Controls on the origin and evolution of deep-ocean trench-axial channels

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ABSTRACT

The type and volume of sediment entering subduction zones affects the style of plate boundary deformation and thus sedimentary and tectonic cycles. Because submarine channels significantly increase the transport efficiency of turbidity currents, their presence or absence in subduction trenches is a primary control on trench fill. To date, comprehensive architectural characterization of trench-axial channels has not been possible, undermining efforts to identify the factors controlling their initiation and evolution. Here, we describe the evolution of the Hikurangi Channel, which traverses the Hikurangi Trench, offshore New Zealand. Analysis of 2D and 3D seismic data reveals that the channel was present only during the last ~3.5 Myr of the ~27 Myr of the trench's existence; its inception and propagation resulted from increased sediment supply to the trench following amplified hinterland exhumation. To test if the controls on the evolution of the Hikurangi Channel are universal, multivariate statistical analysis of the geomorphology of subduction trenches globally is used to investigate the formative conditions of axial channels in modern trenches. Terrigenous sediment supply and thickness of sediment cover in a trench are the dominant controls; subsidiary factors such as trench length and rugosity also contribute to the conditions necessary for trench-axial channel development. Axial channels regulate sediment distribution in trenches and this varies temporally and spatially as a channel propagates along a trench. The presence of a trench-axial channel affects plate boundary mechanics and has implications for the style of subduction margin deformation.

INTRODUCTION

Ocean trenches represent one of the last frontiers for exploration on Earth. Modern trenches are typically associated with forearc subduction margins and areally represent 0.5 % of the ocean floors (Harris et al., 2014). Some trenches host axial channels; others do not. Submarine channels are important drainage networks, transporting large volumes of terrigenous sediment, including organic carbon (e.g. Omura et al., 2017) and pollutants (e.g. Kane et al., 2020) into and within the deep-sea. Trench-axial channels regulate the volume, type and distribution of sediment in a trench. Sediment type, i.e. fine (hemi-) pelagic sediments *vs.* coarser terrigenous siliciclastic material, volume and distribution influence the mechanics of a subduction interface (Rabinowitz et al., 2018), the growth of accretionary prisms (Lewis and Hayes, 1984) and hence the nature of deformation at plate margins (Barnes et al., 2020). Despite their societal and scientific importance, the factors that control the presence or absence of axial channels and their stratigraphic evolution are poorly understood.

Although seafloor studies show the presence of trench-axial channels (e.g. Moore et al., 1982a; Thornburg et al., 1990; Lewis 1994), a lack of subsurface data in trenches has hitherto inhibited characterisation of their stratigraphic architecture and evaluation of factors controlling their existence and evolution. To attempt these tasks, a subsurface investigation of the Hikurangi Trench and its axial channel is performed (Fig. 1), to discern the controls on channel formation and stratigraphic evolution. This subsurface investigation uses the first 3D seismic survey to image a forearc trench-axial channel and an expansive 2D survey covering much of the trench. To test the findings from the Hikurangi Margin, insights from this case study are used to inform a comparative analysis of active subduction trenches globally. A better understanding of the controls on the origin and evolution of trench-axial channels is essential to better understand the erosion, transport and deposition of sediments, from land to the deep-ocean and their recycling at plate boundaries, with implications for the tectonostratigraphic evolution of subduction zones.

DATA AND METHODS

Our dataset comprises >5000 line-kilometers of 2D and 2600 km^2 of 3D seismic data (see supplementary material S1-4). Data are displayed SEG positive; a downward decrease in acoustic impedance is shown as a trough (white reflection). Key surfaces (Fig. 2) were mapped in accordance with the chronostratigraphic framework of Ghisetti et al. (2016). Dimensional and morphometric measurements from global trenches were obtained using data within Geomap App© and published papers (see S5 and S6). Principle component analysis was conducted on the trench dataset to investigate the factors associated with the presence of axial channels.

