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Short, steep, and supercritical—Submarine fans in active rifts

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ABSTRACT

High-resolution seafloor data from the Gulf of Corinth, Greece, reveal new insights into rift-margin submarine fans deposited at the base of fault scarps. The steep (13°) Sythas canyon cuts into the submarine Lykoporia fault and is carpeted by low-relief, elongate rhomboidal bed forms. Across the fault, the canyon passes abruptly into the 6-km-radius Sythas submarine fan. The proximal fan (~3° gradient) contains multiple discontinuous channels, erosional cyclic steps, and scour fields. Channels shallow and broaden onto the medial fan (~1° gradient), which is characterized by trains of depositional cyclic steps that pass into low-relief lobes on the distal fan (~0.18° gradient). These morphological relationships compare to the submarine slopes of fan deltas and submarine fans in fjords but contrast markedly with established channel-levee distributary models of submarine fans. Sediment gravity flows were likely stratified, with a thin, concentrated, coarse-grained, and supercritical basal layer. Smooth interchannel areas suggest the basal layer (<5 m thick) was contained within erosional relief, before dissipating rapidly within ~3 km of the canyon mouth, with flows transformed into dilute, subcritical turbidity currents on the distal fan. This is the first time a continuum of proximal to distal bed forms has been documented on an active base-of-fault-scarp submarine fan and linked to sediment-gravity-flow structure and transitions from supercritical through transcritical to subcritical conditions.

INTRODUCTION

Alluvial fans and fan deltas in the hanging walls of major normal faults have been extensively studied as important archives of tectonic deformation, base-level change, and climatic variation (Gawthorpe and Leeder, 2000). In contrast, coarse-grained, deep-water deposits adjacent to submarine fault scarps have received less attention (Chiarella et al., 2021; Surlyk, 1978). We present new high-resolution bathymetry data collected using an autonomous underwater vehicle (AUV) from an active rift-margin submarine canyon–fan system—the Sythas submarine fan, Corinth Rift, Greece. These exceptional data allow imaging of the spatial distribution of subtle (<1-m-amplitude) seafloor bed forms for the first time. The continuum of bed forms, from canyon to distal fan, permits new insights into flow structure and transformations in steep, coarse-grained, fault-controlled submarine fans. These new data complement studies of modern, fine-grained, low-gradient, deep-water depositional systems (Carvajal et al., 2017; Droz et al., 2020; Maier et al., 2020) and challenge the use of distributary submarine fan models in tectonically active settings.

GEOLOGICAL SETTING

The Gulf of Corinth (130 km long and 30 km wide) is controlled by N-dipping normal faults along its southern margin (Fig. 1). It is characterized by high seismicity and N-S extension rates up to 14 mm/yr (Briole et al., 2000). Rifting became focused on the Gulf of Corinth between 2.0 and 1.8 Ma, and deformation progressively localized onto the N-dipping border fault by 335 ka (Gawthorpe et al., 2018; Nixon et al., 2024). The southern margin has a narrow shelf (0–1 km wide), a steep slope (14°–18°), and a relatively flat basin floor in water depths of ~850 m (Poulos et al., 1996).

The Sythas canyon erodes the submarine fault scarp of the Lykoporia fault, supplying the ~6-km-radius Sythas submarine fan in the immediate hanging wall (Figs. 1 and 2A; Mohamed et al., 2024). Seismic data suggest that the fan has been active since 800 ka (Deiss et al., 2025). The Sythas river catchment is incised into the footwall of the fault and covers an area of ~150 km^2. Gravel bars near the river mouth have a median grain size of pebble grade, and this sediment is transported as bed load during bankfull discharge and transferred to the Sythas canyon and fan (Watkins et al., 2020). Cable breaks offshore evidence high-energy sediment gravity flows resulting from river flood events (Ferentinos et al., 1988; Heezen et al., 1966). Earthquake-related mass failures are additional sources of gravity flows (De Gelder et al., 2022; Gawthorpe et al., 2022).

