Tectonic and climatic influence on the evolution of the Surveyor Fan and Channel system, Gulf of Alaska

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1. Introduction

Proximity of the St. Elias Mountains to the coastline assures that the majority of glacially eroded sediment is deposited in the Gulf of Alaska, much of it in the deepwater Surveyor Fan. A long-offset 2D seismic reflection study, acquired in 2008, linked to previous studies of Surveyor Fan sediment cores, yields information on margin processes, climate events, orogenesis, and exhumation. The results of this study will add to the existing body of work on climate-dominated tectonic systems, and demonstrate how such a system can not only transform the orogen, but the entire margin from source to sink.

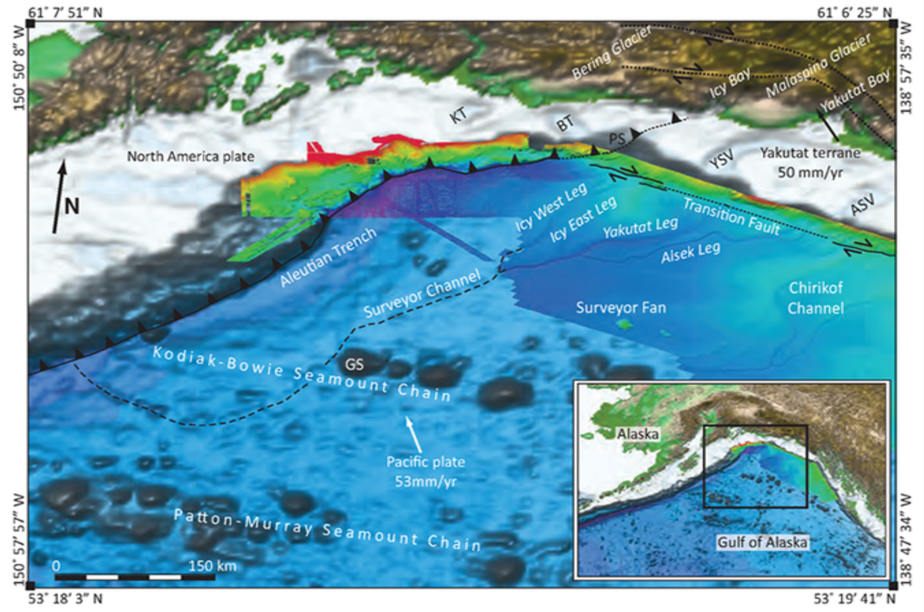

Figure 1. 3D perspective bathy/topo view of the southern Alaska margin, showing tectonic boundaries, and the Surveyor Fan in high-res. bathymetry. ASV- Alsek Sea Valley; BT- Bering Trough; GS- Giacomini Seamount; KT- Kayak Trough; PS- Pamplona Spur; YAK- Yakutat terrane; YSV- Yakutat Sea Valley. Plate boundaries (Gulick et al., 2007); high-resolution bathymetry (Gardner et al., 2006); remaining bathymetry (Smith and Sandwell, 1997); Yakutat terrane motion relative to North America (Elliott et al., 2010); Pacific plate motion (Kreemer et al., 2003).

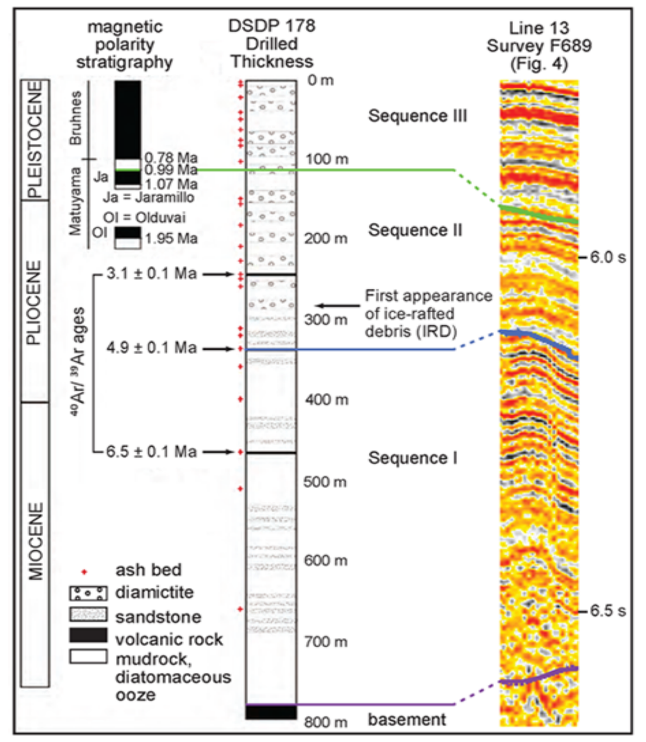

Figure 2. Lithology/age control for Deep Sea Drilling Project (DSDP) Site 178. Modified from Lagoe et al. (1993). Partial seismic section from line 13 of 1989 USGS survey F689 (Fig. 4); seismic data in two-way travel time. $^{40}Ar/^{39}Ar$ ages: Hogan et al. (1978). Magnetic polarity stratigraphy: von Huene et al. (1973). Seismic velocities: Shipboard Scientific Party (1973).

