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Sedimentary architecture of detached deep-marine canyons: Examples from the East Coast Basin of New Zealand

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Short Title – Architecture of detached deep-marine canyons

ABSTRACT

Submarine canyons are conduits for the distribution of sediment across continental margins. Although many canyons connect directly with fluvial or marine littoral system feeders, canyons detached from direct hinterland supply are also recognized. The fill of detached canyons remains enigmatic, because their deep-water setting restricts analysis of their evolution and stratigraphic architecture. Therefore, this study aims to investigate the sedimentary processes that infilled deep-water canyons and the resulting architecture. Miocene outcrops of an exhumed deep-water system from the East Coast Basin, New Zealand are documented and compared with the morphology and seismic scale architecture of

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a modern detached canyon system on the same convergent margin. The outcropping system preserves the downstream margin of a sub-basin deposited at palaeo-water depths >700 m. A 6 km wide by 430 m deep incision is filled by heterogeneous siliciclastic sediments, 50% of which comprise graded thin-beds with traction structures, interpreted to result from oscillatory flows. These are intercalated with concave-up lenses, up to 15 m thick, of sigmoidally-bedded, amalgamated sandstones, which preserve ripple casts on bed-bases, interpreted as deposits at the head of a deep-marine canyon. Palaeo-flow was eastward, into the sub-basin margin. On the adjacent margin of the sub-basin down-dip, stacked and amalgamated sandstones and conglomerates represent the fill of a submarine channel complex, at least 3 km wide. The channels are inferred to have been fed by the up-dip canyon, which traversed the intervening structural high; similar relationships are seen in the bathymetry data. Seismic studies on this margin demonstrate that multiple phases of canyon cut and fill may occur, with downstream architectural evolution comparable to that seen at outcrop demonstrating that detached canyons may act as sediment conduits. Breaching of developing sea-floor structures by detached canyons can modify tortuous sediment pathways, supplying sediment to otherwise starved areas of the slope.

INTRODUCTION

Submarine canyons are a common feature of the continental shelf and slope (Daly, 1936; Johnson, 1939; Shepard & Dill, 1966; Shepard, 1981; Fildani, 2017, and references within) and are particularly common adjacent to active continental margins (e.g. Thornburg et al., 1990; Mountjoy et al., 2009; Vinnels et al., 2010; Bernhardt et al., 2015; Gamberi et al., 2015; Soulet et al., 2016), where canyons are typically short and steep (Covault et al., 2011; Harris & Whiteway, 2011). Not only do submarine canyon fills on active margins frequently

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present excellent hydrocarbon reservoirs, often being infilled with coarse grained sediments, but they also act as major conduits for sediment delivery to the deep-ocean (see Symons et al., 2017, and references within). Hence, understanding the distribution, characteristics and sedimentary architecture of canyon systems is of great importance. However, there is a recognition that not all canyons are directly attached to hinterland sediment supply, instead forming in deep-water, these being termed blind or detached canyons (e.g. Twitchell & Roberts, 1982; Paull et al., 1990; Orange & Breen, 1992; Pratson et al., 1994; Pratson & Coakley, 1996; McAdoo et al., 1997; Orange et al., 1997; Bertoni & Cartwright, 2005; Callec et al., 2010; Brothers et al., 2013). Due to their deep-water location in sites of significant erosion, exhumed examples of the heads of detached canyons are very rare and have not been documented at outcrop, where high-resolution studies of their sedimentology may be developed. Only Bertoni & Cartwright (2005) have previously documented detached canyons from the subsurface, but could not define the infilling stratigraphy without well data. Thus, despite advances in the study of the geomorphology of attached canyon heads (e.g. Kenyon et al., 2002; Gaudin et al., 2006; Gamberi et al., 2015, 2017; Puig et al., 2017), the stratigraphic architecture of detached systems remains to be described and their capacity to transport sediment has been overlooked.

This article presents the findings of an outcrop study of a Miocene-aged canyon fill from the East Coast Basin (ECB) of the North Island, New Zealand (Fig. 1) and submits evidence to describe the system as being detached from a direct hinterland sediment supply. The ECB comprises an active subduction wedge, measuring up to 160 km wide by 600 km long and is dominated by north-east striking, trench sub-parallel faulting (Fig. 1; Lee & Begg, 2002). Compression has created a series of elongate growth structures and intervening trench-slope sub-basins, typically tens of kilometres long by kilometres wide. Sedimentary pathways and subsequent fill of sub-basins varies both temporally and spatially (Neef, 1999; Bailleul et

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al., 2013; Burgreen & Graham, 2014). Bathymetric data demonstrate the presence of canyons cross-cutting thrust-bounded ridges (Mountjoy et al., 2009). Proximity to the active plate boundary has led to exhumation of the western portion of the basin, which allows study of the Miocene-aged fill of the Akitio and Coastal sub-basins (Fig. 1).

The primary aim of this study is to describe the sedimentology and stratigraphic architecture of the fill of a detached submarine canyon. Comparisons are made with sea-floor and seismic data from the offshore portion of the ECB in order to investigate the morphology of canyons and their effects on downstream sub-basins. Immediate objectives are:

1) Construct a high-resolution, outcrop-based lithofacies model for detached submarine canyons.
2) Evaluate the morphology and persistence of canyons in trench-slope systems using sea-floor and sub-surface datasets.
3) Integrate outcrop, bathymetry and sub-surface data to make interpretations of detached canyon evolution and prediction of canyon stratigraphic architecture.
4) Develop models to assist in the prediction of interactions between deep-water sedimentary systems and evolving sea-floor structures.

These research questions are important because detached canyons have not previously been recognized at outcrop. Hence, at present, no rock record exists of their infill or the resulting stratigraphic architecture, limiting understanding of the sedimentary processes within detached canyons and the preservation potential of recognized bedforms.

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GEOLOGICAL SETTING

This study focuses on the Miocene to recent convergent margin sequence of the East Coast Basin. Prior to onset of subduction, the region was a passive margin (Reyners, 2013), with widespread deposition of Palaeogene deep-marine carbonates and marls (Fig. 2; Lillie, 1953).

Activation of the Kermedec–Hikurangi subduction began ca 25 Ma, resulting in the development of the Hikurangi Trough, which defines the eastern limit of the ECB (Fig. 1; Nicol et al., 2007; Barnes et al., 2010; Reyners, 2013). During the Neogene the overriding plate underwent internal deformation in the form of ENE–WSW trending reverse, normal and strike–slip faulting, leading to the development of fold and thrust bounded, trench-slope sub-basins (Nicol et al., 2007; Reyners, 2013). Three main phases of Miocene and later deformation are recognized, related to the overriding plate's response to subduction of the Hikurangi Plateau (Fig. 2; Wells, 1989; Reyners, 2013), comprising: (i) an Early Miocene compressional stage, expressed by significant uplift and thrust faulting (Rait et al., 1991; Chanier et al., 1999; Bailleul et al., 2013); (ii) a Middle Miocene phase of mixed extension and compression, during which an extensional regime developed in the Hawke´s Bay region (Chanier et al., 1999; Barnes et al., 2002); and (iii) renewed basin-wide compression, expressed by rejuvenation of thrusting and uplift, resulting in development of the present fold and thrust belt (Nicol & Beavan, 2003; Litchfield et al., 2007; Nicol et al., 2007; Bailleul et al., 2013).

Predominantly thin-skinned deformation on the eastern margin of the upper plate has resulted in a preponderance of deep-marine Miocene sedimentation (Nicol et al., 2007). A strong tectonic control on the stratigraphy is apparent and the resulting sediments are punctuated by a series of unconformities (Bailleul et al., 2007, 2013; Burgreen-Chan et al., 2016). Sub-basin fill includes widespread deep-marine mudstones, turbidites, mass-transport

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complexes and carbonates of the Palliser Group, as well as shallow marine fringes to palaeo-highs (Fig. 2; Lee & Begg., 2002).