DATA AND METHODS

The data were collected in October 2023 using a Hugin HUS AUV operating from the R/V *Aegaeo*. The AUV followed preprogrammed track lines at 25 or 50 m above the seafloor at a speed of 3–4 knots. This study used data sets obtained from an EM2040 Multibeam Echosounder operating at 400 kHz and an EdgeTech 216 compressed high-intensity radiated pulse (Chirp) subbottom profiler operating at 2–10 kHz. Bathymetric data were processed using the Institut Français de Recherche pour l'Exploitation de la Mer's GLOBE software

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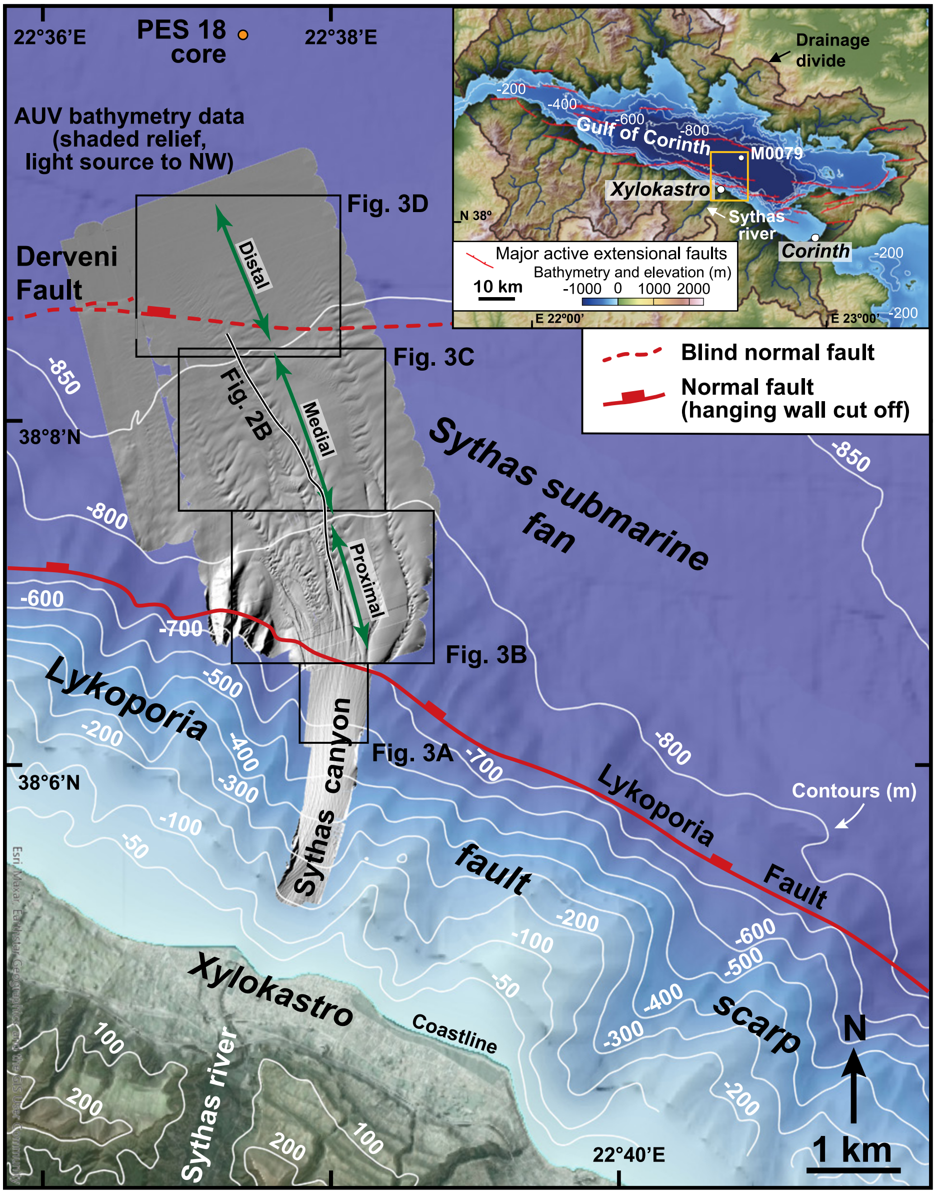

