that deposits on Tufts fan equivalent in age to the Lake Missoula deposits in Escanaba Trough account for less than 10 percent of the total volume of turbidites in the fan. Thus, as a minimum, the fan may have been forming throughout the late Pleistocene.

Tufts fan could have begun to form shortly after Cascadia Channel established the connection with the Pacific Plate through the BFZ. An upper limit on the age of the fan might be given by the time that Pleistocene catastrophic floods in the Pacific Northwest began. McDonald and Busacca (1988) reported evidence for flood-cut unconformities in loess in the Channeled Scabland; the youngest pre-Wisconsin flood episode was about 36 ka. These authors further suggest that this event was one of at least five episodes of flooding in the scabland before the Lake Missoula jökulhlaups. The earliest of these episodes might be as old as 790 ka (McDonald and Busacca, 1988). Recent work has suggested that cataclysmic flooding in the Pacific Northwest might have been common throughout much or all of the Pleistocene, beginning between 2.5 and 1.5 Ma (Bjornstad and others, 2001; Pluhar and others, 2002). The Heceta submarine slide (about 110 ka) blocked the Astoria Channel along the base of the continental slope, effectively blocking an eastern pathway to Escanaba Trough and the Pacific Plate (Goldfinger and others, 2000; Wolf and others, 1999). The Heceta slide, however, is only the youngest of three catastrophic failures of similar size recognized along the Oregon continental margin. Goldfinger and others (2000) estimate that the Coos Basin slide, which is immediately south of the Heceta slide, occurred about 460 ka; this slide deposit would also have acted to deflect southward-directed sediment transport to the west through the Blanco Fracture Zone. An even older large-scale failure, the Blanco slide, occurred 1.2 Ma (Goldfinger and others, 2000). Thus, it is probable that turbidite sediment has been moving through the Blanco Fracture Zone throughout the late Pleistocene, and the initial deposition on the Tufts fan may record the beginning of such turbidite deposition on the Pacific Plate.

Tufts Fan Elements and Tufts Abyssal Plain

The Tufts fan is more than 350 km in length between the Cascadia Channel and the MFZ and is generally 60-70 km wide in the upper and middle fan areas and narrows to about 40 km in the south; it has a total area of about 23,600 km^2 (fig. 13). The airgun seismic-reflection profiles show thick sections of sediment with the acoustic character of classic turbidite deposits over the eastern part of the study area (figs. 2*A*, 13). The growth of the fan, however, did not result in a prominent feeding channel or distributary system such as found on most modern turbidite fans. This, in part, probably results from the confinement of the turbidity currents to the valleys between the numerous elongate ridges on the western flank of Gorda Ridge. Where turbidity currents cannot spread laterally (and form a fan-shaped deposit) because of confinement to a narrow basin, the walls of the basin act as channel margins, keeping the flow thick enough to keep moving (see fig. 9 in Normark and Piper, 1991). The upper-fan and channeled-lobe areas of Tufts fan are thick enough to have buried many of the hills on the flank of Gorda Ridge. Farther south, there is sufficient relief of the elongate ridges to keep the turbidity currents confined as they flow south toward the MFZ. The result is that the Tufts fan has poorly defined channel and lobe features on the middle fan element but has extensive lower fan and basin elements that show little surface relief because of ponding (fig. 13).

The Tufts fan is a very small (in area) turbidite deposit compared to the Tufts Abyssal Plain (see fig. 12 in Normark and Reid, in press). The relief of the Cascadia Channel throughout the area of overbank flow, which is the source of the Tufts fan, is 150-200 m. The deposits of Tufts fan represent only the uppermost, flow-stripped portions of the tremendous turbidity currents that flowed through the BFZ. Significant volumes of the flows confined within the Cascadia Channel likely continued westward some 1,500 km or more (Hurley, 1964; Normark and Reid, in press) towards the end of the channel within Tufts Abyssal Plain (fig. 1). Accordingly, substantially more sediment was probably deposited on the abyssal plain than in the Tufts fan. Volumetric calculations of the amounts of terrigenous sediment on the Pacific Plate suggest that the total volume of Tufts fan turbidite deposits is less than 10 percent of that on the Tufts Abyssal Plain (Normark and Reid, in press).

Conclusions

The Tufts submarine fan formed as a result of late Pleistocene, and perhaps earlier, deposition from turbidity currents that were able to cross to the west of the Gorda Ridge spreading axis through the Blanco Fracture Zone and deposit on the Pacific Plate. Catastrophic floods from glacial Lake Missoula and earlier late Pleistocene outbursts carried enormous amounts of sediment from the Pacific Northwest to the ocean. These floods continued to transport sediment downslope as hyperpycnally generated turbidity currents following the Cascadia Channel to the Pacific Plate, eventually building the 350-km-long Tufts fan as a result of both flow stripping and normal overbank loss of sediment from Cascadia Channel. The Tufts fan buried ridge-and-valley topography on the western flank of Gorda Ridge and eventually became a sedimented pathway to the Mendocino Fracture Zone and Escanaba Trough. By the latest Pleistocene, that is, after about 60 ka, Tufts fan had sufficiently aggraded to allow the largest of the glacial lake outbursts to reach Escanaba Trough, where the flows were trapped and have provided a well-documented record of some of these flood events at ODP Site 1037 (Zuffa and others, 2000).

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Table 1. Key turbidite beds in Escanaba Trough and water depth (top of flow) at the time of deposition of each bed (adapted from Normark and Reid, in press).

Bed	Water depth to top of turbidity current (m)
H	3,126
D	3,136
G	3,144
F	3,165
B	3,173
E	3,188
C	3,194

Table 2. Locations of cores with evidence for glacial Lake Missoula deposits (adapted from Normark and Reid, in press).

Label on (fig. 2A)	Original core number	Water depth (m)	Depth in core (m)	Age (ka)	Reference
C1	6509-21A	3,232	2.3 5.8	15.9 27.2	Duncan and others, 1970
C2	6509-25A	3,334	2.55-2.9	9.67	Duncan and others, 1970
C3	6604-1	3,329	gravel	late Pleistocene	Griggs and others, 1970
C4	6604-3	3,180	3 meters total	late Pleistocene	Duncan, 1968
C5	6609-13	3,266	1.8-2.25	13.15	Duncan and others, 1970
C6	W8809A-29GC	3,288	(near surface)	15.5	Dowsett and Poore, 1999
C7	W8809A-31GC	3,136	0.05-0.06 0.12-0.13	15.38 15.82	Ortiz and others, 1997
C8	W8809A-57GC	3,330	0.14-0.15 0.20-0.21	14.9 15.0	Ortiz and others, 1997