The Pliocene to recent history of the basin records significant uplift, due to acceleration of subduction, resulting in the elevation of the Coastal Ranges and the Axial Ranges (Beanland et al., 1998; Nicol et al., 2002; Litchfield et al., 2007; Nicol et al., 2007; Reyners et al., 2011). This uplift has resulted in the exhumation of the western, onshore, portion of the basin (Fig. 3). The region continues to experience deformation, expressed over the last million years primarily as strike-slip motion due to the rotation of the Australian Plate (Beanland et al., 1998; Nicol et al., 2007; Nicol & Wallace, 2007) and emplacement of the Taupo Volcanic Zone back-arc spreading inducing further uplift of the Axial Ranges (Acocella et al., 2003; Nicol & Wallace, 2007). Offshore, the active accretionary prism is characterized by imbricated thrusting and ongoing development of sub-basins (Lewis & Pettinga, 1993; Barnes et al., 2010).

METHODOLOGY

Fieldwork was carried out as part of a wider study to characterize the lithofacies and depositional environments of the onshore exposures of the Miocene succession of the ECB. The typical fill of the outcropping sub-basins consists of regularly bedded turbidites (Bailleul et al., 2007). During this work sediments unlike the characteristic fill of the sub-basins were encountered on the eastern margin of the Akitio Sub-basin and the western margin of the Coastal Sub-basin (Fig. 3). These areas were studied in detail to refine their lithofacies; bed for bed (1:50 scale) logging, totalling 564 m, was conducted at a number of key sections (Fig. 3). In conjunction 74 palaeocurrent directions were measured from three-dimensional surfaces. A lithofacies scheme was developed and lithofacies associations recognized; these

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were supplemented by information from micropalaeoentological analysis conducted by GNS Science New Zealand to define depositional environments and ages of deposition; samples were taken from hemipelagic mudstone so as to avoid potentially reworked microfossils. Photographs of key outcrops were taken to document the stratigraphic architecture. Digital mapping of lithofacies associations in the field were integrated with aerial photographs (courtesy of Land Information New Zealand – LINZ) and with existing biostratigraphic information (The Fossil Record Electronic Database [https://fred.org.nz/]) in order to produce correlations and determine the distribution of stratigraphic elements.

Bathymetric data (100 m grid), supplied by the National Institute of Water and Atmospheric Research, New Zealand (NIWA), was used to study modern canyons, in particular focusing on the Madden Canyon (Fig. 4). Interpretation of this dataset was conducted in ArcMap©, enabling definition of morophological elements of the Madden Canyon, drainage network analysis and a downstream transect to be traced.

Depth converted 2D seismic data (frequency of 3 to 200 Hz) acquired in 2014 by WesternGeco was used to assess the stratigraphic architecture of the Madden Canyon. Data were interpreted using Petrel©; full stack data are displayed such that a downward decrease in acoustic impedance is represented by a trough (grey) and a downward increase is represented by a peak (black). Major faults and structures were interpreted and regional surfaces were extrapolated from a wider survey; two well ties enabled the base Pliocene to be picked (Fig. 1).

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RESULTS

Lithofacies

Twelve lithofacies (i.e. bed types) are recognized in this study. These are collated in Table 1.

Lithofacies Associations

Associations of the lithofacies can be grouped into packages of related sediments as lithofacies associations, which allows investigation of the sedimentary process and architecture (Fig. 6). Observations are followed with basic interpretations of the lithofacies associations, before integration and interpretation of all datasets below. Two lithofacies associations are recognized:

Lithofacies Association 1 (Fig. 7)

Observations: This association (LA1) is dominated by sigmoidal sandstones (LF7), interbedded with laterally inconsistent thick-bedded sandstones (LF4), laterally variable thin to medium-bedded sandstones (LF3) and mud-clast rich sandstones (LF5). The base of this 430 m thick association occurs within a 6 km wide and tens of metres deep incision into underlying Lower Miocene deep-marine mudstones (LF1) in the north and portions of Takritini Formation sandstone and siltstone in the south (Fig. 3). The first beds above this bounding surface comprise laterally inconsistent thick-bedded turbidite sandstones (LF4) interbedded with turbidite mudstones (LF2), before grading into a package of laterally variable thin to medium-bedded sandstones (LF3) (Fig. 8). These thin-beds show a subtle transition to an interval dominated by graded event-beds (LF6), which are overlain by sigmoidal sandstones (LF7) (Fig. 9). The sigmoidal sandstones coalesce into 14 laterally and vertically offset stacked packages each up to 3 km wide, tens of metres thick, with thinning

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towards their lateral margins (Fig. 10), tapering to the west and are typically intercalated with graded event-beds (LF6) (Fig. 8).

Sigmoidal sandstones form the most prominent component visually (Fig. 8) and are seen to have lateral variety in bed thickness and amalgamation, indicating that these are compound features (Fig. 10). Although a range of palaeocurrents is seen, dispersal was dominantly eastward (Fig. 6), although occasionally beds demonstrate symmetrical ripples. Lower to Middle Miocene palaeocurrents across the wider Akitio Sub-basin show a general convergence upon this area, with outcrops to the south demonstrating northerly palaeo-flow, whilst those to the north of these outcrops generally show southerly flow (Bailleul et al., 2013). The LA1 association only occurs on the preserved eastern margin of the Akitio Sub-basin, where it forms the Three Kings 'flat irons' (Fig. 7A). There is no evidence of this association further west in the sub-basin, either from outcrop or seismic data. Analysis of foraminifera recovered from bounding hemipelagic mudstones indicates middle bathyal water depth (>700 m) and a Langhian (Middle Miocene) age.

Interpretations: The LA1 sediments have previously been briefly interpreted by Neef (1995) as a shallow marine deposit of the Lower Miocene Takritini Formation However, mapping and biostratigraphy of these units show them to be younger, spatially distinct to the Takritini Formation, which they incise into (Fig. 3). This association of deep-water sediments is interpreted to be infilling a major incision on the downstream margin of the sub-basin. The depositional environment and stratigraphic evolution will be interpreted below by integrating all datasets.

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Lithofacies Association 2 (Fig. 11)

Observations: Following the palaeocurrent trend of Lithofacies Association 1 east, across the Coastal Block that separates the Akitio and Coastal sub-basins, a distinctive range of sediments can be examined on the western margin of the Coastal Sub-basin (Fig. 3). These comprise bodies of thick-bedded lenticular sandstones (LF4), of low aspect-ratio (ca 10:1) with frequent lateral and vertical amalgamation into erosional remnants up to 55 m thick, by 3 km wide (Fig. 3). Bases to individual sandstones are very irregular and may scour metres into underlying strata; flute marks with a dominantly eastward orientation are preserved on bed bases (Fig. 12). Internally, a series of sandstone and conglomerate lenses are seen to incise metres into underlying sandstones, giving a laterally and vertically amalgamated series (Fig. 12). The lowermost sandstones exhibit an inverse grading, with flute casts filled with fine-grained sandstone, whilst other sandstones are typically granular to medium-grained (Fig. 11C). Some lenses show a significant conglomeratic component (LF9), where clasts are dominantly composed of sub-rounded cobbles of sandstone and subordinate mudstone (Fig. 11B). The sandstones rarely display planar cross-stratification and very rarely horizontal stratification but are typically structureless, albeit with evidence of widespread dewatering (Fig. 12). Very rarely, silty mudstones (LF2) may be preserved above sandstones; however the upper portion of turbidites are normally absent. Significant injection of sandstone into other sandstones and also into adjacent strata is frequently observed (Fig. 11B).