Figure 1. Sythas submarine canyon and fan. Shaded-relief autonomous underwater vehicle (AUV) bathymetry is shown in gray (lighting from NW). Inset shows location within Gulf of Corinth, Greece.

and CloudCompare, and they have a horizontal resolution of <50 cm and a vertical resolution of <1 cm. Chirp profiles were processed in SeaView and have a vertical resolution of ~10 cm and up to 10 m penetration over the fan.

SYTHAS CANYON AND BASE-OF-SCARP SUBMARINE FAN

The canyon and fan are described based on AUV-imaged erosional and depositional morphology and slope gradient, with the fan subdivided into proximal, medial, and distal domains (Fig. 1).

Sythas Canyon

The Sythas canyon is ~3 km long, has an average thalweg gradient of 13°, and appears mostly smooth, lacking major knickpoints (Figs. 1 and 2A). In its head region, the canyon is U-shaped in cross section, ~100 m deep and ~500 m wide, with steep walls up to 45°. The canyon widens downslope to a mouth coincident with the base of the fault scarp, where it is ~20 m deep and ~650 m wide, with a convex-up floor and walls dipping at ~14°. The gradient at the canyon mouth decreases abruptly from ~13° to ~3°.

The canyon floor is covered by low-relief elongate rhomboidal bed forms, ~50–150 m long, ~10–50 m wide, and several decimeters in amplitude, separated by V-shaped furrows (Figs. 1 and 3A). The angle between the furrows defining individual rhomboid margins is acute (20°–25°; Fig. 3A). Sets of rhomboidal bed forms with different orientations were observed (Fig. 3A).

Proximal Fan

The proximal fan (720–800 m water depth) has a gradient of ~3° and exhibits arrays of discontinuous channels, bed form trains, and scour fields (Fig. 3B). Channels originate from the furrows separating the elongate rhomboidal bed forms in the mouth of the canyon (Fig. 3B). The linear to slightly sinuous channels (40–70 m wide, up to 5 m deep, and 1–3 km long) merge in a tributary-like form near the canyon mouth, resulting in a down-fan decrease in the number of channels, which truncate subparallel stratigraphy in interchannel areas (Figs. 2C and 3B). Five main channels on the proximal fan, spaced up to a few hundred meters apart (channels 1–5; Figs. 2C and 3B), merge into three channels downstream, where the channels shallow and widen, eventually dying out in the transitional area between the proximal and medial fan.

The channels contain trains of regularly spaced crescentic bed forms with U- to V-crests opening downslope (Figs. 2B and 3B). In cross section, these bed forms have short, steep lee sides (9°–12°) and long, gentle stoss sides (1°–3°). Wavelengths range from 46 to 103 m, with amplitudes of 2.7–4.7 m.

Some areas of the proximal fan surface have scour fields, ~250 m wide and ~500 m long (Fig. 3B). Individual scours have complex planform geometries resembling V- or W-shapes. Scour walls are steep (up to 22°) and deep (up to 6 m) and have downstream spacing of ~100 m. Chirp profiles down the axis of the crescentic bed forms and the scour fields show a strongly reflective seafloor, with limited penetration (1–2 m). Reflections are truncated on lee sides and show low-angle, upslope-dipping reflectivity on some stoss sides (Fig. 2D).

Medial Fan

The medial fan (800–850 m water depth) has a gradient of ~1°, and proximal fan channels pass into curvilinear trains of bed forms (Figs. 2B and 3C). Three prominent trains of bed forms occur, one originating from the confluence of channels 1 and 2, one from channels 3 and 4, and one down the western edge of the fan from channel 5 (Fig. 3C). These bed-form trains are ~750–1000 m apart and separated from one another by a smooth, highly reflective seafloor (Fig. 3C).