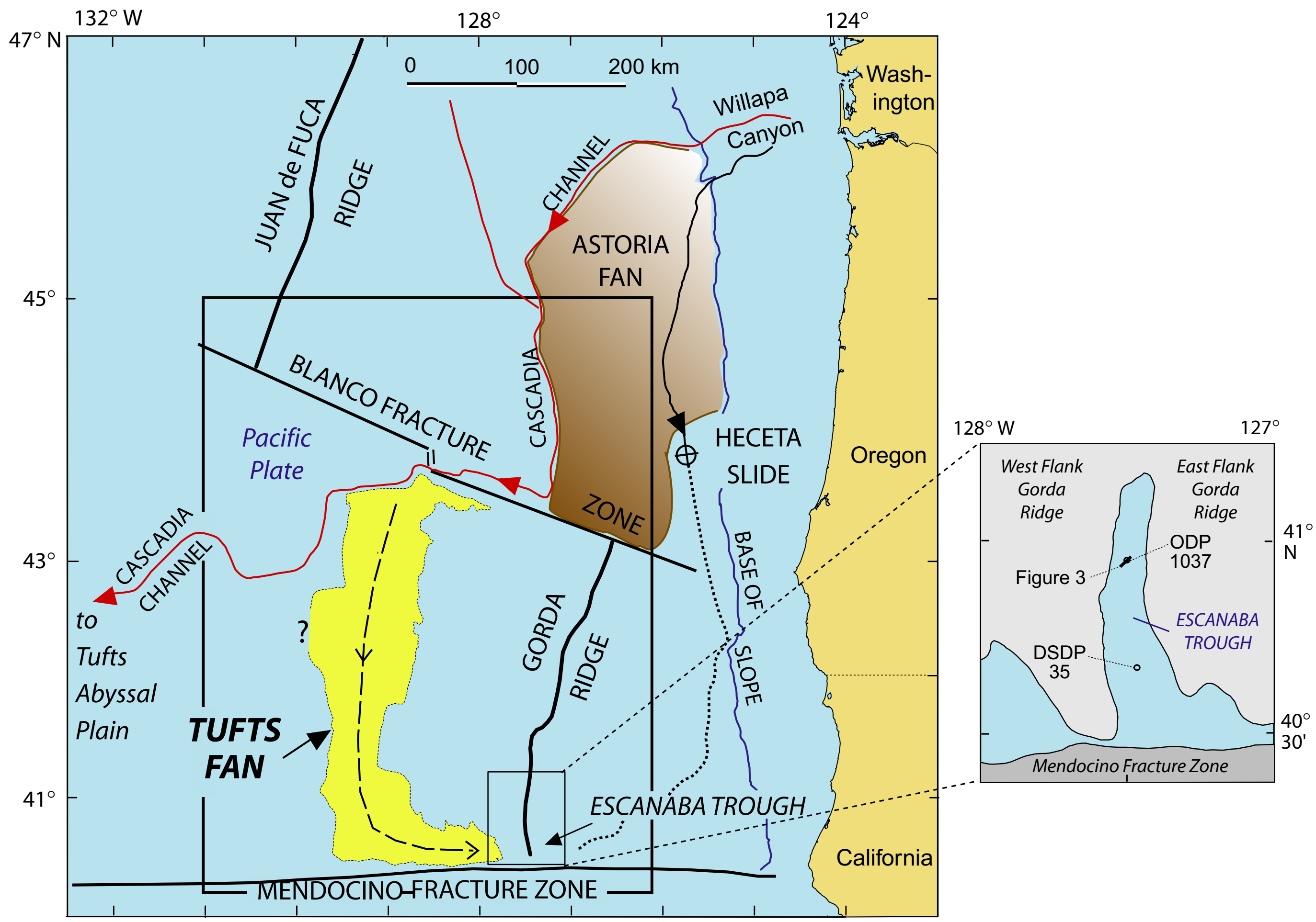


Figure 1. Schematic map showing path of late Pleistocene glacial flood sediment from the Columbia River mouth to the Tufts fan, Escanaba Trough, and Tufts Abyssal Plain (Normark and Reid, in press). Rectangle with thick lines shows location of figure 2; enlargement gives the location of Deep Sea Drilling Program (DSDP) and Ocean Drilling Program (ODP) drill sites and the high-resolution 4.5 kHz profile (fig. 3).

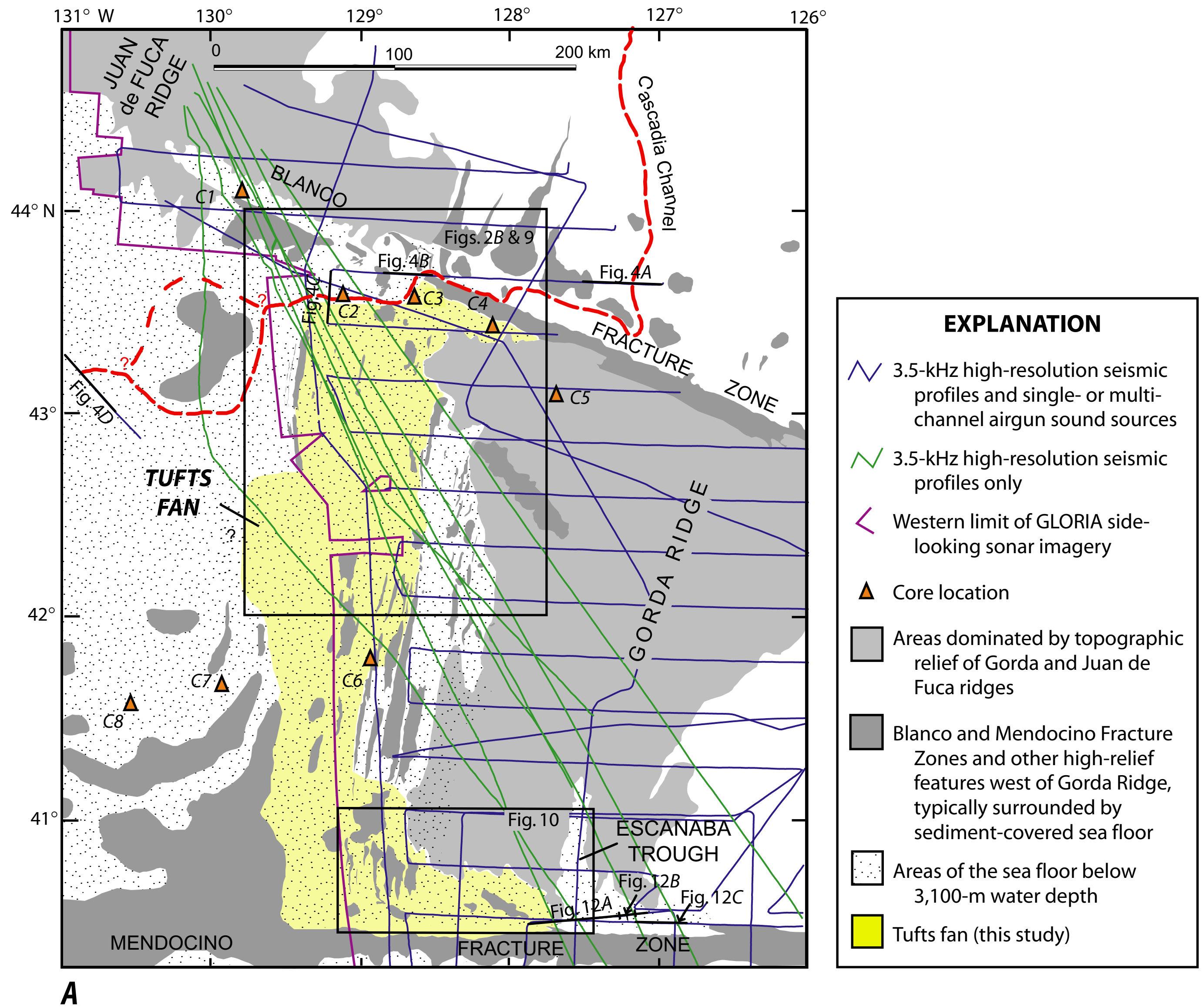
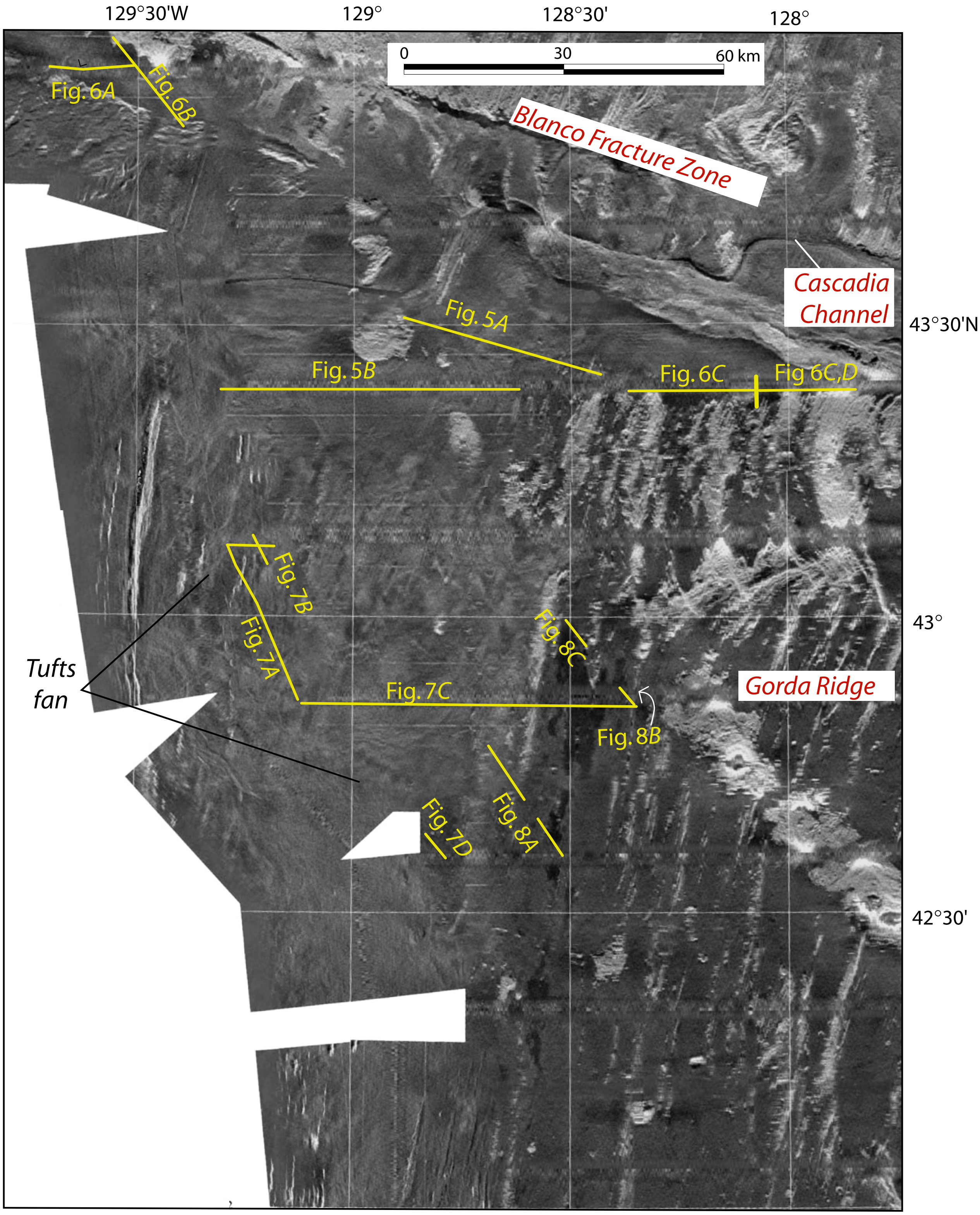