2. Data

Core Data
- DSDP 178: source of limited age control using magnetic polarity stratigraphy (von Huene et al., 1973) and $^{40}Ar/^{39}Ar$ dating of volcanic ash layers (Hogan et al., 1978). Only source of information on depth, lithology, and age control (Fig. 2) for sequences observed in fan.
- ODP 887: provides control within the fan for identifying relative changes in sedimentation rates and timing of climatic and tectonic events (Rea and Snoeckx, 1995).

2D Seismic
- 2008 NSF STEEP MCS dataset, R/V Langseth
- 2004 IODP site survey MCS dataset, R/V Ewing
- 1970's USGS MCS datasets: G175, L378, L677
- 1980's USGS single-channel datasets: F186, F988, F689, F789

Bathymetric Data
- 100 m² resolution data obtained in 2005 for United Nations Convention on Law of the Sea (Gardner et al., 2006).

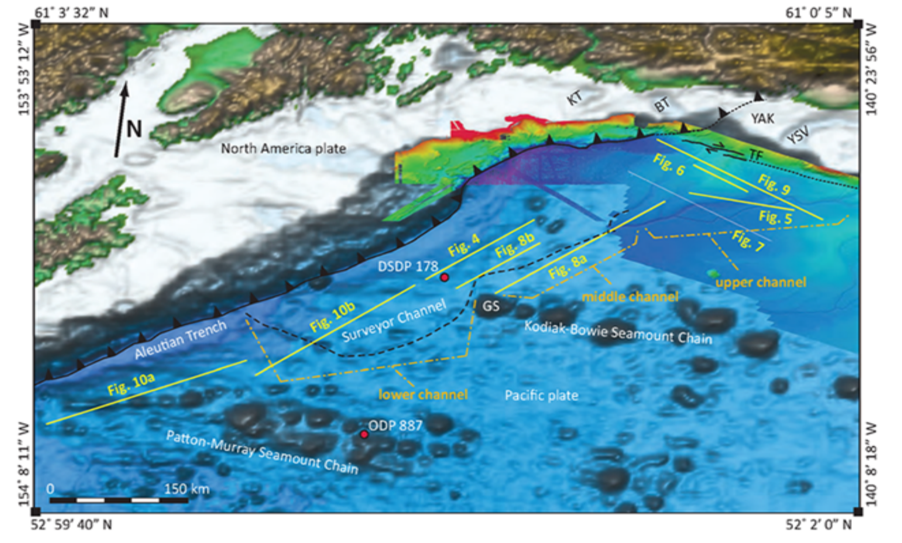

Figure 3. 3D perspective view showing tracklines of 2D seismic reflection surveys and ocean drill sites used in this study. High-res. bathymetry: Gardner et al. (2006); remaining bathymetry: Smith and Sandwell (1997). ASV- Alsek Sea Valley; BT- Bering Trough; DSDP- Deep Sea Drilling Project; GS- Giacomini Seamount; KT- Kayak Trough; ODP- Ocean Drilling Program; TF- Transition Fault; YAK- Yakutat terrane; YSV- Yakutat Sea Valley.

3. Observations and Results

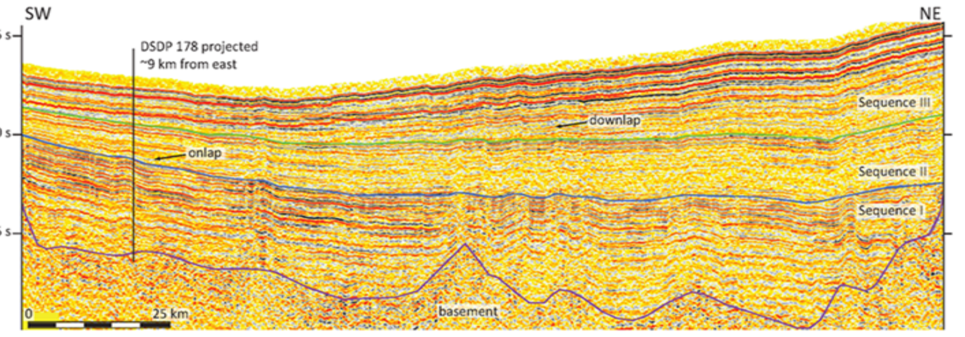

Figure 4. Seismic reflection profile showing interpreted sequences and approx. correlation to Deep Sea Drilling Project (DSDP) Site 178. See Fig. 3 for line location. Vertical axis in two-way travel time. Vertical exaggeration ~35:1 assuming 2000 m/s sediment acoustic velocity. (USGS Survey F689)

Surveyor Channel
- Upper channel (Fig. 4): distinct levees, reflectors that turn down into the channel flank, some sidewall failure, reflection truncation (Figs. 5, 7), and in the thickest section of the Surveyor Fan.
- Middle channel (Fig. 4): typically less channel fill than upper channel and less distinct or no levees (Fig. 8).
- Lower channel (Fig. 4): little to no historical channel fill, no downturned reflectors at sidewall, no levees, and occurs much lower in stratigraphy than upstream channel sections (Fig. 10b).
- Two main Surveyor Channel tributaries: Yakutat and Alsek Legs (Figs. 1, 7). Yakutat Leg related to Yakutat Sea Valley and Malaspina and Hubbard Glaciers. Alsek Leg related to Alsek Sea Valley and glacial system.
- Alsek Leg channel fill deposits first appear at I-II sequence boundary in the upper channel, demonstrating that a leveed channel has been in place since onset of sequence II deposition (Fig. 9); however, downstream in the middle channel where Alsek and Yakutat Legs have merged to form main trunk, channel fill deposits first appear at II-III boundary (Fig. 8a).