THE HIKURANGI CHANNEL

Geological Setting

The SW-NE trending Hikurangi Trench developed over the last 27 Ma by subduction of the Pacific Plate beneath the Australian Plate (Ballance, 1976; Jiao et al., 2014). Convergence rates have increased through the subduction event (Nicol et al., 2007). The southern end of the margin demonstrates a seismically locked plate interface; slow-slip events are occurring in the north (Fig. 1; Wallace and Beavan, 2010). The Hikurangi Trench sits under 2600 to 3600 m of water (Fig. 1). Trench fill, interpreted to be dominantly <3.5 Ma (Ghisetti et al. 2016; Kroeger et al., 2019), thins from ~6 km of sediment in the SW, to <1 km in the NE, where the channel deviates out of the trench (Lewis, 1994). The fill consists of relatively monotonous reflectors interpreted as (hemi-) pelagic, turbidite, mass-transport and contourite deposits (McArthur et al., 2019). Trench traversing flows are sourced by the flushing of slope canyons of the NE South Island and SE North Island (Fig. 1; Mountjoy et al., 2018).

Key events in the margin's history include: (a) North Island exhumation ~27–20 Ma (Jiao et al., 2014); (b) reconfiguration and uplift of the South Island from ~12-5 Ma (Tippett and Kamp, 1993), resulting in increased exhumation rates of both islands at ~6–4 Ma (Jiao et al., 2017); (c) the onset of Taupo volcanism ~2 Ma (Acocella et al., 2003); (d) a Plio-Pleistocene increase in the amplitude of glacio-eustatic sea-level changes, which increased sediment flux (Haywick et al., 1992).

Channel Inception and Stratigraphic Evolution

Pre-channel strata

A distinct horizon (R5b), dated as >3.5 Ma by Ghisetti et al. (2016), occurs at 6.5 –0.5 km depth in the south (Fig. 2A) and can be traced along the trench, occurring at 5 – 0.35 km depth in the north (Fig. 2B). This surface and underlying reflectors dip at up to 14^{o} to the NW. Although often deformed, reflectors below are uniform, moderate in amplitude and frequency. Reflectors above the surface onalp onto it, are flat to gently dipping and exhibit variable amplitude and frequency. This deepest trench fill is imaged as a monotonous package of reflectors, potentially representing turbidity current deposits in the south (Fig. 2A), which thins to the north where drilling identified coeval pelagic sediments (Fig. 2B; Barnes et al., 2020).

Isolated channel forms

The deepest preserved axial channel fills are isolated channel forms that stack vertically and to the SE and lack recognizable levees (Fig. 2C and F). In the south of the trench they are present through several hundred meters of strata (Fig. 2A); they terminate within the trench and are absent in the north (Fig. 2B). The formative conduits of these channel fills were relatively small (<5 km wide), linear and dominantly erosional; they distributed sediment in the trench.

Leveed channel forms

A distinct change in reflector style occurs at ~800 m depth subsurface, above which channel fills are aggradational, generally wider (2.5-10 km wide) and are bounded by compound levees hundreds of meters thick (Fig. 2D and E). This change in reflector style is interpreted to have occurred at ~1 Ma (Ghisetti et al., 2016). As opposed to the early channel forms that show significant lateral offset (Fig. 2F), channels within the upper interval typically follow the course of their predecessor, exhibiting little lateral offset but greater sinuosity (Fig. 2G). Within this interval the channel system was never completely abandoned, with the exception of downsteam reach cut-off following a major avulsion (Fig. 2B), due to channel deflection around a seamount.

Controls on Hikurangi Channel inception and evolution

Propogation of the Hikurangi Channel along the trench began ~3.5 Ma. Channel inception, marked by the transition from background sediments to isolated channel forms that terminate in the trench, ties to an acceleration of the exhumation of New Zealand between 6 and 4 Ma (Jiao et al., 2017), albeit with a temporal lag for increased sediment flux to reach the trench. Amplified delivery of sediment to the trench resulted in increasing lateral flow confinement, promoting channelization (Tek et al., 2020). At its initiation the channel was unable to persist significant distances along the trench; only when sufficent sediment cover supressed trench rugostiy was the channel able to propogate 630 km along the trench.

COMPARISON WITH GLOBAL TRENCHES

To test whether the controls on the inception and evolution of the Hikurangi Channel are important globally, thirty-six trenches, located at convergent oceanic margins, are analysed to investigate the controls on the presence of axial channels. Fourteen of these trenches contain axial channels (see S5). Principle components analysis of twenty-three geomorphological factors reveals trench length, thickness of sedimentary cover and sediment supply as the primary factors that control development of trench-axial channels (Fig. 3). Sediment supply is the volume of sediment transferred to a trench by axial or transverse flows (Underwood and Karig, 1980); sedimentary cover is the total thickness of sediment accumulated in a trench, including accreted sediments (Moore and Karig, 1976), meaning it is affected by the subduction rate and other types of subaqueous processes; the two factors are therefore distinct.