Figure 2. Map and acoustic backscatter mosaic of the study area. *A*, Map shows physiographic features and data used in this study. In addition, the locations of GLORIA imagery used in figures 2*B*, 9, and 10 are noted by black rectangles. Locations of seismic-reflection profiles in figures 4 and 12, and core locations (table 2) are also shown. *B*, GLORIA sidescan-sonar backscatter imagery (full resolution of data used in EEZ-SCAN Scientific Staff, 1986) showing location of figures 5-8.



B

Figure 2. Continued. Map and acoustic backscatter mosaic of the study area. *A*, Map shows physiographic features and data used in this study. In addition, the locations of GLORIA imagery used in figures 2*B*, 9, and 10 are noted by black rectangles. Locations of seismic-reflection profiles in Figures 4 and 12, and core locations (table 2) are also shown. *B*, GLORIA sidescan-sonar backscatter imagery (full resolution of data used in EEZ-SCAN Scientific Staff, 1986) showing location of figures 5-8.

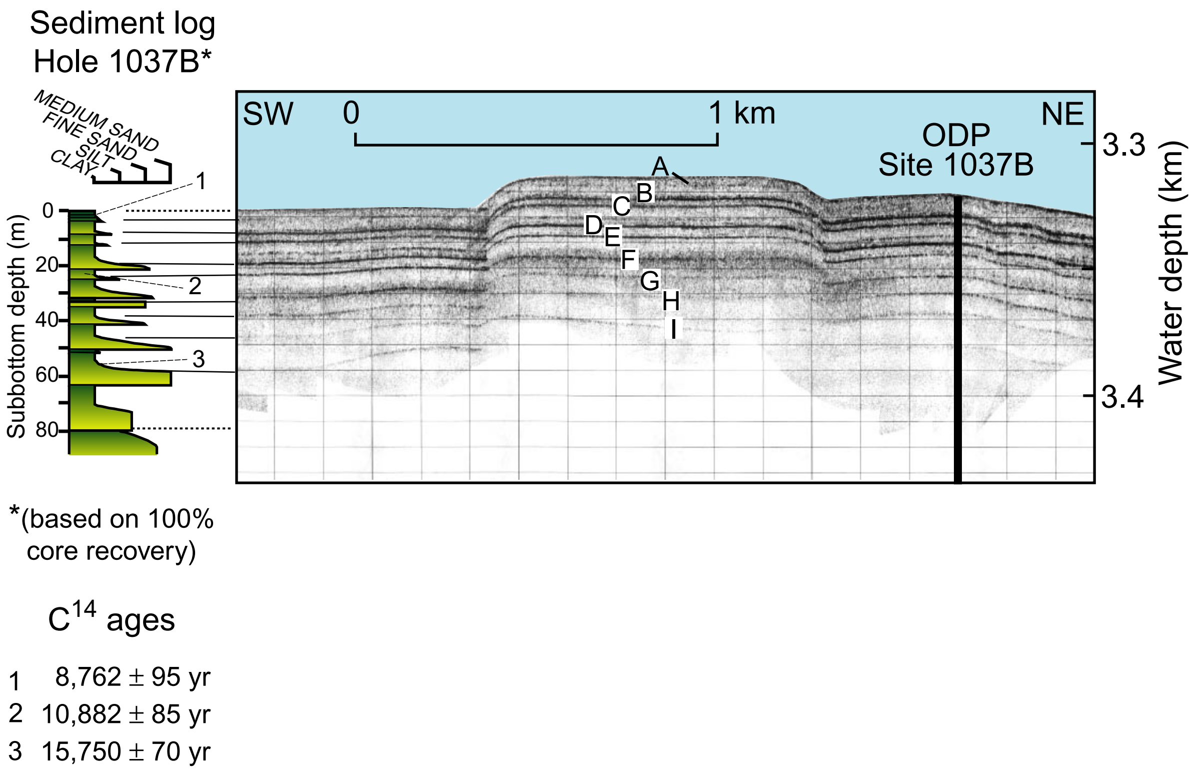


Figure 3. Deep-tow 4.5-kHz high-resolution reflection profile showing the characteristic spacing of the turbidite reflector sequence (A to I) in Escanaba Trough at ODP Hole 1037B; the correlation with the sediment log is given (modified from Zuffa and others, 2000). Locations of ODP Hole 1037B and 4.5-kHz profile are shown in figure 1 (enlarged map).