The bed-form trains gradually widen down fan to several hundred meters and change from crescentic bed forms into a series of sinuous crested sediment waves (70–146 m wavelength, 1.3–3 m amplitude; Figs. 2B and 3C). In cross section, their morphology evolves to shorter, steeper stoss sides and elongate lee sides (Fig. 2E). Chirp profiles reveal aggradation, with some bed forms showing upslope migra-

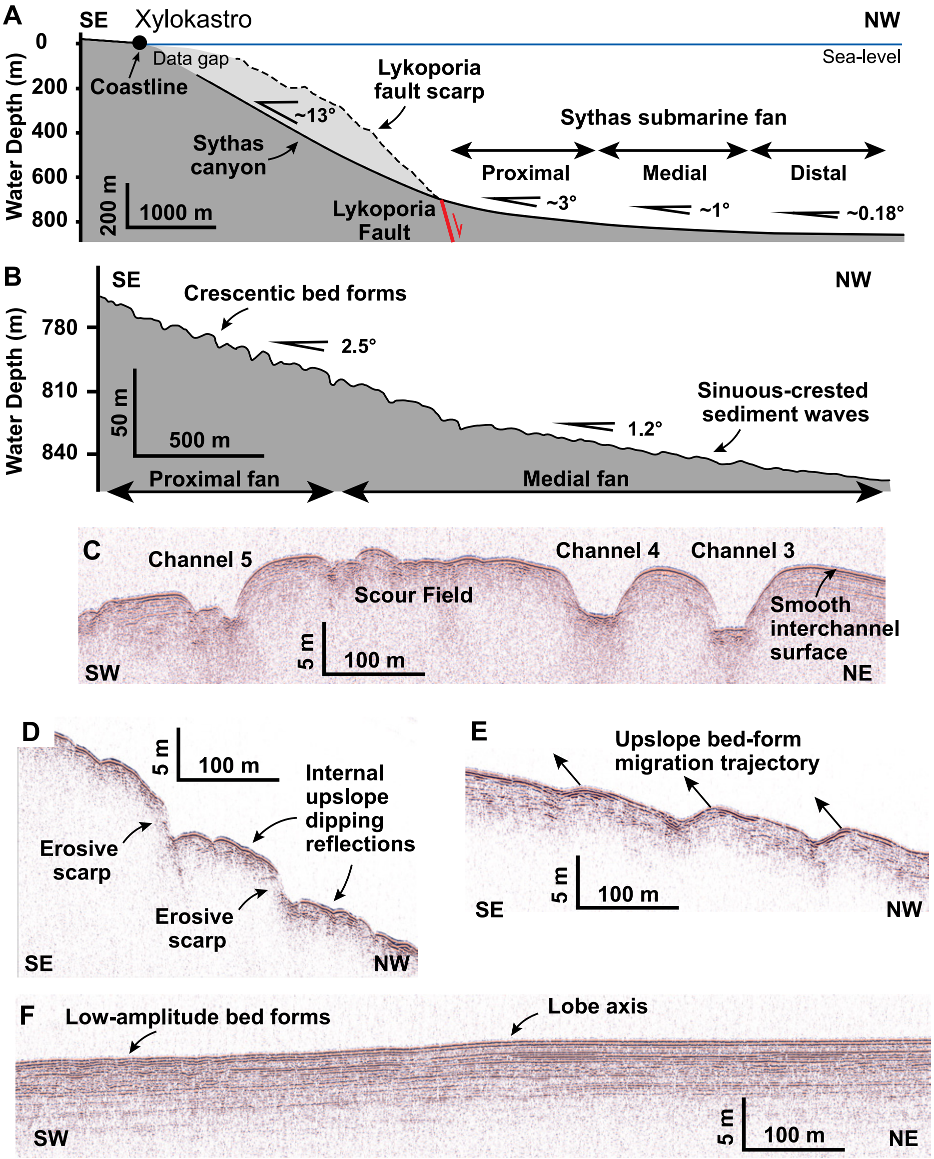

Figure 2. Bathymetry and compressed high-intensity radiated pulse (chirp) profiles. (A) Canyon-fan long profile and Lykoporia fault scarp. (B) Long profile down channel 3. (C) Proximal fan strike profile. (D) Scour field long profile. (E) Medial fan long profile through sediment wave train. (F) Distal fan strike section. See Figure 1 for part A and B locations; see Figure 3 for part C to F locations.

tion (Fig. 2E). The sediment waves gradually die out by decreasing wavelength and amplitude on the distal fan.

Distal Fan

The gradient of the distal fan (850–865 m water depth) decreases from ~1° to 0.18° (Fig. 3D). The trains of sediment waves on the medial fan progressively pass into low-relief lobes (1.5–2 m in amplitude and up to 750 m wide) on the distal fan (Figs. 2F and 3D). Lobes are spaced 1–2 km across the distal fan surface. On the lobes, sediment waves pass into low-amplitude bed forms (0.1–0.2 m amplitude, 20–50 m wavelength; Fig. 3D) with steeper stoss sides and shallower lee sides that progressively decrease in amplitude and wavelength and then die out on the lobe fringes. Chirp profiles have high-frequency, subparallel, continuous reflections that show subtle thinning off lobe axes (Fig. 2F).

DISCUSSION

High-resolution bathymetry of the submarine Lykoporia fault footwall and the Sythas submarine fan shows a down-flow change in morphology from canyon-floor rhomboidal bed forms through proximal fan erosional channels and crescentic bed forms into trains of sediment waves and finally into low-relief lobes on the distal fan (Fig. 4A). We suggest that these morphological features record supercritical sediment gravity flows that rapidly evolved and dissipated as they interacted with fault-controlled slope and basin-floor physiography (Fig. 4B).

Linking Morphology to Flow Characteristics