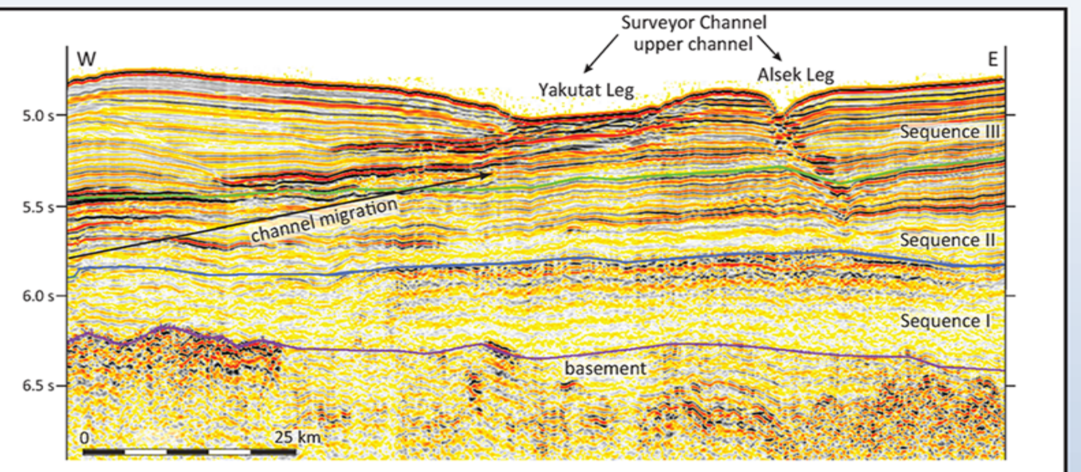

Figure 5. Seismic reflection profile showing interpreted sequences and migration of the Yakutat Leg of the Surveyor Channel. See Fig. 3 for line location. Vertical axis in two-way travel time. Vertical exaggeration ~20:1 assuming a 2000 m/s sediment acoustic velocity. (USGS Survey L378)

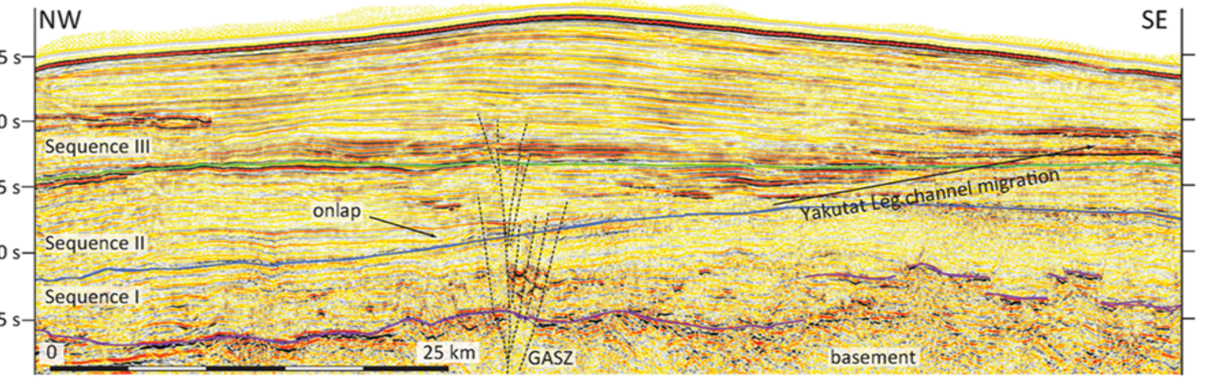

Figure 6. Seismic reflection profile showing interpreted sequences and migration of the Yakutat Leg of the Surveyor Channel. GASZ- Gulf of Alaska Shear Zone (e.g., Gulick et al., 2007). See Fig. 3 for line location. Vertical axis in two-way travel time. Vertical exaggeration ~8:1 assuming a 2000 m/s sediment acoustic velocity. (STEEP Survey)

Channel Migration
- Yakutat Leg: only leg that exhibits significant historic lateral movement. Channel fill deposits migrated 35 km southeast upsection (Figs. 5, 9).
- Migration occurs east of a substantial basement high (Fig. 9). The high underlies a bathymetric ridge formed by a sediment wedge that has aggraded and grown to the southeast.
- Yakutat Leg migration corresponds to reduction in fan growth observed on the two-way travel time thickness maps for sequence II and III (Fig. 12).