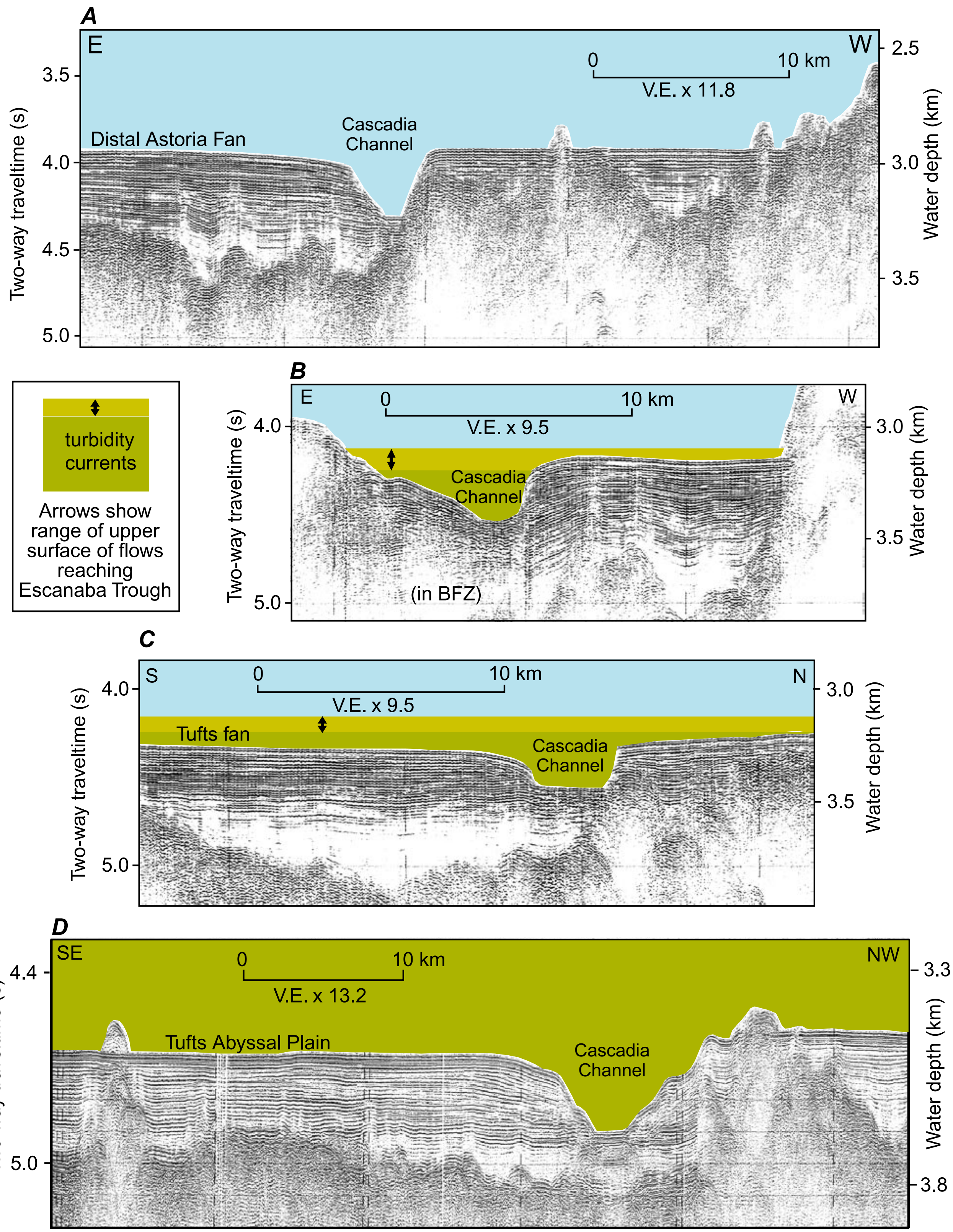


Figure 4. Single-channel, airgun seismic-reflection profiles crossing Cascadia Channel. The profiles are oriented such that the view is down the channel axis to emphasize that the right-hand overbank area is shallower than the left margin on all profiles. Profile locations noted in figure 2*A*. *A*, Profile on the Juan de Fuca Plate. *B*, Profile just north of the exit point in the Blanco Fracture Zone. *C*, Profile immediately south of the Blanco Fracture Zone near the apex of the Tufts fan. *D*, Profile from the easternmost part of Tufts Abyssal Plain.

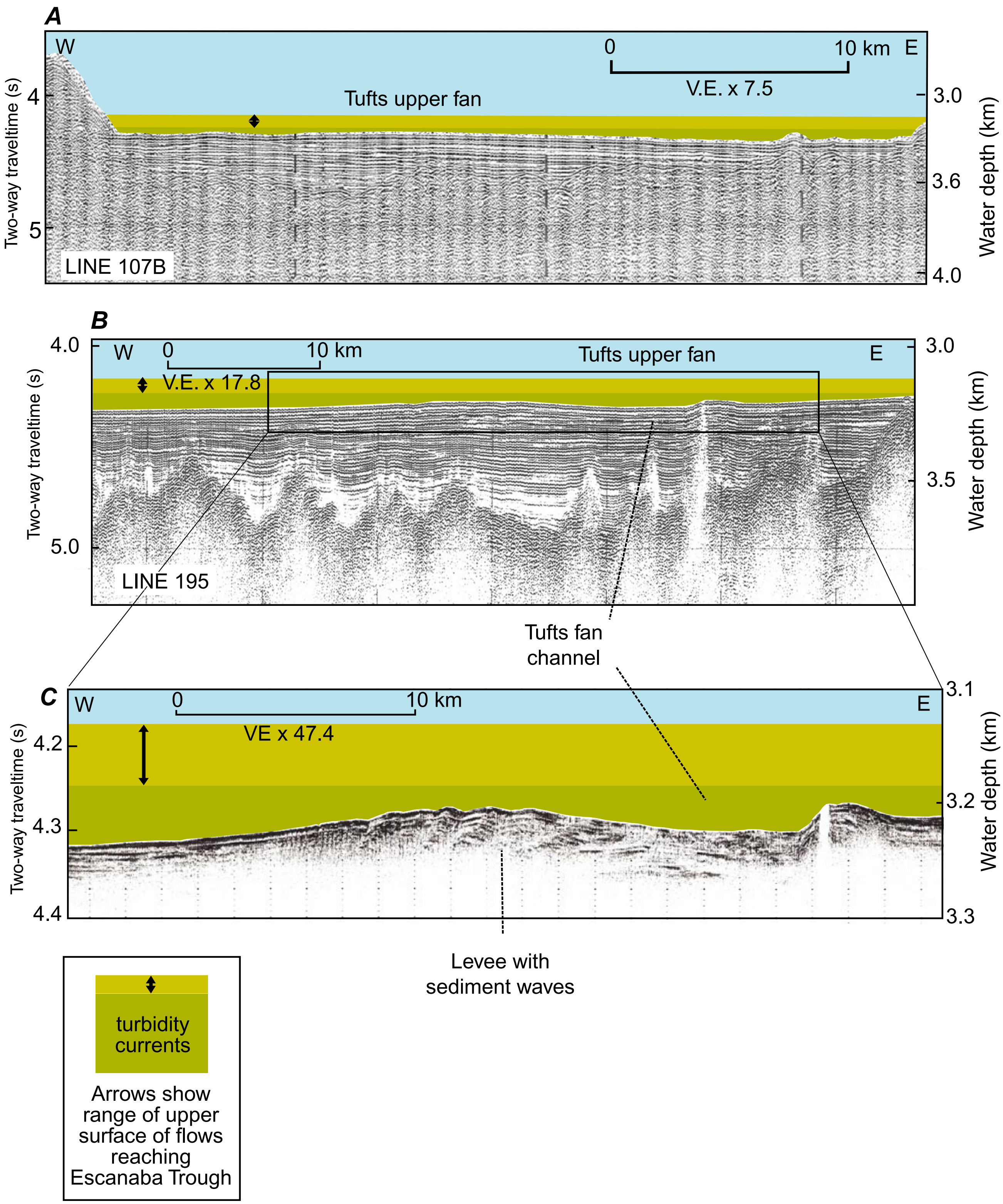


Figure 5. Seismic-reflection profiles across the upper Tufts fan. Locations of profiles are noted on figure 2*B*. *A*, Single-channel airgun profile near the point of overflow of turbidity currents from Cascadia Channel, showing a generally convex upward cross section without a distinct channel. *B*, Single-channel airgun profile farther south crossing the broad, shallow, leveed Tufts fan channel. *C*, High-resolution 3.5-kHz profile highlights Tufts fan channel and adjacent right-hand levee (facing down channel axis) with sediment waves.