A basal stepped incision surface is seen to incise tens of metres into Lower Miocene olistostrome deposits described by Delteil et al. (2006) (Fig. 11A). Whereas overlying units are seen to incise into earlier intraformational sandstones or conglomerates (Fig. 12). The northern contact was not observed, being eroded by the modern Owahanga River (Fig. 12). To the south, these units are laterally bounded by and incise into deformed and irregular thin-bedded turbidites (LF3 with subordinate LF2). These deposits are observed to thin laterally,

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although they are rarely observed to completely pinch-out (Fig. 11D). These thin-beds stack into a package tens of metres thick and occasionally show irregular, isolated, thick sandstone lenses (LF4). Sandstones typically show a range of traction structures exhibiting palaeocurrents oblique to those of nearby LA2 sandstones (Fig. 6). Extensive remobilization and disruption of LF3 and LF2 is near ever-present, recognized as slide scars, rotated blocks and slumps (Fig. 12). Elsewhere the margin of the Coastal Sub-basin is dominated by thin to medium-bedded turbidites (Field, 2005).

Interpretation: This association of deeply scouring, amalgamated, lenticular sandstones and subordinate conglomerates, with associated injectites and laterally adjacent thin-bedded turbidites, is interpreted as a submarine channel-levée complex. This is comparable with other documented systems (e.g. Kane et al., 2007; Hansen et al., 2017; Jobe et al., 2017) and the offshore examples documented below.

Sea floor geomorphology

Although the outcrops provide high-resolution detail on lithofacies and stratigraphic architecture of the studied system, their preserved extent limits investigations of longitudinal system evolution. Therefore, analogues must be sought to study the downstream behaviour of sedimentary systems. Although no two systems are ever truly analogous, a number of canyons are present on the modern Hikurangi Margin (Mountjoy et al., 2009). The Madden Canyon is studied here (Fig. 4), which can help to frame analysis of the outcropping system.

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Morphology of the Madden Canyon

Despite being a major canyon system in the subduction wedge, the Madden Canyon has only been described briefly (Mountjoy, 2009). The present study describes how the Madden Canyon transects the slope.

Madden re-entrant observations: The Madden Canyon re-entrant begins as a deeply incising feature into the shelf, approximately 15 km offshore from the Porangahau River mouth, in water depths of several hundred metres, where a series of gullied incisions have coalesced to form a 25 km wide incision in the Madden Sub-basin, which is mushroom shaped in plan view (Fig. 1). These gullies lead down to the floor of the re-entrant at ca 1 km water depth. Its floor is relatively smooth, except for a series of canyon-facing crescentic features stepping towards the canyon head (Fig. 4). The continental shelf is relatively wide for the Hikurangi Margin in this location, at almost 40 km (Fig. 4).

Madden Canyon breach-point observations: The point at which the canyon breaches the Madden Banks occurs in water depths of approximately 1.4 km (Fig. 4). The breach forms a funnel shaped incision initially almost 9 km wide into the Madden Banks, through which the canyon incises (Fig. 4). Here, basinward facing crescentic features can be observed on the sea floor, being in the order of 2 to 4 km wide but less than a kilometre long (Fig. 4).

Upper reaches observations: The canyon narrows as it cuts through the Madden Banks (Fig. 4). In plan form, this incision is straight, conforming to intra-slope canyons described by Mountjoy et al. (2009) and at least eight knickpoints may be observed in the thalweg (Fig. 4). Beyond the first incised ridge the canyon steepens and narrows, being <4 km wide and incising from 1.6 to 1.7 km water depth. A well-defined thalweg is observed on

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the southern side of the canyon, within which a series of shoreward facing lunate features <2 km wide are apparent (Fig. 4). Laterally, a raised area of sediment is seen on the northern side of the canyon (Fig. 4), which is also visible on seismic data (Fig. 5).

Lower reaches observations: Thereafter, the canyon traverses a further thrust bounded ridge, beyond which it turns slightly to the south, becoming a wider but shallower channelized feature at water depths approaching 2 km (Fig. 4). Here the channel-floor becomes smooth, with incisions being <50 m deep. However, the system does not terminate in the Porangahau Trough, but is baffled by a series of growth structures, becoming tortuous as it passes into the terminal site of deposition, 95 km from the canyon head and at water depths in excess of 2.2 km in the Akitio Trough (Fig. 4).

Interpretation: the head of the Madden Canyon does not directly connect to fluvial or shallow marine feeder systems and can therefore be considered as a detached canyon, i.e. one that is disconnected from direct hinterland supply. Although the crescentic features observed in the re-entrant and breach-point hint at the presence of bedforms, complementary outcrop studies are required for a comprehensive facies characterization of the canyon head setting; similarly outcrop and/or seismic studies are required to show the associated styles of facies architecture (see below).

Seismic stratigraphy

The large-scale architecture, temporal range of the deposits and evolution of the Madden Canyon system may be examined with sub-surface data. Accordingly, a series of seismofacies have been recognized, as outlined in Table 2. As with the outcrop, brief interpretations are given here before integration of all datasets to interpret the studied systems.

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Seismic character of canyon fill

Madden Canyon re-entrant observations: The fill of the canyon re-entrant is dominated by low amplitude, relatively continuous reflectors (seismofacies 1), which extend over kilometres in length and may be up to 100 m in thickness (Fig. 13A). These are interspersed with higher amplitude, lenticular bodies up to 3500 m wide by tens of metres thick, composed of concave-up, discontinuous reflectors (seismofacies 2) which are prevalent in the eastern side of the Madden Sub-basin, adjacent to the spill point, but show an overall backstepping, retrogradational profile (Fig. 13A). Both of these seismofacies show significant incision by relatively broad (up to 1 km wide) but shallow (up to 100 m deep) incisions and when not open on the sea floor these are filled with the chaotic, laterally discontinuous seismofacies 3 (Fig. 13A). A general evolution of the stratigraphy is observed, with older, more tabular but now deformed and rotated strata that is initially deeply incised, overlain by reflectors with a high proportion of seismofacies 2. The succeeding interval is acoustically chaotic (seismofacies 5) and may represent an interval of remobilized material, containing coherent rafts tens of metres thick by hundreds wide (Fig. 13A). Following this chaotic interval is a series of seismofacies 1, incised by seismofacies 3, with a rotation and truncation of strata towards the eastern end of the Madden Sub-basin (Fig. 13A). Gullying behind the re-entrant can be observed in the westernmost part of the cross-line, with relatively narrow incisions hundreds of metres deep into heavily deformed strata of the Madden Sub-basin.

Madden Canyon re-entrant seismic interpretations: The low amplitude, continuous reflectors are interpreted to represent background sediments (Fig. 13A). The very low aspect-ratio lenses apparent in the lower portion of the re-entrant fill (seismofacies 2) appear to have similar, albeit larger, morphologies to the sigmoidal sandstones (LF7) described at outcrop, as shall be discussed below.

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Upper reaches observations: Beyond the breach-point, the upper reaches of the Madden Canyon are dominated by incisional, lenticular features, filled with seismofacies 3 (Fig. 13B). These features are variable but tend to show a high aspect-ratio, incising tens to hundreds of metres and typically <500 m wide, but often coalescing into wider packages with multiple thalwegs (Fig. 12B). These are laterally bounded by banded, alternating high and low amplitude seismofacies 4, which show lateral thickness variations, particularly thinning to the east (Fig. 13B). These features overlie two intervals of widespread chaotic seismofacies 5 (Fig. 13B).

Interpretation: The series of relatively shallow incision fills and adjacent laterally thinning seismofacies are interpreted as a channel-levée system in the upper reaches of the Madden Canyon (Fig. 13B).

Lower reaches observations: By 65 km down the system reflector architecture is subtle. However, relatively shallow incisions filled with seismofacies 3 can be seen in the upper section (Fig. 13C). These occur as vertically stacking units, each <50 m thick and <1 km wide, but are still laterally bounded by banded seismofacies 4, which thins away from the channel. Scours are still apparent to the east of the neighbouring ridge (Fig. 13C). The underlying strata are composed of laterally continuous strata of seismofacies 6.