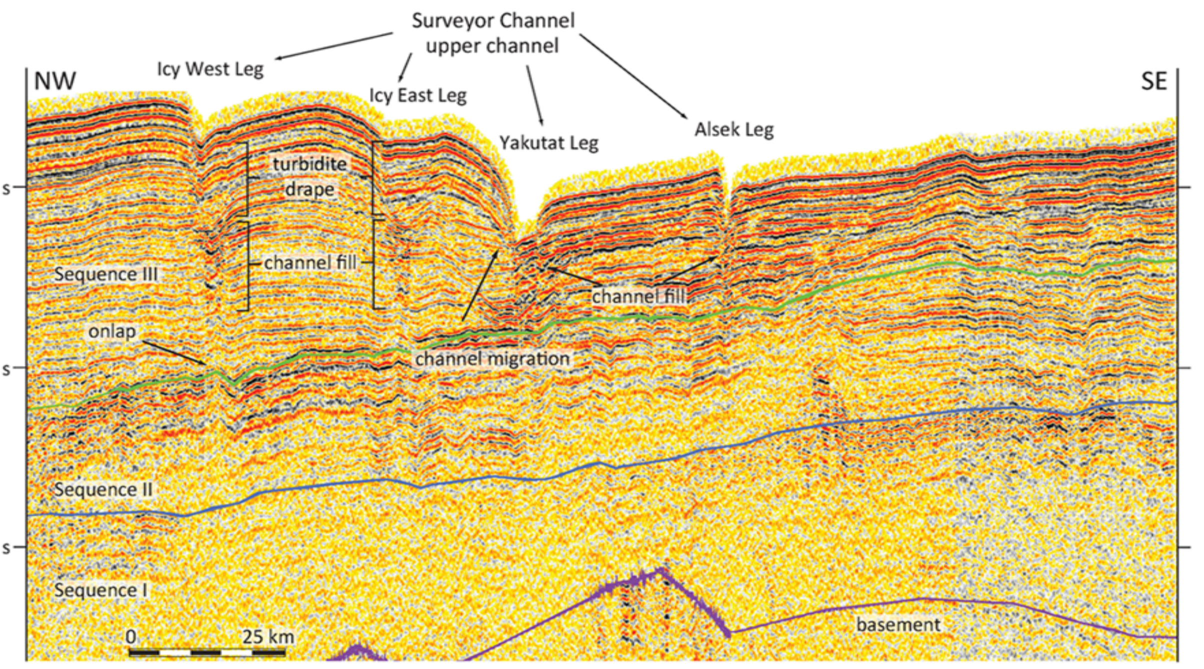

Figure 7. Seismic reflection profile showing interpreted sequences and the four main tributary legs of the Surveyor Channel. See Fig. 3 for line location. Vertical axis in two-way travel time. Vertical exaggeration ~50:1 assuming 2000 m/s sediment acoustic velocity. (USGS Survey F789)

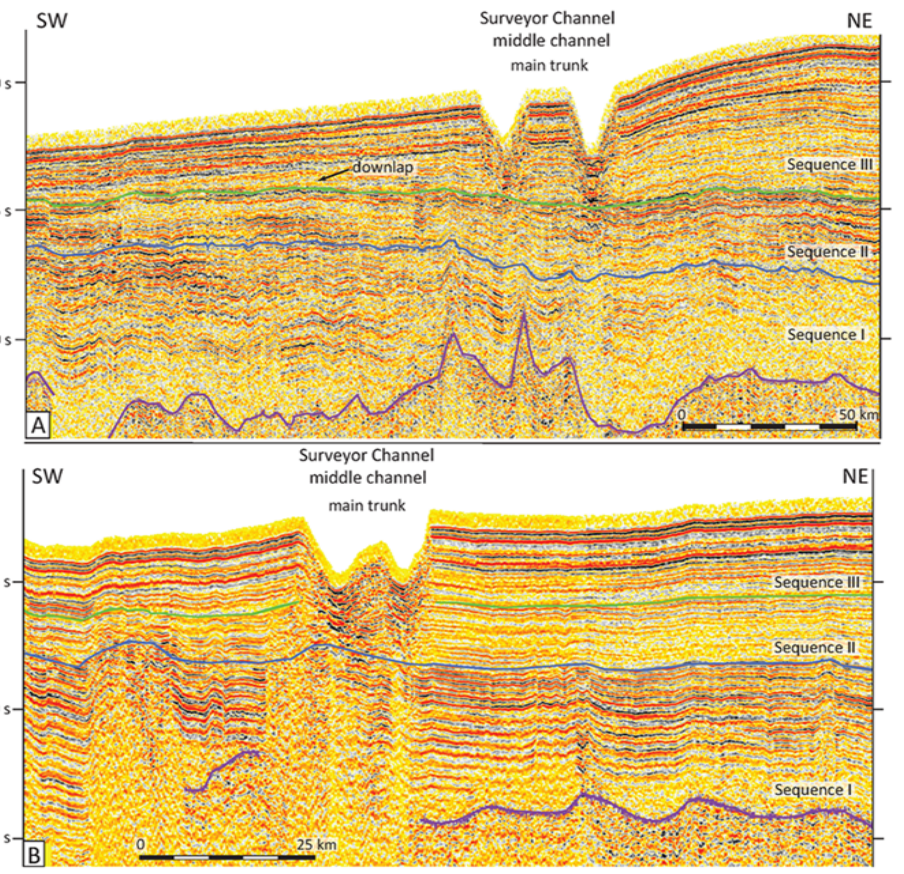

Figure 8. Seismic reflection profiles showing interpreted sequences and the main trunk in the middle channel section of the Surveyor Channel. See Fig. 3 for line locations. Vertical axis in two-way travel time. Vertical exaggeration (A) ~70:1 and (B) ~35:1 assuming 2000 m/s sediment acoustic velocity. (USGS Survey F689)