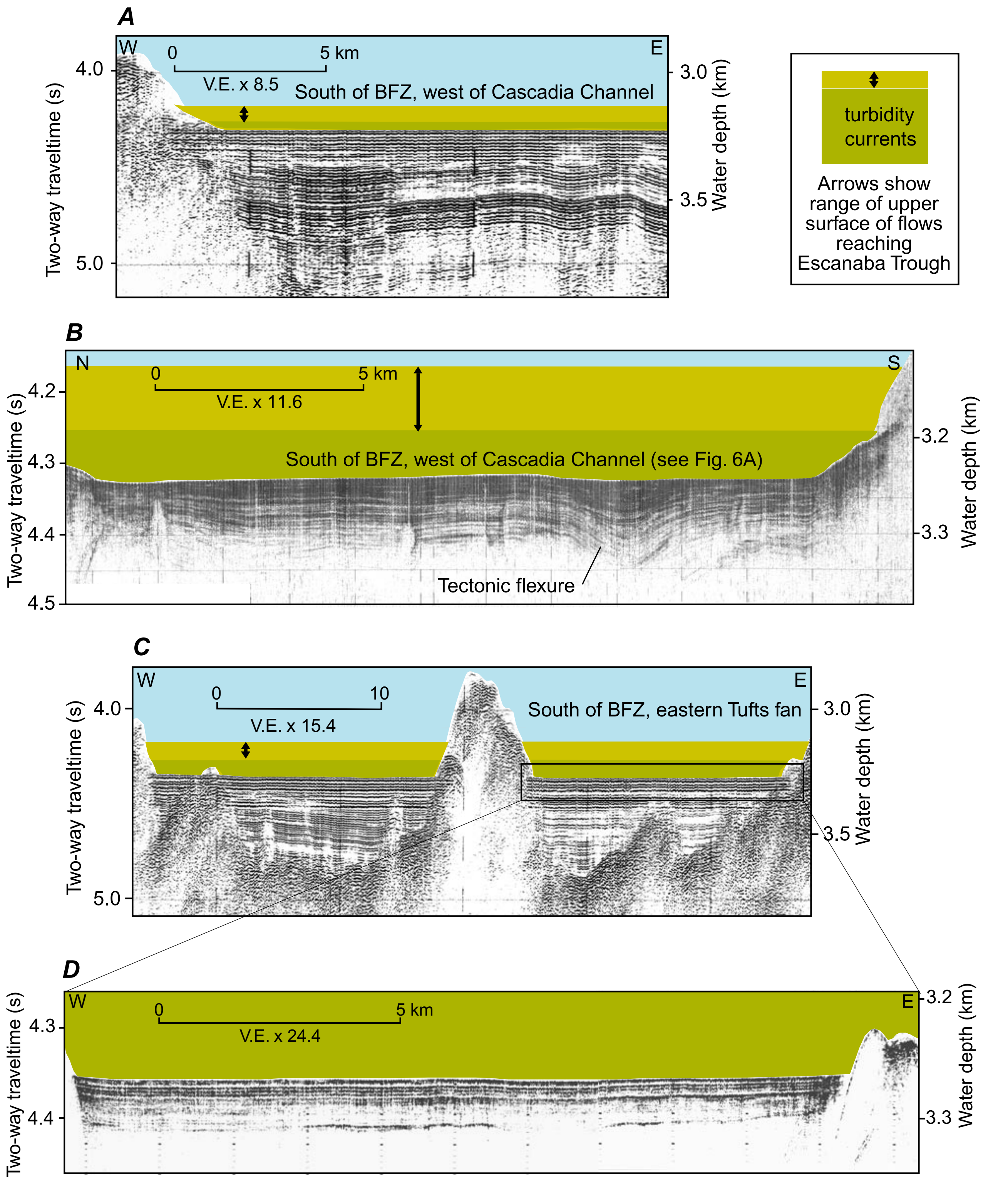


Figure 6. Seismic-reflection profiles in overflow areas adjacent to the Cascadia Channel and upper Tufts fan, showing extensive ponding of sediment from turbidity currents. Profile locations are noted in figure 2*B*. *A*, Single-channel airgun seismic-reflection profile crossing thick, flat-lying deposits ponded in a trough within the southern margin of Blanco Fracture Zone (BFZ), west of Cascadia Channel. *B*, High-resolution 3.5-kHz profile, showing a growth fold within the trough. *C*, Single-channel airgun reflection profile, showing thick, flat-lying deposits east of Cascadia Channel, south of BFZ. *D*, High-resolution 3.5-kHz profile of the eastern part of the profile in *C,* demonstrating that the most recent deposits have smoothed any underlying relief. The acoustic character of the upper part of this sediment fill mimics that seen in Escanaba Trough (figure 3).

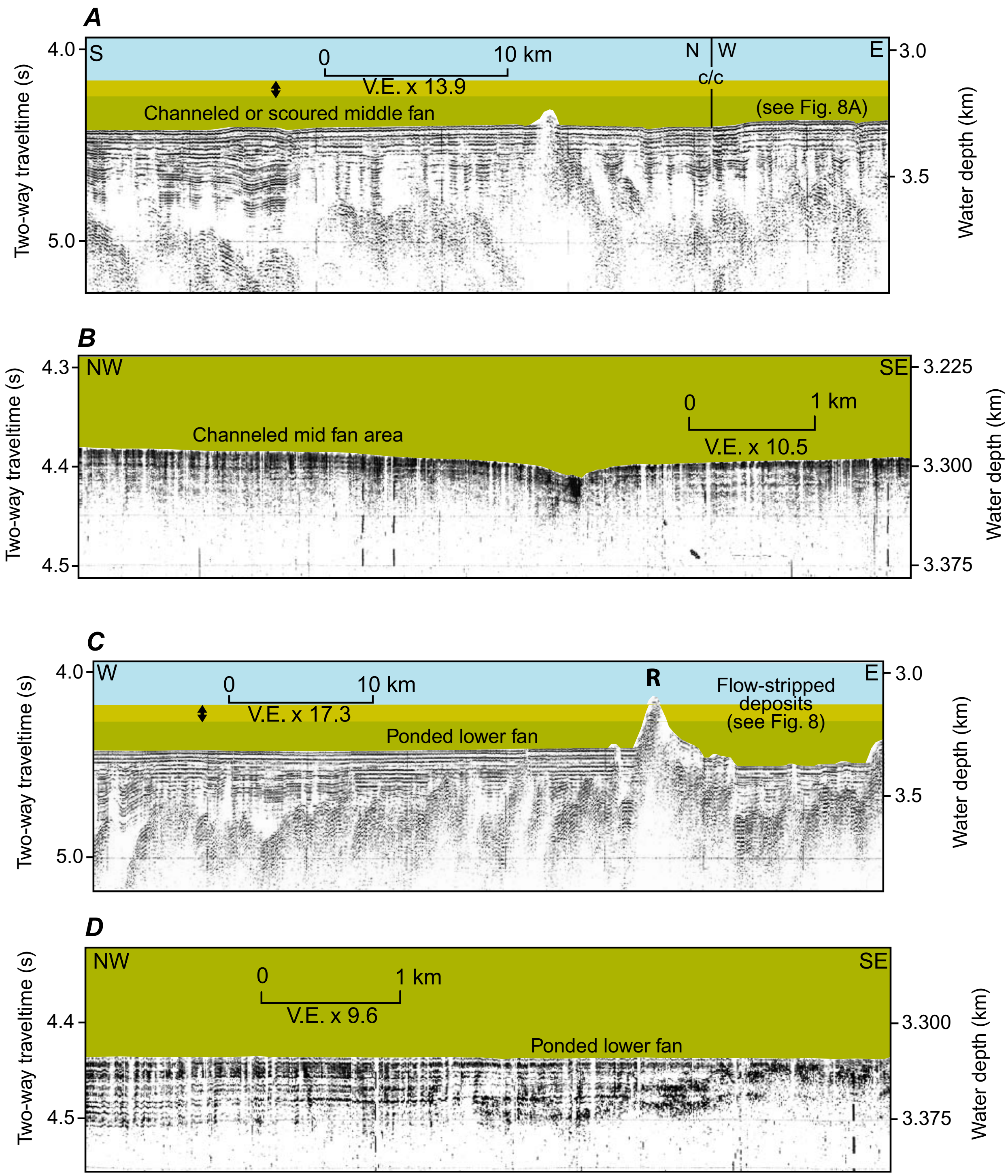


Figure 7. Seismic-reflection profiles across the middle and lower fan areas of Tufts fan. Profile locations in figure 2*B*. See figure 6 for explanations of yellow/green colors and arrows. *A*, *B*, Single-channel airgun seismic-reflection profile (*A*) and high-resolution 3.5-kHz profile (*B*) cross the middle fan area, showing small channels and scour depressions. *C*, Single-channel airgun seismic-reflection profile, showing ponded turbidites on the lower fan as well as flow-stripped deposits trapped between ridges on the flank of Gorda Ridge. The crest of the ridge, marked 'R', is near 3,100-m water depth; even the thickest flows that reached Escanaba Trough could not overtop the ridge at the location of this profile. *D*, High-resolution 3.5-kHz profile across the ponded lower fan.