Interpretation: The subtle features observed in the lower reaches are interpreted as the distal part of a channel-levée system (Fig. 13C). Although no longer canyon confined, this is interpreted as the downstream expression of the Madden system.

Terminal depocentre observations: The fill of the Akitio Trough, over 95 km downstream is dominated by seismofacies 1, being low amplitude laterally continuous packages (Fig. 13D). However, the upper 400 m of fill demonstrates thickening packages of higher amplitude seismofacies 6, which onlap the margins of the sub-basin (Fig. 13D).

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Terminal depocentre interpretations: The upper fill of the Akitio Trough is interpreted as the current site of terminal deposition of the Madden Canyon. This would appear to be a relatively recent development, overlying background sediments (seismofacies 1).

Integration and interpretation of datasets

Distinct variations between lithofacies associations are seen in the style of sediment, range of structures present and variation in bed thickness. When placed in context with observations from the sea-floor and subsurface, interpretations of the outcropping lithofacies associations and their depositional environments can be made.

Stratigraphic architecture of canyon heads

The morphology of the Madden Canyon was described from analysis of bathymetric and seismic data; its interpretation sheds light on the range of sedimentary processes that may result in the infill of submarine canyons. The wide, mushrooming re-entrant in the Madden Sub-basin (Fig. 4) is likely to be the result of sediment evacuation from the sub-basin and gullying behind the breach-point, subsequent to its formation behind the Madden Banks thrust-propagated ridge (sensu Mountjoy et al., 2009; Fig. 4; 13A). No direct link exists between the Porangahau River and the Madden Canyon, and drainage analysis indicates that the ridge separating the Coastal Sub-basin from the Madden Sub-basin would favourably capture littoral systems (Figs 4 and 13A). Presently the Porangahau River delivers the relatively low volume of muddy sediment to the shelf, of ca 0.140×10^6 tonnes per year (Griffith & Glasby, 1985). The canyon-directed crescentic features represent positive relief on the sea floor and are interpreted as sediment waves migrating towards the canyon breach-point. An equivalent interval was not observed in the outcropping system.

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The breach-point of the Madden Canyon can be seen on both bathymetry and seismic data immediately behind the Madden Banks (Figs 4 and 13A). Given the series of stepped incision into the Madden Banks and mass wasting (Figs 4 and 13A), it is inferred that this breach formed by a series of retrogressive failures on the downstream portion of the Madden Banks (sensu Pratson & Coakley, 1996). The subsurface expression demonstrates a number of mass-transport complexes (MTCs) which may be related to the retrogressive failures. Above the first MTC, tabular seismofacies 1 is frequently incised by channels filled with seismofacies 3, which prevail to the sea floor (Fig. 13A). Here, a major incision surface is apparent, cutting through stratigraphy towards the eastern spill point from the Madden Sub-basin, representing the modern development of the Madden Canyon, with rotation of strata implying continued growth of the Madden Banks (Fig. 13A). The fact that multiple stages of canyon cut, fill and disruption by MTCs have been recognized demonstrates the complexity of the development of breach-points, which at times record significant periods of infill, as well as major periods of re-incision and erosion as documented on other margins (e.g. Smith et al., 2005). The sediment waves observed here are smaller than in the re-entrant and are interpreted to represent sediment migrating towards a staging point at the head of the canyon, which represents the spill point, before eventual translation down the canyon. If the concave-up features observed in the subsurface also represent deep-water sigmoidal sandstones then they can be inferred to be representative of the infill stage of these canyons.

In the absence of core, the detailed lithofacies and stratigraphic architecture of these deep-water canyons is unknown. However, this study may integrate these descriptions of an active canyon with the outcropping system, comparing their large scale architecture, to interpret their depositional environment and leverage insights to the detailed sedimentology of deep-marine canyons.

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Although infilling an incision, the outcropping sediments and their architecture are unlike documented deep-water channel fills in the East Coast Basin (Neef, 1992) and are dissimilar to turbidite channel fills in downstream portions of submarine canyons (e.g. Kane et al., 2007; Pattison et al., 2007; Di Celma 2011; Hansen et al., 2017; Jobe et al., 2017). The large-scale architecture is however similar to that in the subsurface of the Madden Canyon, particularly the interval above the first unconformity, which initially demonstrates channel fills, before development of a series of retrogradational concave reflectors in an interval ca 500 m thick (Fig. 13A). These are encased in more homogenous reflectors, which may comprise siltstones to mudstones (for example, LF1 and LF2), but may also include a proportion of irregular thin-bedded turbidites, similar to those seen interspersed with the thicker deposits at outcrop (LF3). The presence of structured sediments in this interval may indicate a period where the canyon head was largely being infilled, following a major incision. The width and depth of the strata described here (preserved width of 6 km, by 430 m deep) are also comparable to those of the modern Madden Canyon breach-point (ca 9 km wide by 400 m deep). Therefore, the outcropping LA1 lithofacies association of traction dominated, thin-bedded turbidites and sigmoidal sandstones are interpreted to represent the fill of a submarine canyon head. This canyon is referred to as the Kings Canyon.

The position of the Kings Canyon head on the eastern, downstream margin of the sub-basin, with eastward palaeocurrents implies that this was a spill-point out of the sub-basin, rather than an entry point from up-slope. The first fill of this canyon comprises typical deep-water deposits, with marine mudstones and channelized sandstones, before the development of the sigmoidal sandstones during conduit infill, giving a similar evolution in architecture to the first cycle of Madden Canyon reflectors. Therefore, the Kings Canyon was probably always submarine, although the fact that it coincides with a basinal shallowing event and unconformity (Bailleul et al., 2013) indicates that it may have formed during a relative sea-

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level lowstand, but still in deep-water given limited Miocene sea-level fluctuations (Miller et al., 2005). The sigmoidal sandstones are similar to sediment waves described in active canyon systems (e.g. Xu et al., 2008) and have a similar architecture to those observed in the Madden Canyon breach (seismofacies 3). If these features represent deep-water sigmoidal sandstones, they provide evidence of sediment migrating into the canyon system and they can be inferred to be representative of the infill stage of these canyons. Preservation of these bedforms implies a change from dominantly erosive and bypassing currents during the early stage of canyon formation and fill to a more passive system during the infill.

The integrated investigation allows interpretation of a mixture of firstly strongly erosive and subsequently depositional processes to have combined to produce the observed stratigraphic architecture in the heads of both the outcropping Kings Canyon and the offshore Madden Canyon. As such, the unconformity surfaces are assumed to indicate a significant period of downstream bypass (e.g. Stevenson et al., 2015).

Stratigraphic architecture of the upper reaches of canyons

The upper reaches of the Madden Canyon are where the most significant intra-canyon incisions are observed, with a series of stepped incisions (Fig. 4), which are seen to amalgamate laterally and vertically in the subsurface (Fig. 13B). These are similar to steps described in other submarine canyons, such as the Monterey Canyon, USA (Paull et al., 2011) and the Var Canyon in the Mediterranean (Malinverno et al., 1988). Intra-canyon bedforms such as these were interpreted by Paull et al. (2011) to have formed by episodic sediment failures. A raised area to the north of the canyon is interpreted as an overbank levée; the surficial wave form of the levée seismofacies fits well with the large-scale wave-forms adjacent to the modern channel (Fig. 4; 13B).

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The relative location, scale of channels, architecture of lateral and vertically stacked channel fills with overbank sediments and geometry of the upper reaches of the Madden Canyon fill appear similar to the outcropping system described by lithofacies association 2 (Figs 3 and 12). These high-aspect ratio, vertically stacked sandstones are interpreted as the fill of submarine channels within a canyon, which probably was wider than its preserved 3 km. The degree of injection into the incised sediments is a common feature of submarine channel complexes (e.g. Jackson et al., 2011). The coarse grain size, degree of bed amalgamation and absence of fines indicates that the majority of flows were bypassing or that a significant portion of deposits were removed by subsequent flows and transported downstream. Although no direct relationships can be observed due to the erosive nature of the channel cuts, the lateral thin-beds are interpreted to represent overbank levées (sensu Kane & Hodgson, 2011).