The rhomboidal bed forms on the Sythas canyon floor resemble rhomboidal features developed on beaches and in hurricane washovers (Morton, 1978), albeit the bed forms here are much larger. Experimental studies suggest rhomboidal bed forms mainly develop in thin supercritical flows, with furrow angle and rhomboid length being a function of Froude number and slope (Devauchelle et al., 2010). The Sythas canyon is steep (average 13°), and the long wavelength and acute angle of the rhomboidal bed forms suggest that flows in the canyon were thin and strongly supercritical, possibly laminar close to the seafloor, with periodic downstream-migrating surges (i.e., roll waves; Fig. 4B). The sets of rhomboids with different orientations support the idea of oblique interactions between roll waves close to canyon walls.

The development of channels from furrows on the canyon floor immediately downstream of the canyon mouth suggests that supercritical flows were important in channel development, and flow structure was highly heterogeneous downstream of the canyon mouth. The lack of draping infill on channel walls points to no single channel being dominant on the active sector of the fan (Fig. 4).

The trains of regularly spaced channel-confined crescentic bed forms on the proximal fan bear strong similarities to erosional cyclic steps (Hage et al., 2018; Slootman and Cartigny, 2020). These bed forms suggest the flows that debouched from the canyon at the base of slope and expanded over the proximal fan underwent a series of transitions from supercritical to subcritical, rather than a single hydraulic jump at the slope break. Such transcritical behavior may be typical in strongly stratified flows with dense near-bed layers (Dorrell et al., 2016; Hage et al., 2018; Salinas et al., 2020), suggesting that they resemble the flows with dense near-bed heads monitored in some turbidity currents (Fig. 4B; Hughes Clarke, 2016; Paull et al., 2018; Pope et al., 2022). The relatively short wavelength of the bed forms, 50–100 m, suggests they were formed by relatively thin flows and/or thin near-bed concentrated parts of flows. Furthermore, the smooth interchannel seafloor suggests that concentrated, near-bed flow layers were largely confined by the <5 m erosional relief and that the interchannel areas only experienced the upper, dilute, turbulent part of flows (Fig. 4B).