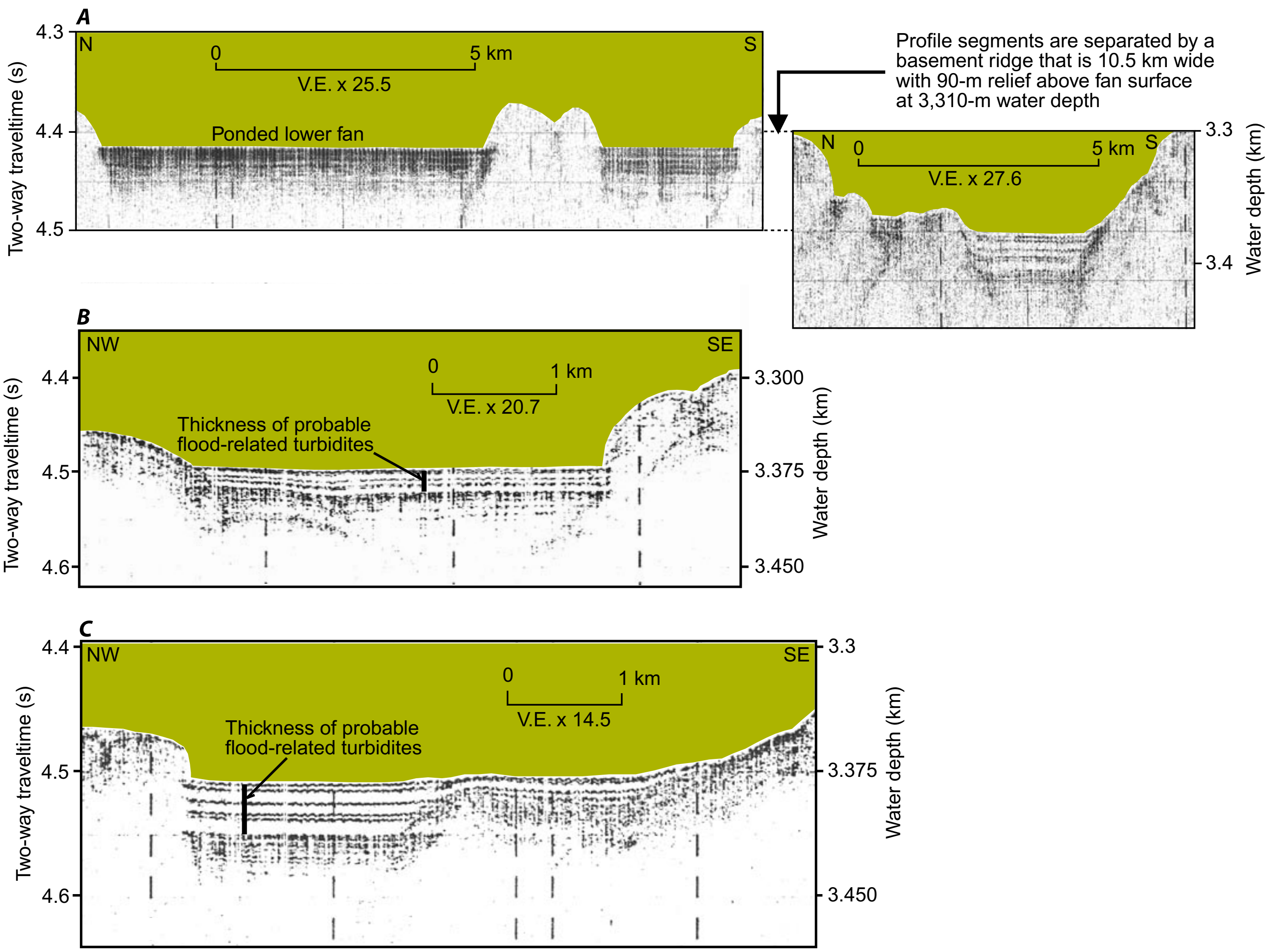


Figure 8. High-resolution 3.5-kHz reflection profiles with evidence of flow stripping adjacent to the Tufts fan. Profile locations in figure 2*B*. *A*, This profile from the lower Tufts fan shows the typical character of sandy turbidites on the fan (left segment of profile) and an acoustic character similar to that found in Escanaba Trough in an isolated pocket (east end of profile; see text for details). *B, C,* Profiles showing ponded turbidites with a character similar to that of the Escanaba Trough fill (see fig. 3). The flat-lying deposits resulted from thicker, presumably flow-stripped turbidity currents reaching these isolated basins.

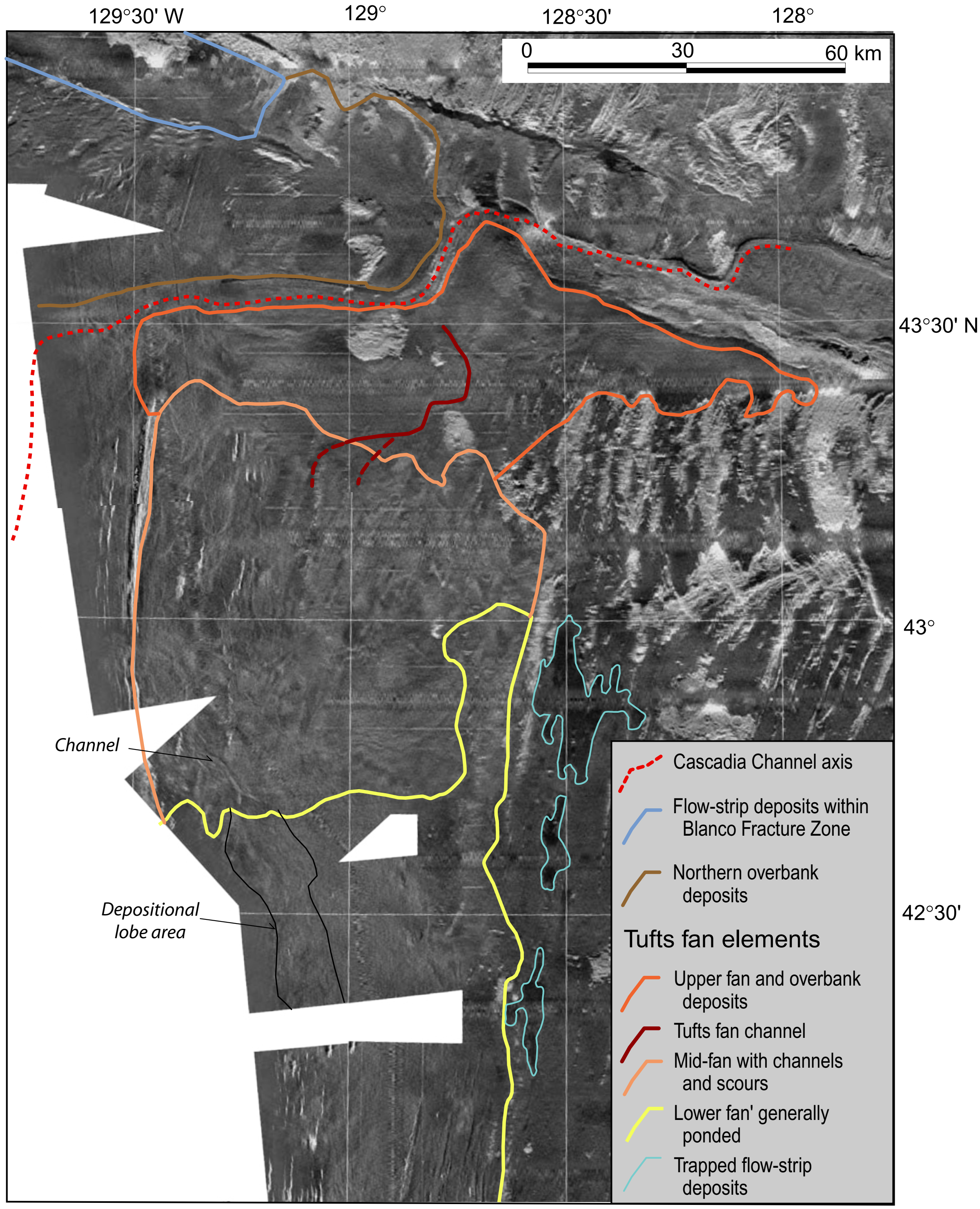


Figure 9. GLORIA sidescan-sonar backscatter image of the upper, middle, and lower Tufts fan and of the Tufts fan channel (dark red; see also fig. 5). Image location is the same as figure 2*B* and is shown in figure 2*A*. Outlined areas north of Cascadia Channel are the northern overbank deposits between abyssal hills (within brown line) and flow-stripped deposits within troughs of the Blanco Fracture Zone (within thick blue line; see fig. 6*A*, *B*). The dark orange polygon encompasses the upper fan and adjacent overbank deposits (figs. 5 and 6*C*, *D*). Light orange line encompasses the middle fan with small channels and scours around abyssal hills (fig. 7*A*, *B*). Yellow delineates the northeast corner of the lower fan (fig. 7*C*, *D*). Turbidity-current deposits that were trapped in small basins show as very low amplitude backscatter (black shading) along the eastern margin of the Tufts fan (see along longitude 128°30′ W) and are outlined in thin blue lines (see also fig. 8).