The relationship of LA2 to the spill-point association described above (LA1) is thought to reflect a downstream transition from a canyon head to a narrower mixed incisional/aggradational channel belt in the upper reaches of a sediment conduit. This implies that a through-going canyon system breached the Coastal Block. That the modern systems show similar downstream evolution and breach growth structures provides credence for the presence of structure-breaching systems in the stratigraphic record. It should be noted that the structural high does not exhibit any major weaknesses or lineaments between the canyon head and the down-dip channel complex (Fig. 3); nor do the preserved intervening strata exhibit evidence of sediment mobility, for example mud pipes or volcanoes. Therefore, there is no evidence of a structural predisposition for this area to become a sediment transport corridor. This indicates that development of the canyon may have been controlled by the sedimentation, rather than owing to any structural weakness. The erosive nature and coarse grain size of the channel fill implies a significant degree of sediment bypass.

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Architecture of the lower reaches of canyons

The lower reaches of an active margin canyon system were not observed at outcrop, therefore the authors cannot say whether sediment remained in the Coastal Sub-basin or whether it was transported further down the slope. However, some inferences on the transport potential and likely stratigraphy of the downstream system can be made from the bathymetric and seismic datasets.

Progressing downstream, entrenchment of the channel within a wider overbank system is seen (Fig. 4) and expected (Kane & Hodgson, 2011). The channels and levée constitute less than 300 m of strata and overlie reflectors passively filling the Porangahau Trough (seismofacies 6), implying that this portion of the system has developed more recently as sediment overspills from the Porangahau Trough (Fig. 13D). The Madden Canyon does not connect with the trench-axial Hikurangi Channel, which captures many other conduits on this margin (Mountjoy, 2009). Rather it appears to be terminating in the Akitio Trough (Fig. 4). It may be inferred that it has previously deposited sediment in other upstream sub-basins, before breaking through ridges, thereby creating a fill and spill morphology through a series of sub-basins (e.g. Beaubouef et al., 2003).

DISCUSSION

Comparison of attached and detached canyons

Harris & Whiteway (2011) defined three canyon types: (1) those directly attached to fluvio-deltaic systems (for example, the Monterey Canyon); (2) shelf incising canyons (for example, the La Jolla Canyon, USA); and (3) those forming in deep water, where they are detached from a direct hinterland supply (for example, the Barbados Canyon). Types 1 and 2

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are attached to direct hinterland supply, either directly to a fluvial system or shallow marine systems fed by a nearby terrestrial source, whereas type 3 occurs in deep water and is detached from a direct terrestrial sediment supply. A summary of documented attached versus detached canyons is presented in Table 3. Although attached canyons are typically longer and may terminate in deeper water, it is the upstream, head area where the types of canyons differ most (Table 3).

The heads of submarine canyons are very rarely preserved at outcrop; they represent the most proximal sites in deep-water systems and are often long-lived points of sediment dispersal, which are the parts most prone to erosion. Gamberi et al. (2017), documented the stratigraphic architecture of canyons attached to fluvio-deltaic systems in the Mediterranean (Table 3). These authors described coarse-grained foresets tens to one hundred metres thick infilling canyon heads, resulting from the progradation of deltas (Fig. 14A). Although highly variable, bathymetric studies of canyon heads attached to hinterland feeder systems describe canyon morphologies unlike that of the documented Madden Canyon (e.g. Nelson et al., 1970; Normark, 1970; Greene et al., 2002; Kenyon et al., 2002; Laursen & Normark, 2002; Hasiotis et al., 2005; Gaudin et al., 2006; Arzola et al., 2008; Noda et al., 2008; Puig et al., 2017), or other detached systems (Table 3; Fig. 14). Attached systems typically have a narrow, incisional head, forming at relatively close proximity to shore, in shallow water (Table 3).

Where exactly canyon systems develop along a margin is due to the positioning of points of weakness and narrowing of shelves (e.g. Covault et al., 2007), presenting a topographic low that can be exploited by currents (e.g. Morley, 2009). Weaknesses may be the result of many factors, such as structural influence, for example transfer zones (e.g. Morley, 2009), fluid circulation, for example gas escape (e.g. Orange et al., 1997), sediment loading by concentrated sediment delivery (e.g. Puig et al., 2017), cascading (e.g. Micallef &

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Mountjoy, 2011; Lai et al., 2016), or by headward erosion (e.g. Pratson et al., 1994; Pratson & Coakley, 1996; Green et al., 2007).

The cut, fill and abandonment cycle of detached canyons on active margins may result in a higher preservation potential, when compared with attached canyons, which may act as long-lived conduits. For example the Congo Canyon system (Africa) has been an active sediment dispersal point since at least the Oligocene (Anka et al., 2009). As such, subduction wedges, with exhumed deep-water systems may represent the best opportunity to locate detached canyons at outcrop, in order to describe their sedimentary architecture and stratigraphic evolution.

Detached canyon evolution

The association of sediments cropping out on the eastern margin of the Akitio Sub-basin and the western margin of the Coastal Sub-basin is interpreted to represent the relatively proximal fill of a submarine canyon, which cut the intervening thrust-cored ridge. This example of autogenic sedimentation has been compared with modern examples of canyons on the Hikurangi Margin and elsewhere to help answer questions on the development of deep-marine canyons on active margins (Table 3).

Given the setting within a deep-water subduction wedge, and that the lowermost sediments of the Kings Canyon fill are turbidite dominated and contain deep-water microfossils, the Kings Canyon is interpreted to represent the fill of a submarine canyon originating in a deep-water setting, as proposed for other systems by McAdoo et al. (1997) and Callec et al. (2010). As with the Madden Canyon and other detached systems, the deep water depth (>700 m), combined with the position on the eastern, downstream margin of the

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outcropping sub-basin and architecture of deposits indicates that the Kings Canyon probably was detached from any littoral systems (Fig. 14B). Additional Miocene-aged deep-marine deposits are present in sub-basins to the west and the fore-arc basin to the Axial Ranges, implying >50 km distance from land (Neef, 1999).

Although it is inferred that some modern detached canyons are the result of the present sea-level highstand (Covault et al., 2007), this is not the case in the examples herein. The outcrops show no shallow marine strata within the canyon fill, the first sediments of which contain deep-water foraminifera, suggesting initiation in a deep-water setting. That the evolving Madden Canyon re-entrant floor presently sits at 1400 m of water depth also implies that no likely sea-level change would be sufficient to connect this system to a fluvial feeder; however supply may be enhanced during sea-level lowstands (e.g. Covault et al., 2007). Material being excised from the Madden re-entrant gullies would undoubtedly enter the Madden Canyon (Fig. 4). Drainage analysis conducted on the bathymetry dataset indicates that, even if sufficient material was supplied from the Porangahau River, the ridge separating the Coastal Sub-basin to the west of the Madden Sub-basin would not presently allow transmission of sediment into the Madden Canyon (Fig. 4). Furthermore, other detached canyons are seen at greater water depths to the north-east of the Madden Canyon (Fig. 4) within a subduction wedge that is being progressively uplifted.

Analysis of the Madden Canyon shows that a series of small, stepped incisions sit outboard of the canyon head, which cuts the middle of the Madden Banks ridge without obvious structural weakness (Fig. 4). The downstream component of the outcropping canyon incises mass-wasting deposits, indicating that the systems recorded here may also have formed at a weak zone resulting from headward erosion (Fig. 15A). However, it is impossible to pinpoint the control(s) of formation for the outcropping system.