Regional Sequence Boundaries
- Sequence I-II boundary occurs at ~330 m depth in the DSDP 178 core, dated at ~1 Ma based on $^{40}Ar/^{39}Ar$ dating of ash layers (Hogan et al., 1978) (Fig. 2), making it coincident with the onset of glacial int. A. There is no observed change in lithology across the I-II boundary at DSDP 178.
- Sequence II-III boundary occurs at 130 m depth in the DSDP 178 core, dated at ~1 Ma based on magnetic polarity strat. (von Huene et al., 1973a) (Fig. 2), making it coincident with the onset of glacial int. C. The II-III boundary is 10 m above a change in fan lithology from abundant diamictite to less diamictite (Shipboard Scientific Party, 1973).
- Both sequence boundaries are synchronous with doubling in terrig. sed. flux observed at ODP 887 at ~5 Ma and ~1 Ma.
- Terrig. sed. flux at ODP 887 also doubles at glacial int. B (Rea and Snoeckx, 1995), but no observed regional sequence boundary or change in lith. that could be interpreted as onset of glacial int. B. Therefore, sequence II includes glacial int. A and B.

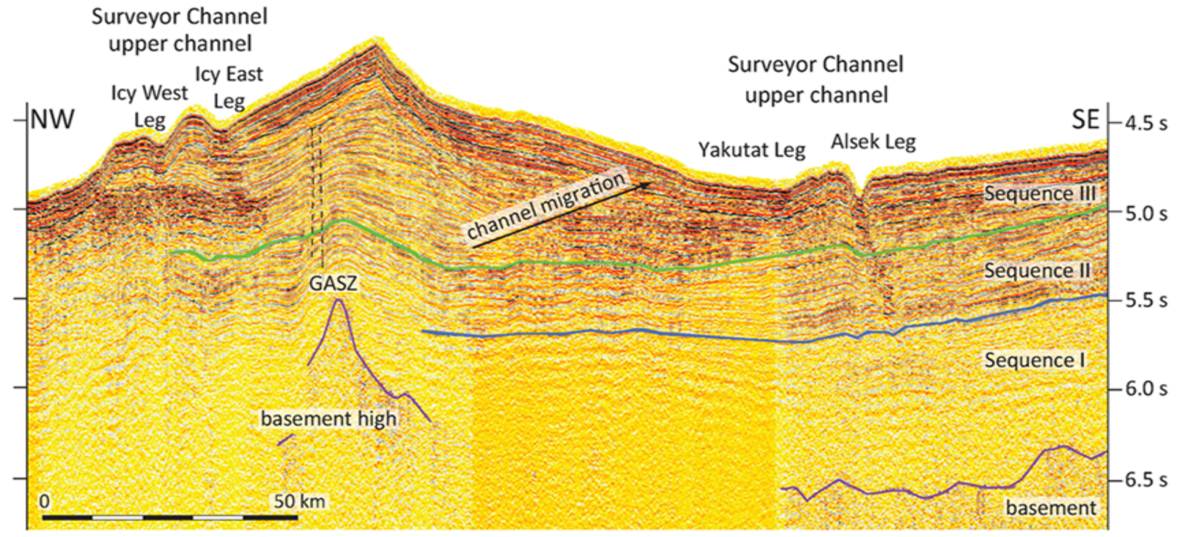

Figure 9. Seismic reflection profile showing interpreted sequences and four main tributary legs of the Surveyor Channel. Also evident is the basement high and sediment wedge that influenced migration of the Yakutat Leg. GASZ- Gulf of Alaska Shear Zone (e.g., Gulick et al., 2007). See Fig. 3 for line location. Vertical axis in two-way travel time. Vertical exaggeration ~35:1 assuming 2000 m/s sediment acoustic velocity. (USGS Survey F689)

4. Tectonic Control on Channel Position

- Zone of extension, flanked by the Kodiak-Bowie Seamount Chain to the north and the Patton-Murray Seamount Chain to the south, contains majority of lower Surveyor Channel (Fig. 4)- heavily faulted and regionally extensive (Fig. 10).
- The zone of extension and Aleutian Trench combined give the lower channel section the highest axial gradient of any Surveyor Channel section (Ness and Kulm, 1973). However, some channel fill is recorded in the erosional lower section of the Surveyor Channel (Fig. 10b).
- This channel fill in the lower section could be representative of sediment deposition between glacial maxima, whether from terrigenous sources or channel sidewall failures upstream.
- The current channel fill therefore could be an accumulation of fill since the last glacial event, or represent an amalgamation of interglacial deposits that were not fully eroded during glacial maxima.