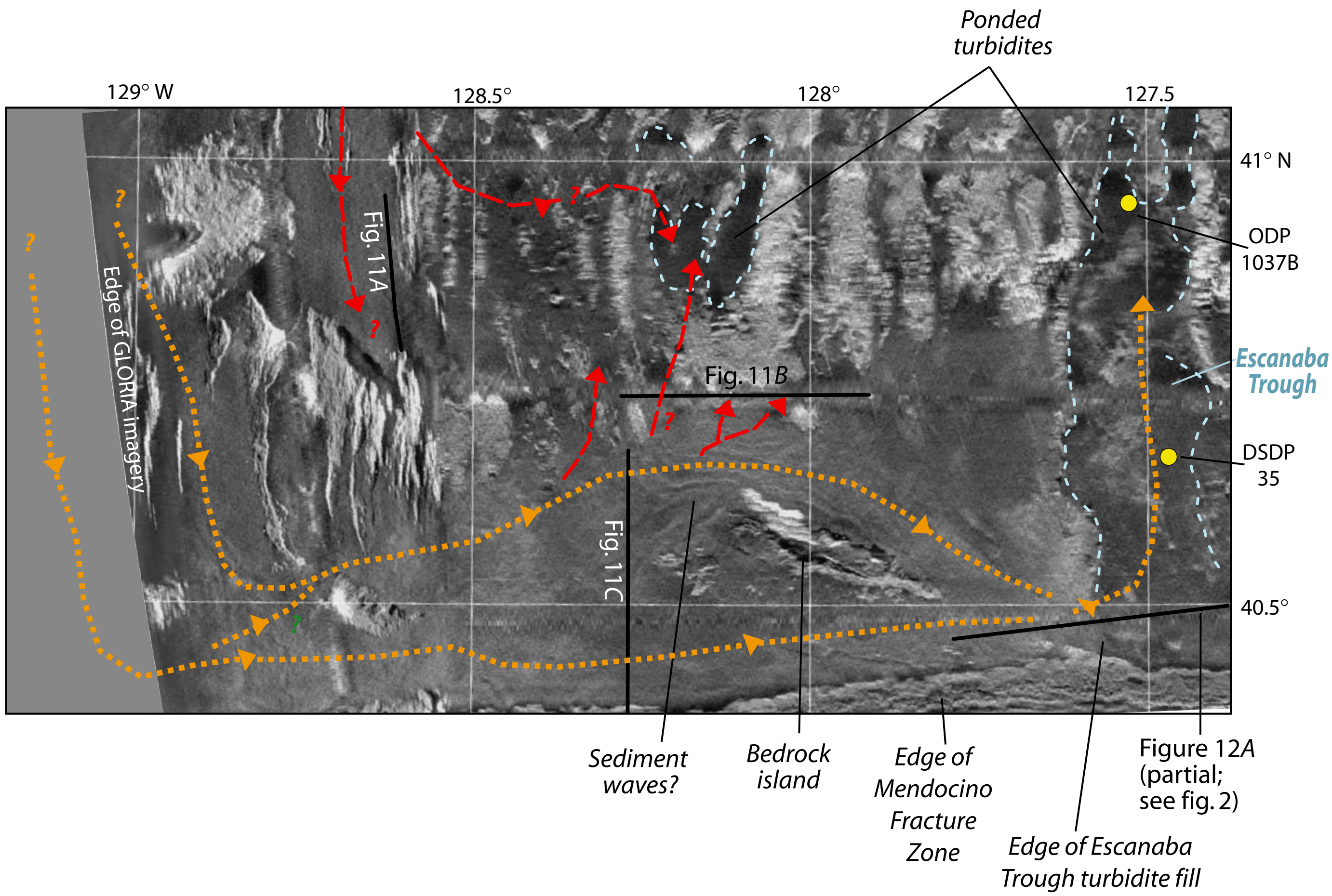


Figure 10. GLORIA sidescan-sonar backscatter image of the sea floor immediately north of the Mendocino Fracture Zone along the pathway of turbidity currents that flowed into Escanaba Trough. Image location noted in figure 2*A*. Much of the sediment-smoothed area (darker gray to black shading) is underlain by several hundred meters of ponded turbidite sediment (fig. 11). Locally, the ponded sediment (outlined in thin dashed blue line) shows as very low amplitude (black) backscatter in areas between the ridges of the southern terminus of Gorda Ridge (see fig. 11*B*). Much of the area within Escanaba Trough is also low backscatter (also outlined in thin dashed blue), which is consistent with the ponding of the turbidity currents after being trapped in the spreading-center axis. Orange dashed lines show direction of possible flow paths; red dashed lines show possible directions of flow stripping over low hills within the western Gorda Ridge flank. Solid yellow circles indicate locations of ODP and DSDP core sites. Location of seismic-reflection and 3.5-kHz profiles of figures 11 and 12*A* are shown.

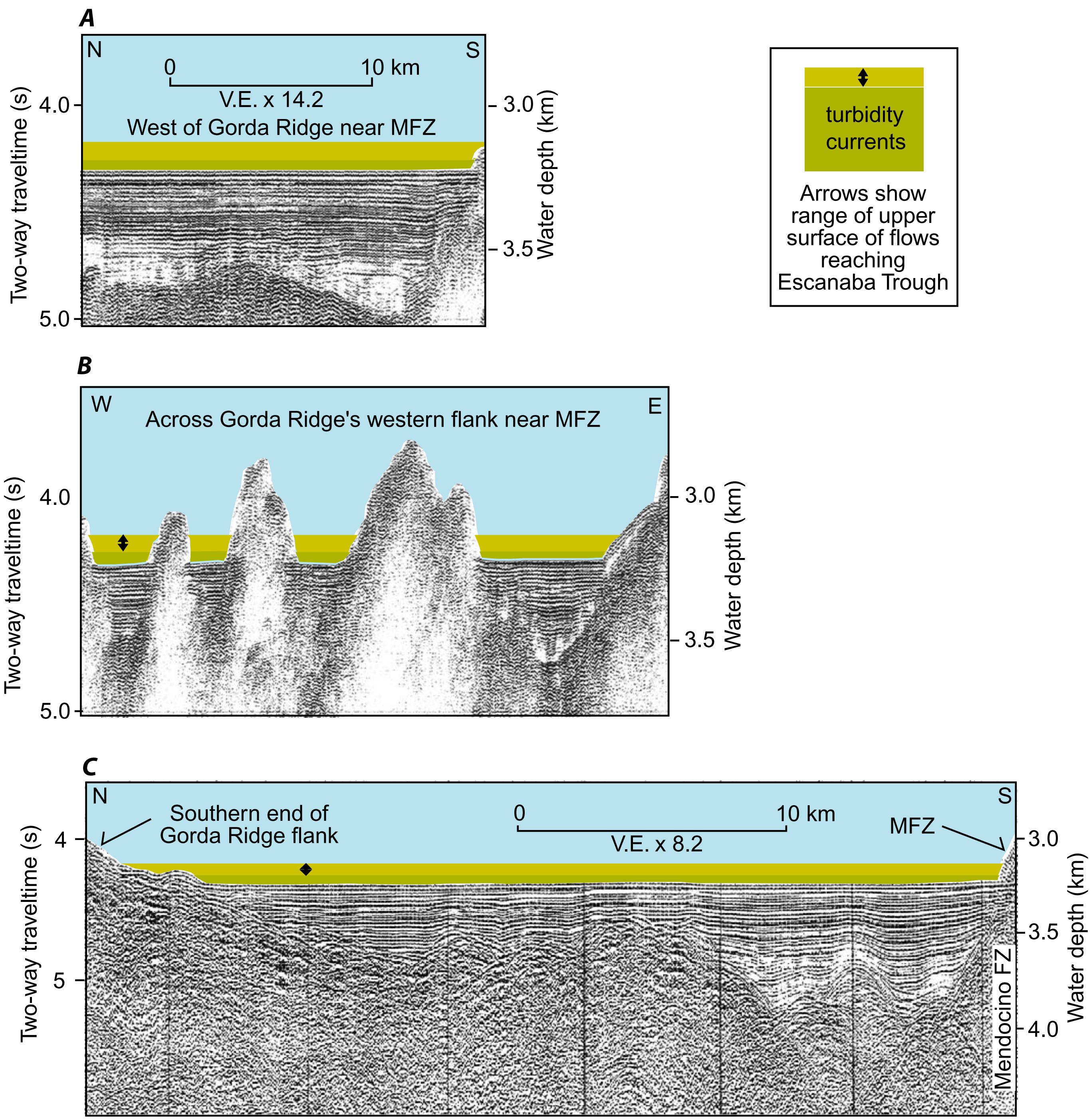


Figure 11. Single-channel, airgun seismic-reflection profiles showing extensive ponding of sediment from turbidity currents in the area north of Mendocino Fracture Zone (MFZ). Image locations noted in figure 10. *A*, North-south profile showing the smoothed sea floor and deep packet of ponded sediments. *B*, East-west profile that crosses the ridges on the west flank of Gorda Ridge, showing ponding in the valleys. *C*, Airgun profile showing the extensive ponding and lack of a well-defined channel leading to Escanaba Trough, north of the Mendocino Fracture Zone.