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The formation of canyons is inherently linked with a phase of reworking of sediment and bypass downstream (sensu Stevenson et al., 2015). At this early stage of development it is unlikely that substantial material was preserved in the head, i.e. whilst sediment delivered by high-density turbidity currents was accumulating downstream (Fig. 15B). This inference is supported by the relatively coarse fill of the downstream channels (Fig. 12), when compared to the fill of the canyon head (Fig. 8), indicating that sedimentation was not coeval along the canyon. The question remains open as to where the sediment filling the canyons originated. Undoubtedly some of the material was derived from the erosion of the conduit and retrogressive failures in the canyon, as seen in the Madden Canyon (Fig. 4; 13). Sediment may also have been delivered by tortuous systems routing sediment through up-dip sub-basins (sensu Burgreen & Graham, 2014), or bottom currents known to be active on the Hikurangi Margin (e.g. Carter et al., 2004). This implies that detached canyons have a limited and sporadic sediment supply compared to attached canyons.

Subsequent fill of the Kings Canyon head comprises 430 m of stratigraphy, without significant internal scour, indicating a relatively passive infill of the canyon head, with currents concentrating fine sediment to form the sigmoidal sandstones (Fig. 15C). Although similar bedforms have been reported on the sea floor of attached canyons (e.g. Xu et al., 2008), they have yet to be described from outcrop and may have a very low preservation potential in attached canyons with through-going flows. The authors interpret preservation of these bedforms to have occurred in the final stages of canyon development, where aggradation of sediment under traction and bedform development indicates that the majority of material was being stranded in the canyon head, rather than bypassing downstream (Fig. 15C). A retrogradational fill may be inferred, as seen with the lenses in the Madden Canyon head (Fig. 13A), leading to the development of a stacked series of sigmoidal sandstones.

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Whilst the sub-surface tracing of the Madden Canyon demonstrates multiple phases of canyon cut, fill and abandonment, the Kings Canyon was occluded after one phase (Fig. 15D). This may have been related to changes in the basin dynamics and slope gradient development that made this pathway disadvantageous whilst opening other pathways elsewhere. Chanier et al. (1999) indicating extension during the Middle Miocene contemporaneous to the Kings Canyon development. Alternatively, a period of mass-transport is recognized elsewhere in the Akitio Sub-basin during the Middle Miocene, corresponding with disconformity three of Bailleul et al. (2013). This can be compared with the sub-surface expression of the Madden Canyon head, where multiple MTCs are seen to disrupt the fill potentially blocking sediment conduits (Fig. 13A) and favouring development of pathways in other locations. This situation may arise when the re-entrant retreats to such an extent that it incises the up-dip sub-basin-bounding ridge, catastrophic failure of which could provide enough material to inundate a sub-basin (e.g. Mountjoy & Micallef, 2012). Otherwise, systems may be abandoned due to a terminal shut-down due to a reduction in sediment supply.

Implications for downstream sub-basins

The inferred relationship between the Kings Canyon head and the channels of the Owahanga locality is consistent with a fill and spill connection between the Akitio and Coastal sub-basins and implies that detached canyons may be significant sediment conduits. The extent to which this particular system extended outboard cannot be directly constrained, although Field (2005) postulated significant channelization within the offshore portion of the Coastal Sub-basin in the Middle Miocene. If this is the case, one might expect these channel

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systems to continue outboard, as seen with the Madden Canyon (Fig. 4) and in other accretionary wedge traversing channels (e.g. Callec et al., 2010).

Moreover, the identification of this channel system demonstrates the presence of at least one transverse sediment conduit cross-cutting the Hikurangi Margin in the Miocene. To the south, where it is narrower, transverse channels are seen to bypass the subduction wedge and link with the Hikurangi Channel (Mountjoy et al., 2009); where the wedge is wider, conduits such as the Madden Canyon terminate within the slope (Fig. 4). The result is that the sub-basins fed by the Madden Canyon demonstrate a considerable thickness of syn-subduction sediment (Fig. 5), whereas sub-basins that are bypassed demonstrate starved, underfilled signatures (Fig. 1), with the Hikurangi Channel transferring sediment into the Pacific (Lewis, 1994). An underlying control may be the slope gradient and associated width of the subduction wedge; the Madden Canyon sits in roughly the widest, lowest gradient region of the Hikurangi Margin, whilst the steeper southern and northern ends see direct linkage to the Hikurangi Channel (Fig. 1).

These relationships carry implications for the distribution and reservoir quality of sediment deposited in the East Coast Basin and subduction wedges in general. Previously, studies of the Miocene strata have reported a dominantly fine grain size, in mostly thin-bedded strata (e.g. Johnston, 1980; Neef, 1992; Field, 2005; Bailleul et al., 2007, 2013). The present study demonstrates the presence a coarse-grained component, which was concentrated in and preferentially bypassed outboard by sediment conduits, with only the fine portion being trapped in up-dip sectors of the basin.

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Recognition of detached canyons as sediment conduits

Detached canyons are present on active and passive margins, where they are seen to occur at a range of water depths, distance from shore and often demonstrate significant lengths (Table 3). Given the difficulty in monitoring activity in submarine canyons (e.g. Talling et al., 2015) relatively little is known about the depositional processes that occur within them, the preservation potential of those deposits, or the capacity of detached canyons to transfer sediment to the deep ocean. This study shows that detached canyons may be significant sediment conduits of coarse-grained material. This sediment transfer potential has been overlooked in studies of sediment delivered to the deep seas, with implications for the development of downstream sediment accumulations and the carbon cycle (e.g. Allen & de Madron, 2009). Despite developing in a trench-slope system, where one might expect sediment pathways to be tortuous (e.g. Burgreen & Graham, 2014), the observed detached canyons, both modern and ancient are seen to cut thrust-cored ridges (Figs 4 and 5). These canyons are also seen to develop on a range of slope gradients and at varying water depths (Fig. 1), both here and around the globe (Table 3). From the case studies documented here it is concluded that sedimentary processes are responsible for the development of detached canyons at low points in the lateral ridges (sensu Pratson et al., 1994). Therefore, rather than concentrating at transform zones between fault segments or through fault-controlled saddles (e,g, Morley, 2009), major sediment conduits may be generated in locations that may not be directly structurally-controlled.

The positioning of detached sediment conduits may in-turn influence the fill and spill nature of intra-slope sub-basins. Simple models may predict that sediments were first delivered to the outermost sub-basins and subsequently intra-slope sub-basins are backfilled

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(e.g. Badalini et al., 2000), or that the most proximal sub-basins are filled first and then the downstream depocentres (e.g. Beaubouef et al., 2003). The examples here highlight that conduits may contribute to the fill of intra-slope accommodation, which upon being filled to spill may then break out to the next sub-basin downstream. Fill and spill related incision may lead to the development of apparent unconformities within sub-basins, which may not be present across the slope as a whole. Hence the importance of these conduits, which may distribute the better reservoir quality sands across the margins, cannot be understated.

This first outcrop description of a detached canyon head provides new insights, enabling greater understanding of these style of systems and particularly the type of sediments that may be preserved within them. It is likely that detached canyons are dominated by erosive processes such as erosional turbidity currents and debris flows, the latter related to instabilities predetermined by the developing topography (e.g. McAdoo et al., 1997). The incised nature of these detached conduits is likely to be associated with slope instabilities; numerous remobilizations are evident in ancient and modern datasets (Figs 4, 5 and 10). An associated risk for sea-floor infrastructure in the vicinity of detached canyons can be anticipated. The sedimentary record demonstrates that the infill of canyon heads, at least in the studied basin, is dominated by a relatively passive fill, with significant mudstone deposition, whilst coarse grade sediment was largely bypassed downstream. Accordingly, detached canyon heads themselves may not be ideal hydrocarbon reservoirs; they may instead form up-dip baffles or seals to stratigraphic pinch-outs.