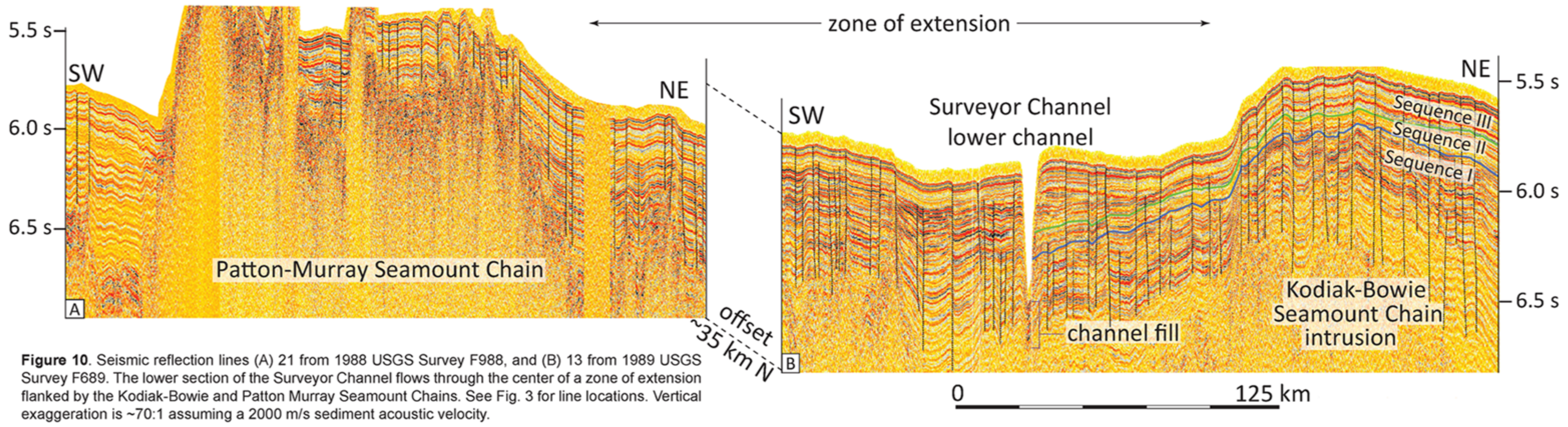

Figure 10. Seismic reflection lines (A) 21 from 1988 USGS Survey F988, and (B) 13 from 1989 USGS Survey F689. The lower section of the Surveyor Channel flows through the center of a zone of extension flanked by the Kodiak-Bowie and Patton Murray Seamount Chains. See Fig. 3 for line locations. Vertical axis in two-way travel time. Vertical exaggeration is ~70:1 assuming a 2000 m/s sediment acoustic velocity.

5. A New Volume Estimate

- We calculated Surveyor Fan sediment volume based on thickness measured between seafloor and basement on all available seismic reflection profiles.
- We estimate the volume of the Surveyor Fan to be ~6.8x10⁵ km³, comparable to the size of the Amazon Fan, and making it the fourth largest fan body by volume after the Bengal, Indus and Amazon Fans (Curry et. al, 2003).

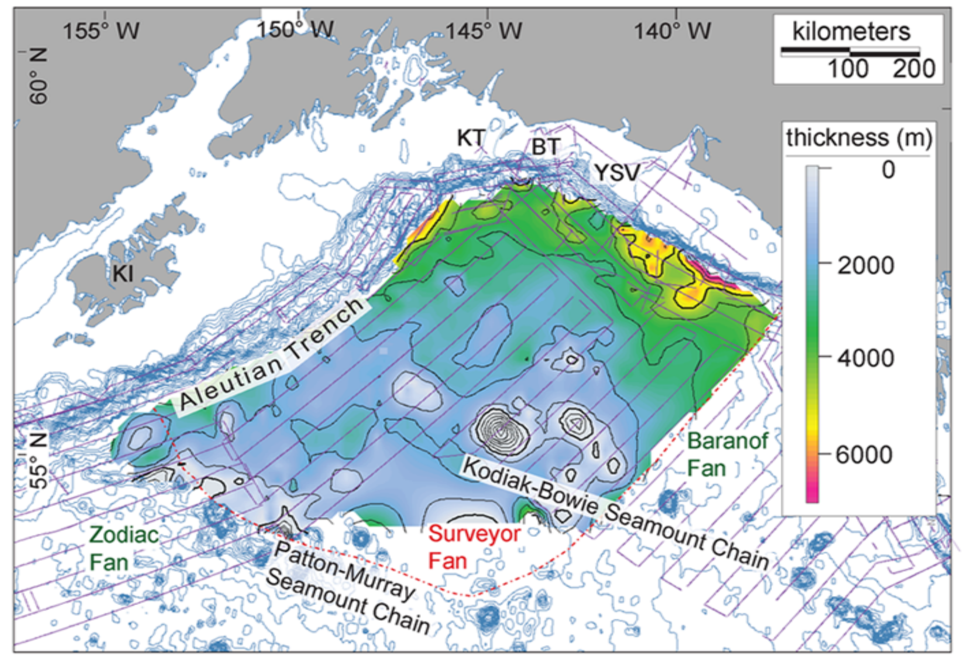

Figure 11. Isopach map showing Surveyor Fan sediment thickness, estimated Surveyor Fan boundary (red dashed line), and seismic line location used in calculation and boundary study (purple line). KI- Kodiak Island; KT- Kayak Trough; BT- Bering Trough; YSV- Yakutat Sea Valley.