The trains of sinuous crested sediment waves extending across the medial fan resemble depositional cyclic steps (Slootman and Cartigny, 2020). This suggests that the flows were still supercritical or transcritical but had lost their

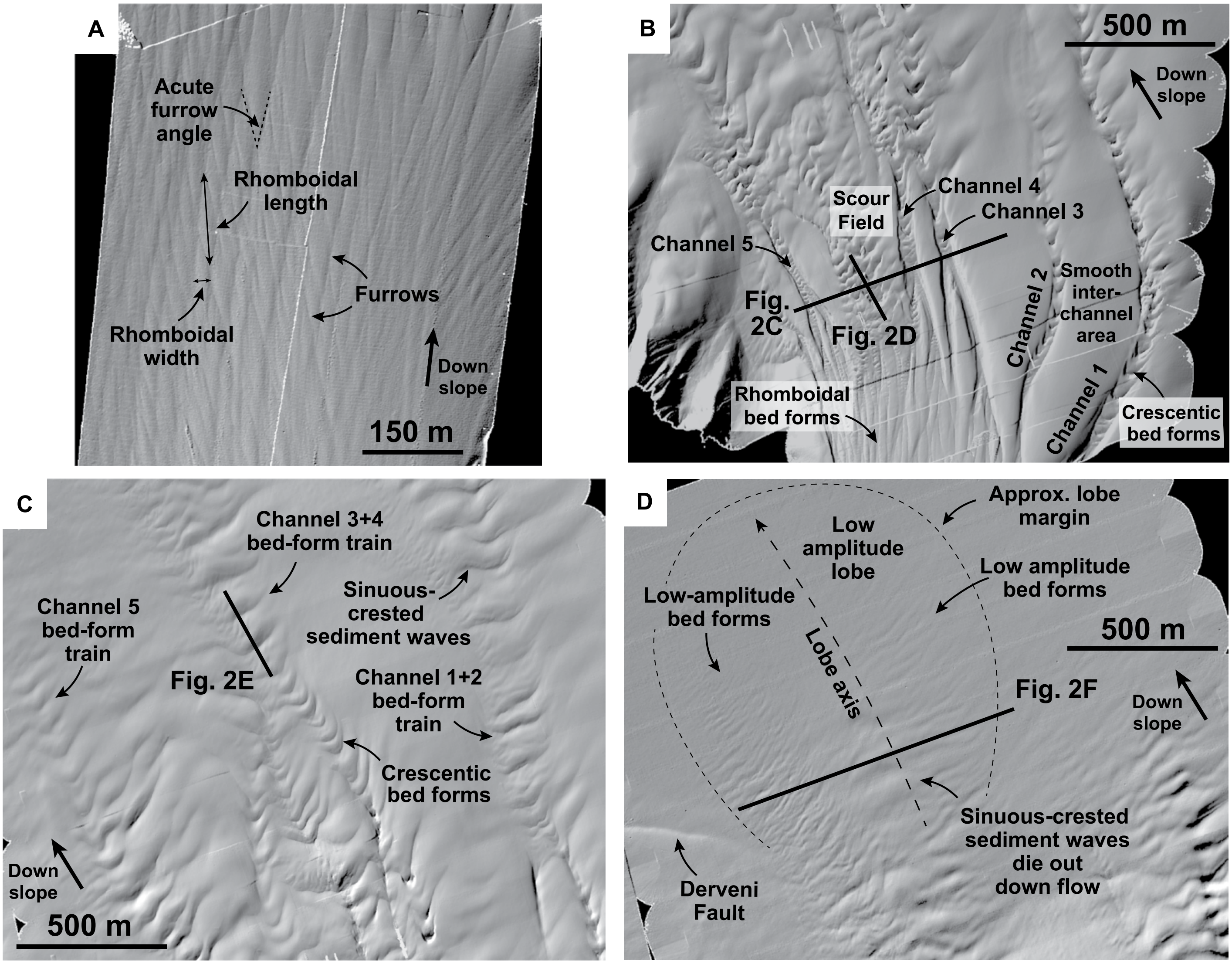

Figure 3. Details of submarine fan geomorphology: (A) canyon floor, (B) proximal fan, (C) medial fan, and (D) distal fan. Locations are shown on Figure 1.