Trenches with axial channels

Channel-bearing trenches are well supplied by terrigenous sediment, fed via slope bypassing canyons. Three end-members can be identified:

1) Trenches containing channels that traverse their host trench for kilometers to thousands of kilometers, before terminating in a trench-hosted fan (e.g. southern Chile Trench, Thornburg et al., 1990).

2) Trenches containing stretches of channels tens to hundreds of kilometers long, which escape their confines to terminate on the subducting plate. Channels may escape if the trench is blocked by seamounts or landslides (e.g. the Hikurangi Channel, Lewis et al., 1998).

3) Trenches in which slope channels continue uninterrupted onto the subducting plate (e.g. Cascadia, Komar, 1973). Here, sedimentation rates outpace subsidence and the trench is infilled. While these trenches do not presently demonstrate axial channels, their fill may contain deposits of ancient axial channels, formed when the trench had negative relief.

Channel-bearing trenches contain sufficient sedimentary fill, derived axially or from transverse systems, to suppress the trench rugosity, therefore permitting uninterrupted axial flow and channelization.

Trenches without axial channels

Trenches may not contain axial channels because:

1) They lack adequate terriginous sediment supply to form one (e.g. most trenches of the SW Pacific, Clift et al., 1998).

2) Trench rugosity is prominent and cannot be suppressed by sediment influx. In such cases, ponding against topographic obstacles inhibits channelization, even when sediment supply is high (e.g. the Izu-Ogasawara Trench, Soh et al., 1988).

3) Although a subduction margin may be well supplied with sediment, trenches may have a limited sediment supply due to trapping of sediment in trench-slope basins (e.g. Japan Trench, von Huene et al., 1982).

CONTROLS ON THE PRESENCE OF TRENCH-AXIAL CHANNELS

Most trenches don't contain axial channels (Fig. 3). A sustained supply of terrigenous sediment is essential to instigate and sustain a trench-axial channel system (Underwood and Karig, 1980); however, this alone does not necessitate the presence of an axial channel, e.g. the Calabrian Trench (Polonia et al., 2011). A sediment supply threshold exists: enough sediment must be supplied to the trench to heal trench rugosity, preventing ponding of turbidites and facilitating the flow run-out required for channelization (Underwood and Karig, 1980). This threshold is not static, but inherently linked to convergence rates and trench rugosity at each margin; trenches with high subduction rates and prominent intra-trench topography require greater sediment supply to generate an axial channel (Underwood and Bachman, 1982). The presence of trench rugosity, such as that formed by transform faults or by seamounts within the trench don't rule out the existence of an axial channel, merely that the channel may not persist far along the trench (e.g. Moore et al., 1982b).

Trench-axial channels form when sediment supply is sufficient to suppress trench rugosity, but not to completely fill the trench. However, localized trench occlusion due to landslides or subducting plate topography may divert channels away from the trench (e.g. Lewis et al., 1998). Trench length is a controlling factor for the presence of an axial channel simply because the longer a trench, the more likely the conditions to facilitate channelization will be met.

Insights from the Hikurangi Margin and comparative analysis suggest a common model for the formation and evolution of trench-axial channels (Fig. 4). At the onset of subduction, when a trench is topographically complex, it is unlikely that terrestrial drainage networks can supply enough sediment to allow the formation of an axial channel. Sediment starved trenches with high rugosity cannot support axial channels; sediment entering the trench ponds in local accommodation (Fig. 4A), e.g. the Tonga Trench (Clift et al., 1998). Ongoing convergence, uplift and exhumation of the upper plate result in increasing terrestrial drainage and sediment supply to the trench, promoting trench fill.

Aggrading trench fill suppresses trench rugosity and a short axial channel may form, building a sedimentary wedge along the trench that permits channel propagation along the trench before terminating (Fig. 4B), e.g. the Bougainville Trench (Tiffin et al., 1987). As a trench matures, lateral confinement increases and sediment supply continues to rise, its axial channel may propagate for tens to thousands of kilometers along the trench, e.g. the Chile Trench (Thornburg et al., 1990). Finally, a trench may become filled with enough sediment to lose its topographic expression, allowing channels to avulse and for trench-perpendicular channels to become established (Fig. 4C), e.g. Cascadia (Komar, 1973).