CONCLUSIONS

Canyons are present on submarine slopes around the globe, many without any direct linkage to hinterland systems. Given their deep-water setting in sites of significant erosion,

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the fill of these detached canyons and particularly their heads have not hitherto been described. This study documents the sedimentology and stratigraphic architecture of an exhumed deep-water system from outcrops in the East Coast Basin of New Zealand and compares the architecture with modern, detached sea floor canyons. The key conclusions are that:

- Outcrops show a heterolithic range of sediments, including kilometres wide, thick-bedded sigmoidal sandstones encased within traction dominated thin-bedded turbidites. Ripple casts preserved on the bases of these concave-up thick-beds indicates that sediment was emplaced gradually, without significant erosion of the sea floor. These sediments infill a 6 km wide and 430 m deep incision into the downstream margin of a trench-slope sub-basin, with palaeo-flow into this margin; they were deposited at palaeo-water depths in excess of 700 m.
- The described architecture is comparable in morphology, seismic scale architecture and downstream evolution to documented detached canyon heads offshore. Combined with the regional deep-water context and palaeo-bathymetry indications from microfossils leads to the interpretation of the documented system representing a detached submarine canyon.
- A significant volume of erosion and bypass is implied during formation of detached canyons by the size of the incision, comparable with the scale of offshore detached canyons. Given the deposits in the head, the majority of this reworking occurred prior to infill of the head region and represents a phase of downstream bypass.
- Beyond a breached structural high, the downstream expression of the canyon fill demonstrates significant erosion, channelized fill and a coarser grain size. This demonstrates the ability of this detached canyon to breach sea-floor structures and transport coarse material outboard. The same sediment distribution capacity is

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recognized in sea-floor examples, where multiple structures are incised by channels that run for tens of kilometres, distributing sediment to fill otherwise starved intra-slope accommodation.

- Aside from their location, this study enables the definition of key differences between attached and detached canyons:
    - Attached systems rely upon direct supply of sediment from terrestrial or shallow marine sources. Detached systems require more convolute supply, for example via tortuous pathways, bottom currents or cannibalisation of up-dip sediments; they experience lower sedimentation rates and sporadic sediment supply.
    - Although a number of formation mechanisms are possible, detached canyons appear more likely to develop in association with mass-wasting of submarine slopes.
    - The stratigraphic architecture of attached and detached canyon heads differ, attached systems typically either being eroded or infilled by prograding shallow marine systems. Detached canyons may preserve a wider range of the stratigraphic architecture within their heads.
    - Attached canyons are known to be long-lived sites of sediment dispersal. Detached canyons may typically have shorter lifespans, being abandoned as their sporadic sediment supply is terminated. Hence detached canyon heads may have a greater preservation potential and the capacity to form up-dip stratigraphic pinch-outs.

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- The capacity for detached canyons to act as significant sediment conduits, transferring coarse-grained, reservoir grade sediment across submarine slopes, has been overlooked in existing studies of sea-floor systems.
- It is important to recognize detached canyons in the subsurface, because these sediment conduits represent pathways leading to depocentres of potentially reservoir grade sediment. However, the location of canyons may be difficult to predict a priori.

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FIGURE CAPTIONS

Fig. 1. (A) East Coast Basin onshore geological map (Leeand Begg, 2002) and offshore bathymetry [courtesy of the National Institute of Water and Atmospheric Research, New Zealand (NIWA)]; inset map shows the tectonic setting of the North Island of New Zealand and the Hikurangi Trough: ASB – Akitio Sub-basin; CSB – Coastal Sub-basin; MSB – Madden Sub-basin. (B) Schematic cross-section of the Hikurangi subduction complex, after Barnes et al. (2010).

Fig. 2. Subduction related tectono-stratigraphy of the East Coast Basin (modified from Bland et al., 2015, and Burgreen et al., 2016). Regional tectonism adapted from Chanier et al. (1999); Reyners et al. (2013) and Burgreen et al. (2016).

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Fig. 3. (A) Geological map of the study area, comprising an onshore portion of Miocene trench-slope sub-basin fill, modified from Lee & Begg (2002). (B) Cross-section of mapped elements. (C) Google Earth® overlay of Miocene units and mapped elements on the eastern margin of the Akitio Sub-basin.

Fig. 4. (A) Bathymetry of the Madden Canyon and its down-stream evolution; data courtesy of the National Institute of Water and Atmospheric Research, New Zealand (NIWA). (B) Interpreted bathymetry of the Madden Canyon. Structural interpretations are derived from our analysis, that of Barnes et al. (2010) and Lee & Begg (2002); bathymetry and bathymetric contours (500 m) courtesy of NIWA.

Fig. 5. Interpreted seismic lines MC2D LA (A), MC2D LB (B) and MC2D LC (C) courtesy of WesternGeco. Cross-line LA approximately follows the Madden Canyon from its re-entrant to the site of terminal deposition in the Akitio Trough. In-lines LB and LC highlight the irregular, scouring nature of the lower reaches, where the canyon has evolved to become a low relief channel.

Fig. 6. Quantitative observations from lithofacies associations one and two, including a breakdown of sediment type, style of structures, palaeocurrents and bed thickness.

Fig. 7. (A) View of the Three Kings flat irons from hill to the NW (-40.573632, 176.203040). Note that multiple similar horizons are intercalated with the flat irons prominent in the photograph and that these continue as less well exposed ridges to the south. (B) Panel of a sigmoidal sandstone (LF7) overlying graded thin-beds (LF6) with person for scale (ca 1.8 m tall), taken facing west from behind the southern flat iron (-40.665348, 176.208443), dashed lines highlight bases of amalgamated bed-forms. (C) Close up of the base of a sigmoidal bed-form, from the left of the person in (B). (D) Close up of graded thin-beds (LF6) seen to the right of (B).

Fig. 8. Correlation panel of four logs through the Three Kings stratigraphy. Note that thin-bedded intervals have been averaged and detailed logs are supplied in the supplementary material. For log locations see Fig. 3C.

Fig. 9. Higher resolution example of Log D. For location of log D refer to Fig. 3C and key as Fig. 8.

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Fig. 10. Correlation panel through one sigmoidal sandstone (LF7) body, illustrating a lateral variety and numerous internal amalgamation surfaces.

Fig. 11. Photographs and photomosaic of Lithofacies Association 2. (A) View of stepped incision surface south of the Owahanga River mouth. (B) Stacked and amalgamated sandstone (LF4) and conglomerate (LF8) channel fills, with significant internal injections of sandstone (LF12) at Owahanga Beach (-40.688666, 176.343776). (C) Base of channel incising Lower Miocene strata at Owahanga Beach, with hammer for scale (-40.689021, 176.344009). (D) Laterally variable thin-beds (LF3) adjacent to the channel fill at Owahanga Beach (-40.696314, 176.335890).

Fig. 12. Correlation panel of logs E, F and G through the Owahanga Beach stratigraphy. Extent of channels mapped in yellow and draped on Google Earth® image.

Fig. 13. Interpreted sections from: (A) the Madden Sub-basin; (B) the upper reaches of the canyon system; (C) the lower reaches of the canyon system in the Porangahau Trough; (D) the terminal site of deposition in the Akitio Trough. Data courtesy of WesternGeco. Being the background sediment, seismofacies 1 is not annotated: BSR – bottom-simulating reflection; MTC – mass-transport complex; SF – seismofacies.

Fig. 14. (A) Simplified morphology of a fluvio-deltaic attached submarine canyon system, with cross-sections a–a' inspired by Gamberi et al. (2017) and b–b' by Kane & Hodgson (2011). B) Simplified morphology of a deep-water canyon detached from a direct terrestrial sediment source, with cross sections c–c' and d–d'.