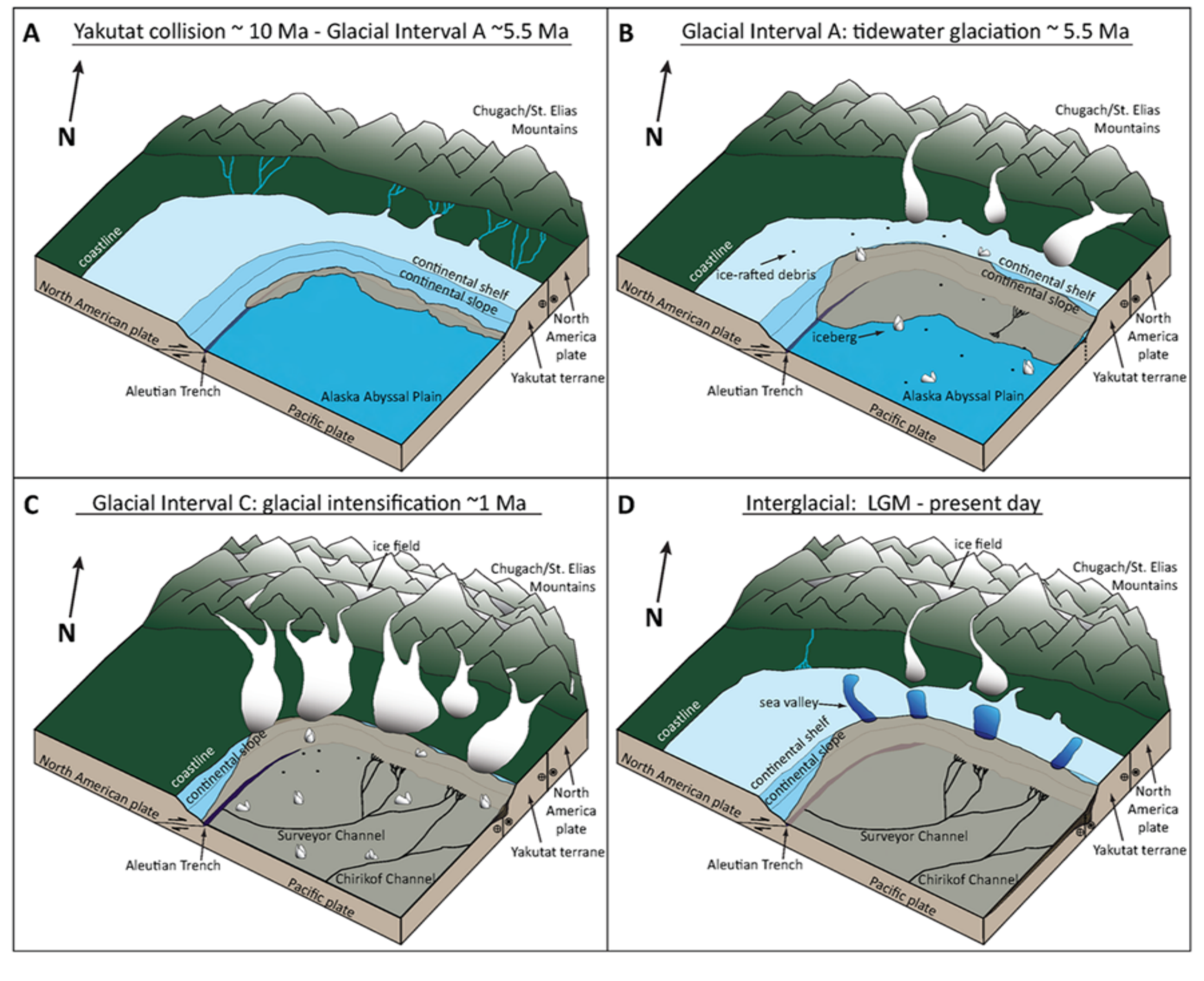

Figure 13. Schematic illustration of Surveyor Fan and southern Alaska margin sedimentary evolution over the last 10 Myr. Terrigenous sediment depocenter distribution represented by brown area on the seafloor. For simplicity, successive time steps do not show plate motion.

6. Glacial Intervals and Channel Inception

- Proximity of Surveyor and Chirikof Channel upslope heads to shelfal sea valleys (Fig. 1) suggests tributaries developed once glacial ice carved valleys to shelf edge, focusing fan sed. input to only a few shelf-edge locations.

Glacial Interval A
- Glacial int. A may not be severe enough to drive glaciers across the full shelf. Early Alsek Leg only present in proximal fan: sea valley maybe not necessary to form this proto Surveyor Channel (Fig. 13a, b).
- Glacial int. A and resulting proto Surveyor Channel (Fig. 13b) and depocenter shift (Fig. 12a to 12b) could be responsible for angular discordance and a large change in seismic amplitude in strata across the I-II seq. boundary.

Glacial Interval C
- Increased sedimentation associated with the glacial int. C was extreme, shifting from ~750 to 2000 mg/(cm²k.y.) in the distal fan (Rea and Snoeckx, 1995).
- All tributary leg channel fill deposits except for the Alsek first appear in the sediment record near the sequence II-III boundary (Fig. 7) in the upper channel, and the Alsek Leg appears at II-III sequence boundary in all but the most shelf-proximal seismic lines (Fig. 9).
- We interpret this to indicate that glacial int. C was impetus for further channel growth across the Surveyor Fan (Fig. 13b, c), and pronounced aggradation and progradation of the channel levees in sequence III (Fig. 12b, c).