Although factors such as trench-axial gradient and climatic change have been inferred to exert a primary control on the presence of axial channels (Ness and Kulm, 1973; Underwood and Bachman, 1982), this study shows that they play a minor role. For example, the channelized portion of the Hikurangi Trench has the joint lowest axial gradient of all subduction trenches (av. 0.5˚). Axial channels occur in trenches across all of Earth's climate zones (Fig. 3).

CONCLUSIONS

Assessment of the bounding conditions of subduction trenches identifies the key controls on the presence of a trench-axial channel to be the rate of terrigenous sediment supply and the deposition of sufficient sediment cover to suppress trench rugosity. A sweet spot for axial channel development may arise in the evolution of a trench, where it receives sufficient sediment to develop an axial channel, but has not been overfilled to a point at which the channel may escape the trench confines. Initially, terrigenous sediments entering a trench are spatially restricted, compared with later dispersal of sediment along a trench by an axial channel. Hence, simple models of trench fill are invalid in the presence of axial channels and their levees, which regulate sediment distribution and promote lateral and longitudinal heterogeneity in trench fill.

The type, volume and timing of sediment deposited along a trench has implications for the evolution of subduction zones, the type of material and fluids subducted and recycled by arc volcanism, and the mechanical development of accretionary prisms. The presence of a trench-axial channel results in a temporal and spatial variation in the sediment type being subducted and its effects on plate boundary mechanics, the length scale of which will extend as a channel propogates along a trench. Mapping the nature of trench sediments is therefore an important consideration in modelling subduction deformation.

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FIGURES

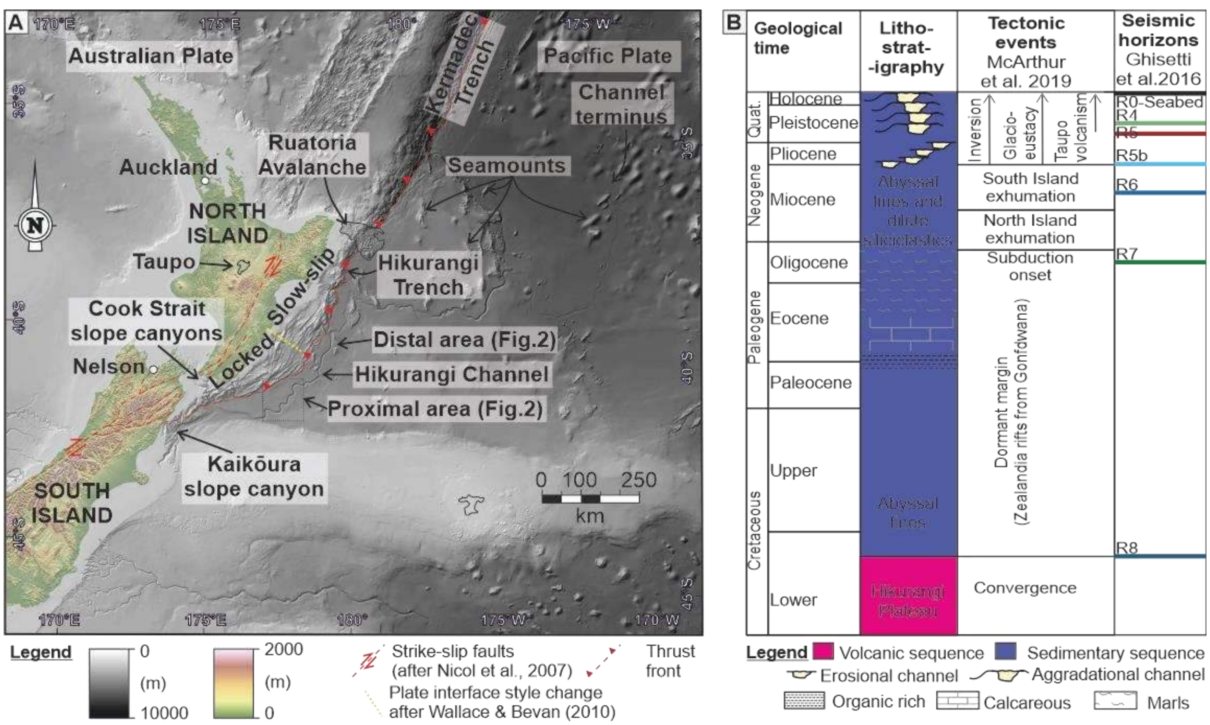

Figure 1. (A) Map of the Hikurangi Margin courtesy of NIWA. (B) Lithology and geological history of the Hikurangi Trench.