capacity to be net erosional on the lower-gradient medial fan surface (Fig. 4B). Flow monitoring in Howe Sound, British Columbia, suggests that the majority of concentrated turbidity currents responsible for forming cyclic step bed forms dissipate rapidly, deposit the coarser-grained fraction, and become more dilute (Hughes Clarke, 2016; Stacey et al., 2019). It is likely that the flows evolved in a similar way on the Sythas fan, with deceleration, dilution, and progressive loss of the dense near-bed supercritical head on the medial fan, within 3 km of the canyon mouth (Fig. 4B). As such, the flows on the medial fan would be like the stage 2 flows of Pope et al. (2022).

The low-amplitude bed forms on the fringes of the distal fan lobes are similar to mixed sand-mud low-amplitude bed waves identified in lobe fringes (Baker and Baas, 2020), suggesting that the flows evolved to fully mixed, dilute subcritical to transitional turbidity currents (Fig. 4B). The reduction in gradient from the medial fan (1°) to distal fan (0.18°) most likely enhances the transition to subcritical flow conditions, leading to loss of flow capacity and deposition of the broad lobes. A box core, located ~1 km down flow from the distal fan lobes (PES 18; Fig. 1), is dominated by mud-grade sediment with very rare, <1-cm-thick, fine- to medium-grained sand beds (Lykousis et al., 2007), supporting the interpretation that flows transition to dilute, low-concentration, subcritical turbidity currents on the distal fan, ~5 km from the canyon mouth.

New Model for Fault-Controlled, Coarse-Grained Submarine Fans

Widely used models of submarine fan evolution portray single, levee-confined feeder channels that may pass into a channel-lobe transition zone to feed compensationally stacked lobes (Normark, 1978; Walker, 1978). Such models have been developed in mud-sand systems in settings with gradual basinward-decreasing slope. These systems contrast markedly with the Sythas system, which developed across a steep, fault-controlled slope with an abrupt gradient decrease at the base of slope (Fig. 4A). The distinctive characteristics of the Sythas fan point to a short, steep canyon that feeds coarse-grained supercritical flows to a submarine fan with multiple active channels containing erosional cyclic steps. The channels focus flows to trains of depositional cyclic steps and low-relief distal fan lobes (Fig. 4A). This spatial transition of depositional elements has more affinity with the submarine slopes of coarse-grained fan deltas and submarine fans in fjords (Gales et al., 2019; Prior and Bornhold, 1988, 1990). The steep apex of fjord submarine fans contains anastomosing gravelly swales and elongate ridges that transition through incised chutes with axial arcuate steps into sandy splays and low-relief hummocky lobes on the lower slopes of the fans (Prior and Bornhold, 1988). The downslope change in morphology on fjord submarine fans is strikingly similar to the changes documented