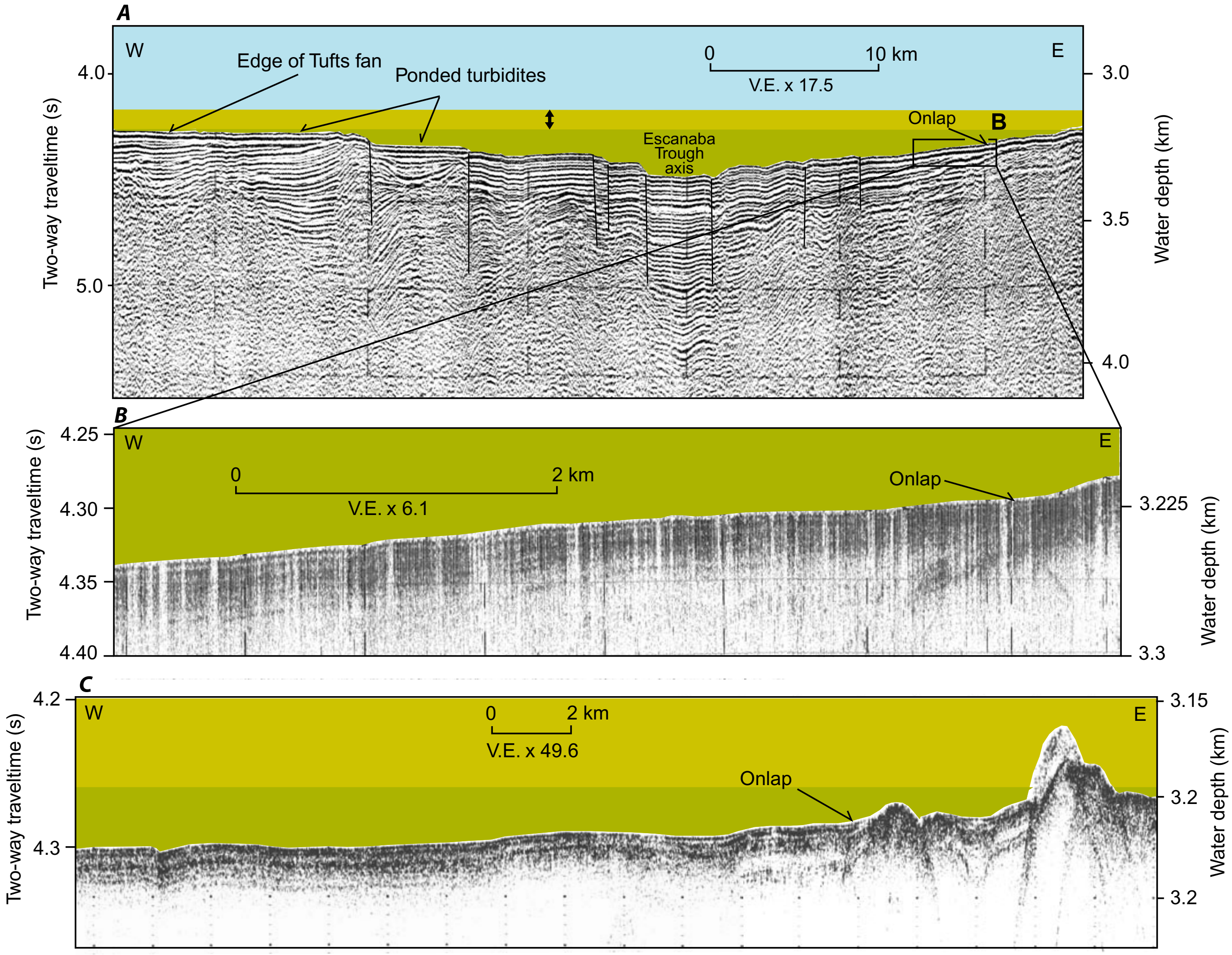


Figure 12. Seismic-reflection profiles across the southern end of Escanaba Trough (parallel to the Mendocino Fracture Zone) showing the eastward onlap of the turbidite deposits that are contiguous with Escanaba Trough fill. Image locations noted in fig. 2*A*. See figure 11 for explanation of yellow/green colors and arrows. *A*, Airgun seismic-reflection profile. *B*, *C*, 3.5-kHz high-resolution profiles.

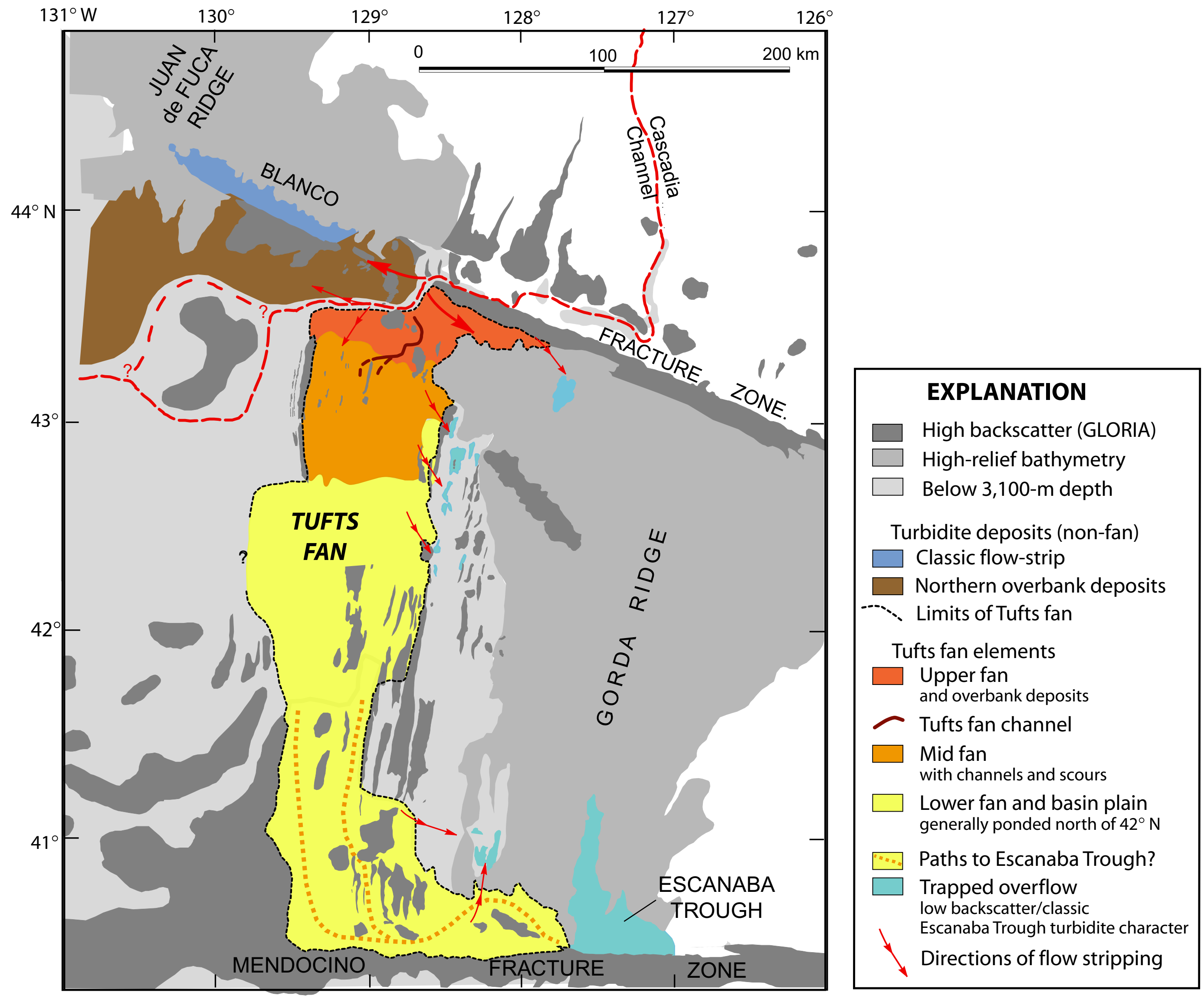


Figure 13. Acoustic-facies interpretation of the Tufts fan and areas with flow-stripped and trapped turbidite sediment. Outside of the GLORIA map area (see fig. 2), the western limit of Tufts fan is poorly constrained but is assumed to be formed by north-south-trending ridges on the flank of Gorda Ridge similar to the fan boundary north of 43° N latitude. Available data suggest that the flow pathway(s) from Tufts fan to Escanaba Trough are now marked by areas with thick ponded deposits and, as such, are probably part of the basin-plain element for this system. See text for details. Area shown is same as for figure 2.