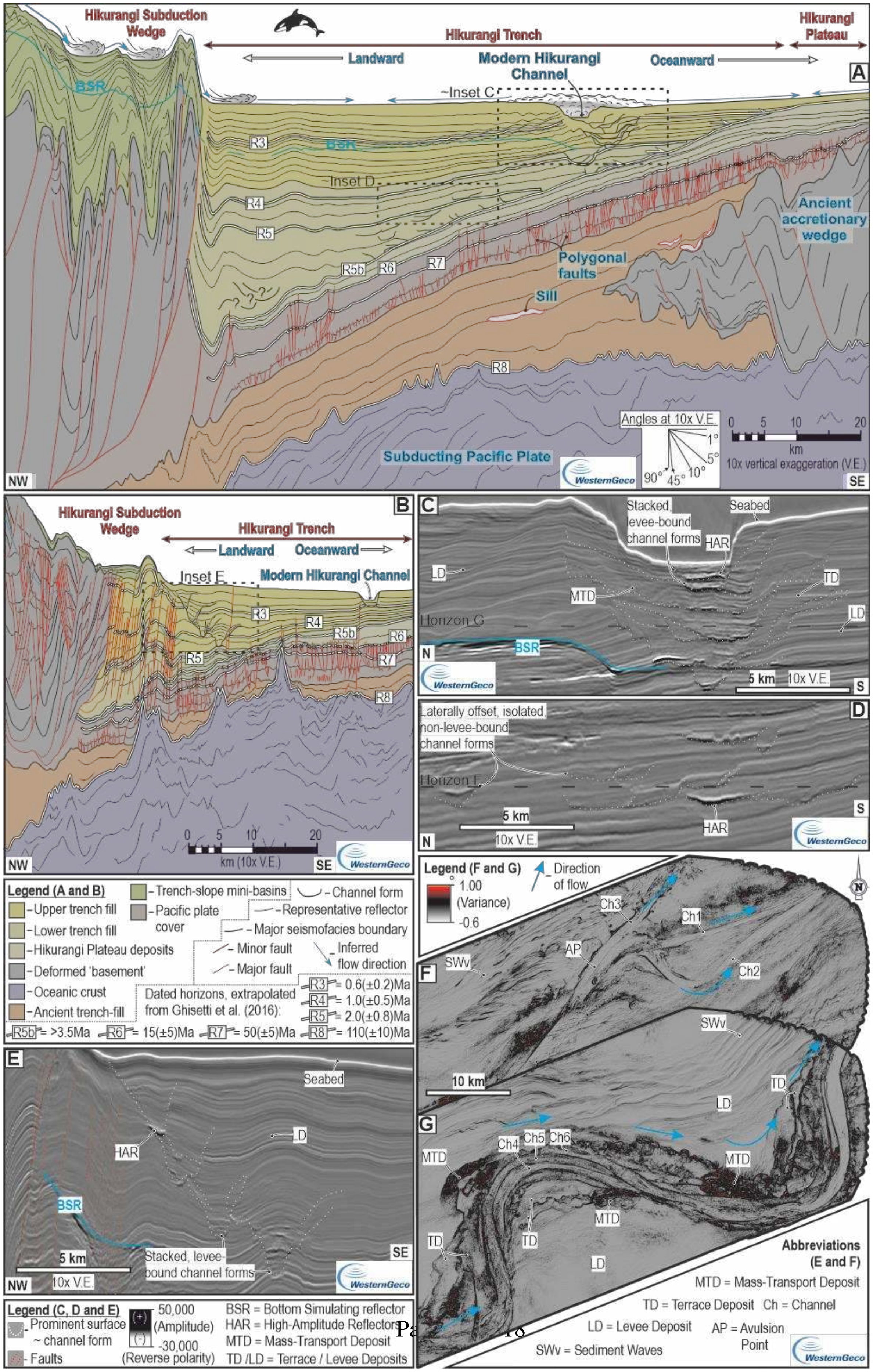
Hikurangi Subduction Wedge
Hikurangi Trench
Landward
Oceanward
Modern Hikurangi Channel
Hikurangi Plateau
~Inset C
Inset D
BSR
R3
R4
R5
R5b
R6
R7
R8
Polygonal faults
Sill
Ancient accretionary wedge
Subducting Pacific Plate
Angles at 10x V.E.
10x vertical exaggeration (V.E.)
NW
SE
Inset E
Stacked, levee-bound channel forms
Seabed
HAR
LD
TD
MTD
Horizon G
Laterally offset, isolated, non-levee-bound channel forms
Horizon F
5 km
10x V.E.
N
S
Legend (A and B)
Upper trench fill
Lower trench fill
Hikurangi Plateau deposits
Deformed 'basement'
Oceanic crust
Ancient trench-fill
Trench-slope mini-basins
Pacific plate cover
Channel form
Representative reflector
Major seismofacies boundary
Minor fault
Major fault
Inferred flow direction
Dated horizons, extrapolated from Ghisetti et al. (2016):
R3 = 0.6(±0.2)Ma
R4 = 1.0(±0.5)Ma
R5 = 2.0(±0.8)Ma
R5b = >3.5Ma
R6 = 15(±5)Ma
R7 = 50(±5)Ma
R8 = 110(±10)Ma
Legend (F and G)
1.00
(Variance)
-0.6
Direction of flow
Ch1
Ch2
Ch3
Ch4
Ch5
Ch6
AP
SWv
10 km
Legend (C, D and E)
Prominent surface ~ channel form
Faults
50,000
(Amplitude)
-30,000
(Reverse polarity)
BSR = Bottom Simulating reflector
HAR = High-Amplitude Reflectors
MTD = Mass-Transport Deposit
TD /LD = Terrace / Levee Deposits
Abbreviations (E and F)
MTD = Mass-Transport Deposit
TD = Terrace Deposit
Ch = Channel
LD = Levee Deposit
AP = Avulsion Point
SWv = Sediment Waves
WesternGeco