Necessity of shelf-edge glaciation
- No observed regional sequence boundary associated with glacial int. B. We suggest that sed. distribution during glacial int. B was not significantly different than glacial int. A. The increase in sedimentation was not enough to spur a major change in fan sed. distribution, as observed with glacial int. C.
- Further evidence for necessity of shelf-edge glaciation for major channel formation in the Surveyor Fan.
- Channel fill of Icy Legs exhibits change in acoustic character, from high amplitude channel-fill deposits to laterally continuous turbidite drapes (Fig. 7). We interpret the boundary between as a "shutting off" of the Icy East and West Legs.
- The glacial system upstream of Pamplona Troughs may have become extinct or merged with Bering system.
- Icy Legs' shut down further supports necessity of shelf-edge glaciers to begin and maintain the Surveyor Channel.

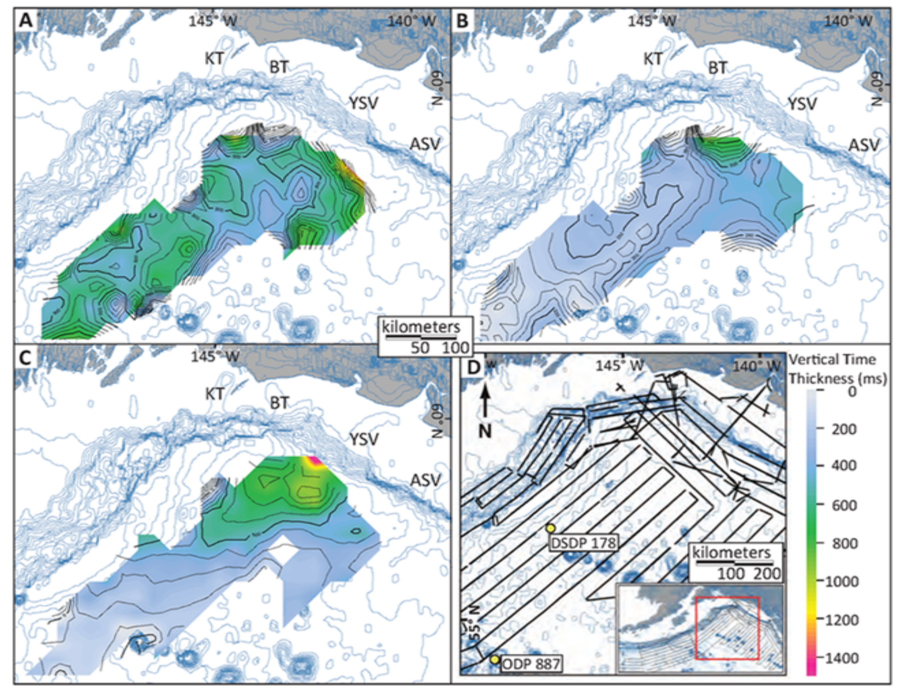

Figure 12. Isopach maps of (A) sequence I, Pacific plate formation - ~4.9 Ma, (B) sequence II, ~ 4.9 - 0.9 Ma, and (C) sequence III, ~1 Ma - present. Seismic reflection data tracklines used in calculation are shown in (D). ASV- Alsek Sea Valley; BT- Bering Trough; KT- Kayak Trough; YSV- Yakutat Sea Valley.

7. Glacial vs. Fluvial

- Sea valleys/troughs remnants of cross-shelf glacial transit: in the past, glaciers delivered sediment directly to slope at a glacial maximum.
- In spite of location and ability to bypass sediment to slope, glacial sea valleys may not be a direct proxy for fluvially-influenced shelf canyons.
- In glacial systems, sed. flux is greatly reduced during interglacial compared to glacial maxima, whereas a fluvial system could have a relatively constant sed. flux from highstand to lowstand (Covault and Graham, 2010).
- We suggest that sea valleys may bypass some sed. during interglacial times, but overall provide increased shelf accommodation space (e.g., Bering Trough, Worthington et al., 2010).
- Max. sed. delivery to fan occurs during glacial maxima due to associated increase in glacial erosion.
- Therefore, Surveyor system after glacial interval A has been built by periodic sed. pulses associated with glacial maxima, and has a shorter 'active' life than a fluvial system with a coeval origin.

8. Conclusions

1) Thickening of sequences into Yakutat shelf is evidence of long-term connection of Surveyor Fan to St. Elias sediment sources.

2) Glacial int. A reorganized fan sediment distribution by spurring Surveyor Channel genesis. Glacial int. C extended Surveyor Channel across Alaskan Abyssal Plain by pushing glaciers to the shelf edge and increasing the sed. flux to unprecedented levels.

3) Correlation of glacial int. C and the MPT to the II-III sequence boundary supports the Berger et al. (2008) hypothesis that MPT was a threshold where climate, compared to exhumation, started dominating erosion in the St. Elias orogen via glacial intensification.

4) Terrig. sed. flux into the Surveyor Fan/Channel system is periodic due to glacial-interglacial cycle, possibly leaving large portions of system essentially inactive during interglacial.

5) Glacial cross-shelf sea valleys are not direct proxies for fluvial canyons, but share characteristics.

6) NE-SW zone of extension between Kodiak-Bowie and Patton-Murray Seamount Chains creates a regional bathymetric low that funnels the lower Surveyor Channel to the Aleutian Trench.

7) We provide an updated estimate of Surveyor Fan volume at ~6.8x10⁵ km³, making it the fourth largest fan body by volume after the Bengal, Indus and Amazon Fans.

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*This work is a manuscript in review with Geosphere.

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