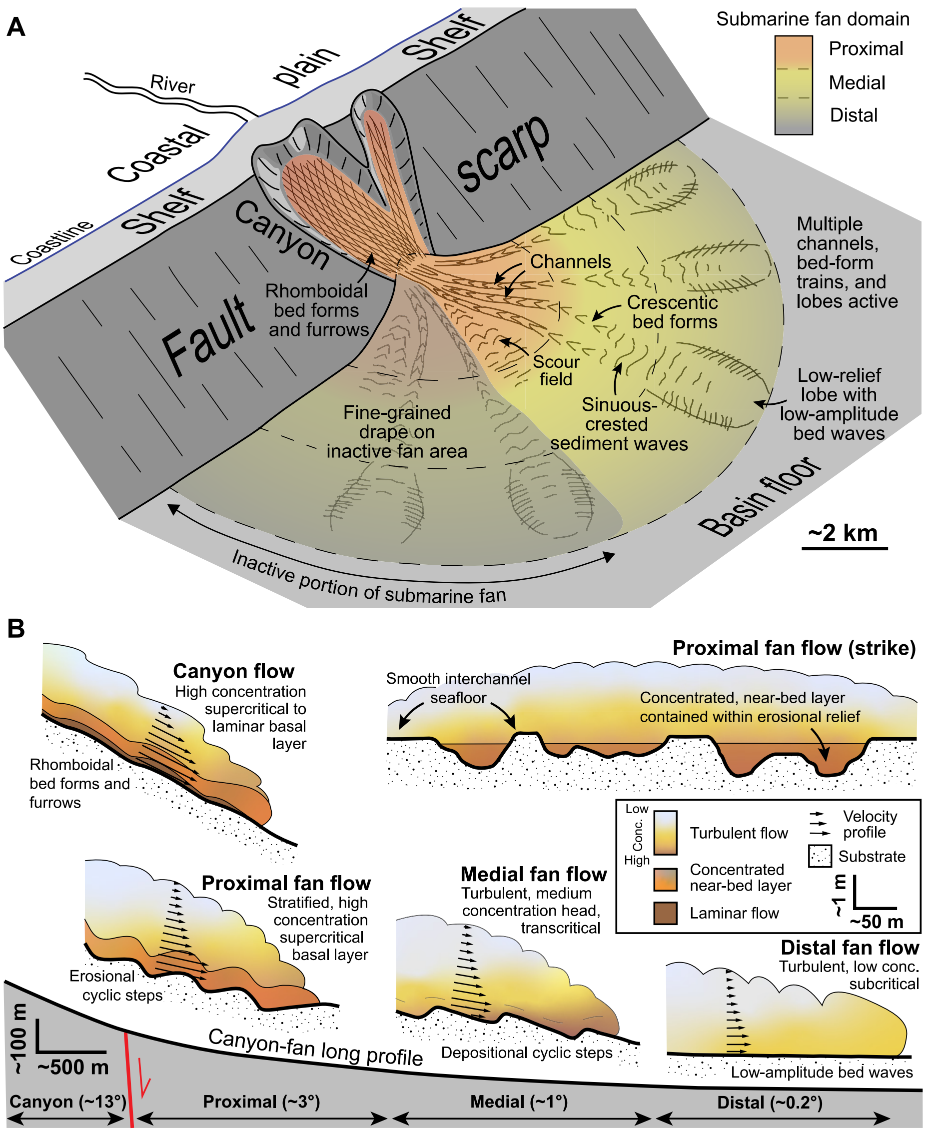

Figure 4. (A) Rift-margin submarine canyon–fan model. (B) Interpreted turbidity current flow characteristics and evolution down canyon and fan.

here from the fault-controlled Sythas canyon and fan (Fig. 4). However, the swale-ridge morphology occurs on the unconfined fjord fan apex, whereas the morphologically similar rhomboidal bed forms in this study are confined within Sythas canyon, with the discontinuous channels on the proximal Sythas fan located immediately down-flow of the canyon mouth.

In conclusion, AUV high-resolution seafloor data have imaged, for the first time, a continuum of proximal to distal bed forms on an active base-of-fault-scarp submarine fan over kilometer distances. We interpret the rapid down-fan changes in geomorphology to be driven by the rapid dissipation of dense, stratified supercritical turbidity currents and transitions from supercritical through transcritical to subcritical conditions (Fig. 4B). These results provide new insights into the sedimentary processes acting on rift-margin submarine fans and allow much better understanding of the controls on their sedimentology and stratigraphy, such as fault slip rates and climate-related sea-level or sediment-supply variations.

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