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Figure 2. (A) Proximal and (B) distal interpreted depth sections of Hikurangi Trench fill (uninterpreted data S3 and S4). (C) Enlargement of isolated channel fills from the proximal area in the base of the trench fill. (D) Enlargement of upper ~800 m of the trench fill in the proximal area. (E) Enlargement of upper ~800 m of the trench fill in the distal area. (F) Depth slice using variance attribute analysis to illustrate the proximal, lower, isolated channel forms containing relatively linear early channels (Ch1-3), which diverge through the trench fill. (G) Depth slice using variance attribute analysis to illustrate the proximal, upper leveed channel form containing channels Ch4-6.

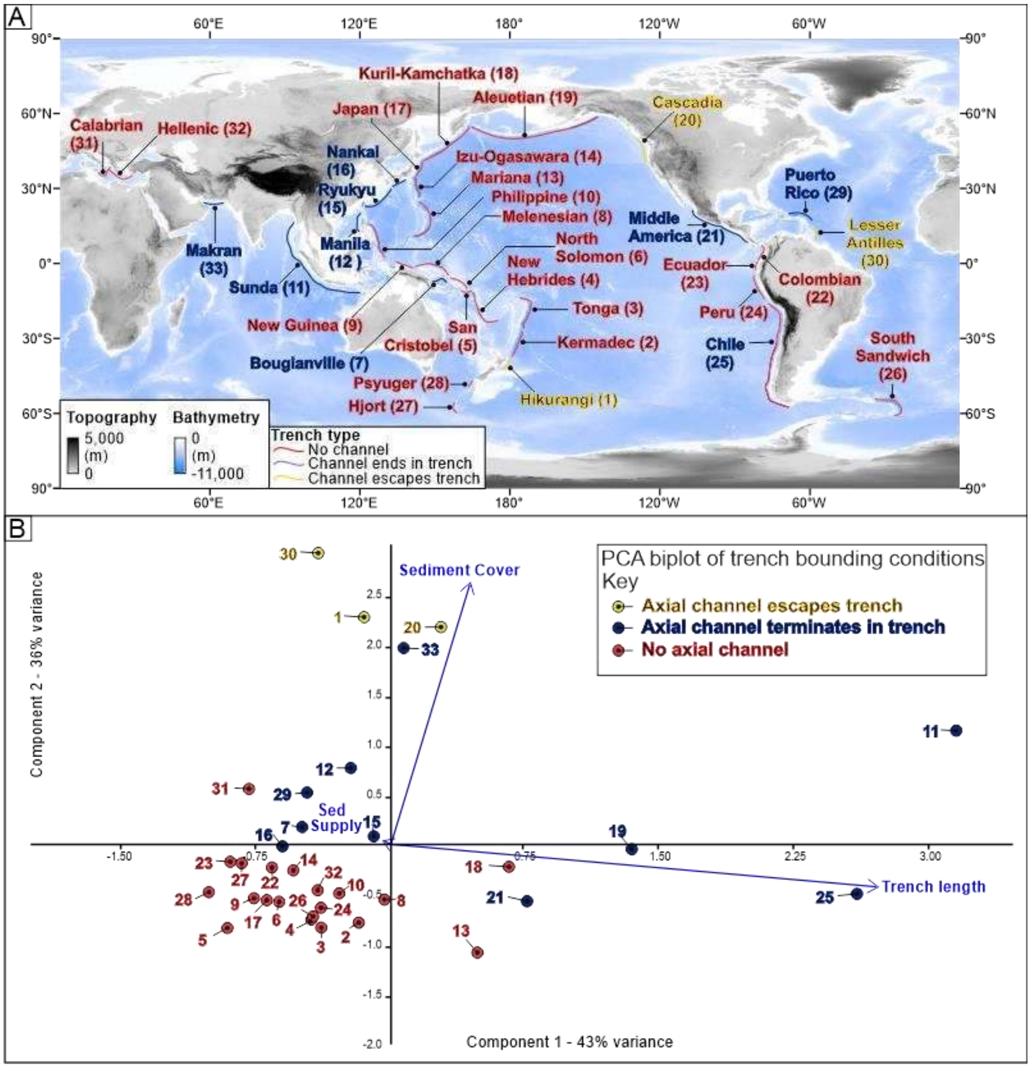

Figure 3. (A) Global distribution of subduction trenches and axial channels. (B) Principle components analysis biplot (eigenvalue scale) of trench geomorphological factors. See S5 for details of each trench and channel.

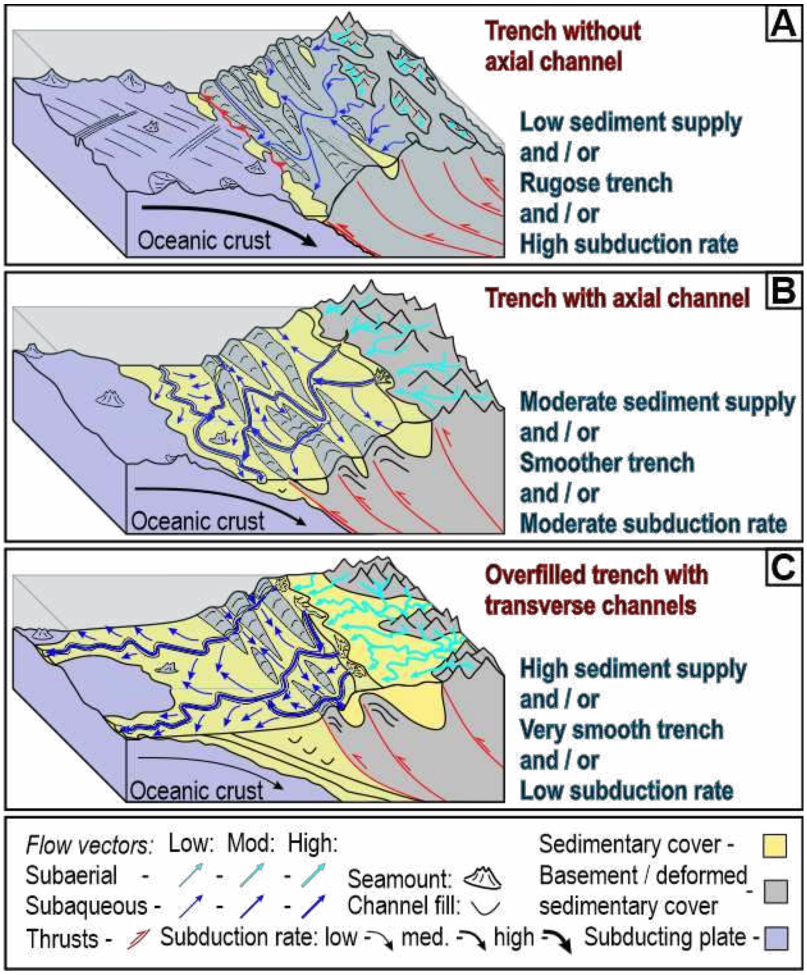

Figure 4. Schematic representation of controls on trench fill and axial channel evolution.