Fig. 15. Schematic representation of detached canyon development in a trench-slope system. (A) Mass-wasting of sea-floor relief creates weak zone. (B) Initiation of canyon by stepped incisions and bypass of coarse material down-stream to form a channel-levée complex. (C) Infill of canyon head by passive sedimentation follows aggradation and shut-down of the channel-levée system. D) Abandonment of spill point as basin topography reset by mass-transport complex (MTC).

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Table 1. Lithofacies described at outcrop			
Lithofacies type	**Grain size and bed thickness**	**Observations**	**Interpretation**
LF1 – Hemipelagic mudstone	Mud; thin (1 cm) to very thick (<75 cm)	Light to dark grey mudstone occurring in beds up to 75 cm thick, which often amalgamate into packages metres to tens of metres thick. Beds are typically laterally continuous over outcrop scale. Bedding may be recognized by broad colour changes and or concreated horizons. Typically exhibits a blocky texture, with a conchoidal fracture. Rarely shows small biocoenotic macrofossils, such as Inerocamerus spp. molluscs or macro foraminifera (e.g. Bathysiphon spp.). Rare disseminated fragments of organic matter occur. It may show bioturbation, with horizontal burrows such as Nerities sp. and Phycosiphon sp. Large-scale deformation in the form of slumps and slide scars is often evident	This massive, blocky, mudstone is interpreted to represent background hemipelagic sedimentation in the marine environment. This may occur in shelf to deep-water settings. Deformation implies deposition on an often unstable slope, with remobilization of gravitationally-unstable sediment
LF2 – Turbidite silt to mudstone	Silty mud; thin (1 cm) to thick (<50 cm)	Dark to very dark grey, silty mudstones, occasionally laminated, rich in organic matter, often with visible plant fragments, may or may not show bioturbation, such as horizontal burrows, e.g. Nerities spp. and/or sub-vertical burrows such as Ophiomorpha spp. or Thalassinoides spp. Beds are typically laterally continuous over outcrop scale. Typically occurs above turbidite sandstones (LF3–LF4) and below LF2 (hemipelagic mudstone)	This organic rich, silty, often laminated silt grading to mudstone is interpreted as the fallout from suspension clouds of turbidity currents (Bouma T_e)
LF3 – Laterally variable thin to medium-bedded sandstones	Fine to very fine (very rarely medium) grained; thin to medium-bedded (<20 cm)	Pale grey to beige, well-sorted sandstone. Typically shows a sharp, irregular base, occasionally lower portions of the beds show planar laminations and upper portions may show ripples and cross-lamination with silt – mudstone. Beds are not necessarily normally graded and may show variation in the order of structures. Beds may show significant lateral variation in thickness, occurring as lenses, pinching and swelling or thinning laterally. May be rich in carbonaceous material, which often highlights planar and ripple lamination. Sandstones are typically texturally immature, displaying a variety of lithic fragments and glauconite. Bioturbation is variable and macrofossils were not observed. Typically proceeded by LF2 or LF3 mudstone	Deposition from dilute, low-density turbidity currents (Bouma $T_{c–d}$). The presence of traction structures implies deposition from waning flows. The lateral variation may be a result of thinning and pinch out against a confining surface when apparent or, when lens shaped, have infilled a scour surface. When filling scours these deposits may be inferred to have a bypass component, especially when directly overlain by hemipelagic (LF2) mudstone (sensu Stevenson et al., 2015)

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LF4 – Laterally inconsistent thick-bedded sandstones	Fine to very fine (very rarely granular to medium); thick-bedded (<200 cm)	Pale grey to beige irregularly bedded sandstones. Bed bases are very irregular, with decimetre-scale incisions truncating underlying strata. Sole marks, primarily flute casts may scour centimetres into the underlying sediment. Beds variably show planar cross-stratification, extensive dewatering and convolute bedding, grading to planar lamination and ripple lamination at the bed tops or may be massive and contain abundant sand-clasts and mud-clasts. Laminations are often highlighted by organic rich bands and carbonaceous debris up to 10 cm long is common. Bed amalgamation is very common and beds typically show a lenticular form, thinning over tens to hundreds of metres in width. In rare examples beds are granular to medium grained and may have a significant glauconite and bioclastic component. Bioturbation is rare and occurs as large vertical burrows (e.g. Ophiomorpha spp.) at bed tops and macrofossils were only observed as broken shell fragments <1 cm	These relatively coarser grained, often cross-stratified, lenticular beds are interpreted as the fill of low aspect ratio scours and or small channels by deposits of high-density turbidity currents. The bioclastic and glauconitic bed bases imply that at least part of these flows initiated in a shallow marine environment; however, the fact that the upper portions of these beds commonly show carbonaceous material and carbonized wood fragments implies some terrigenous mixing
LF5 – Mud-clast rich sandstones	Fine to very fine grained; thin to thick-bedded (<100 cm)	Pale to medium grey, normally ungraded, sharp based sandstones, typically lacking internal structure and with mud clasts throughout, although often concentrated in local clusters or horizons. Clasts are up to 30 cm long, but are typically <3 cm. Small clasts are typically sub-angular and elongate, becoming more spheroidal and rounded as they increase in size. Typically matrix-supported, but beds may rarely be up to 50% clasts. Beds may also be rich in plant debris and or bioclastic fragments. Bioturbation was observed only at the bed tops	These mud-clast rich deposits are interpreted as the result of high-density erosive turbidity currents, entraining semi-lithified mudstones, inferred to be present up-slope. By entrainment of fines, these flows probably lost turbulence and acted as laminar or semi-laminar flows, lacking in current structures, but had not evolved into hybrid event beds (sensu Haughton et al., 2003, 2009)
LF6 – Graded event beds	Very fine sandstone grading to siltstone; graded beds typically <25 cm	Pale grey sandstones grading normally into mottled siltstones. Bed bases are sharp. Planar, current or wave ripple lamination is sparse and hummocky cross-stratification is occasionally observed. Bioclastic material is often concentrated in discrete horizons. Extensive bioturbation may give beds a mottled appearance, or show large burrows such as Ophiomorpha spp. and Scolicia spp. Sandstones typically grade up into intensively bioturbated cross-laminated sandy siltstones when not scoured by overlying events. Foraminifera indicate relatively deep, mid to	These highly gradational beds, which show a range of traction structures but also structures more commonly associated with shallow water, are interpreted to have been deposited in a relatively deep-water setting that had very frequent currents passing by. Hummocky cross-strata and wave ripples are known to be produced in deep-water settings, particularly where oscillatory flows were carrying the sediment (see Tinterri, 2011, and references within)

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		upper bathyal water depths (ca 700 m)	
LF7 –Sigmoidal sandstones	Fine to very fine grained; beds up to 300 cm thick, but may amalgamate up to 13 m thick	Massive, moderately well-sorted, organic rich sandstones. Bed bases are typically sharp but preserve bidirectional wave ripple casts. Rarely the lower tens of centimetres may show planar cross- or horizontal stratification, but beds are typically internally structureless, with rare dewatering features. On a large scale, sigmoidal bedforms are apparent, leading to the development of foresets as beds amalgamate into units tens of metres thick and tens to hundreds of metres wide, thus forming low aspect lenses. Foraminifera of encasing hemipelagic mudstones record mid to upper bathyal water depths of ca700 m	These massive sandstones are interpreted to have formed in relatively deep but highly confined settings with strong currents organizing significant quantities of sand to form the large-scale bedforms. The preservation of ripple casts indicates that these deposits were emplaced progressively without significant erosion of the sea floor. The range of structures, sigmoidal bedforms, and lenticular form gives the interpretation of mouth-bar like deposits (see Tinterri, 2011, and references within), but in a deep-marine setting according to foraminifera. These may be comparable with downstream migrating sandwaves recorded within modern submarine canyons (e.g. Xu et al., 2008)
LF8 – Matrix-supported polymict conglomerates	Pebble to boulder sized clasts set within granular to fine grained matrix; beds are typically up to 150 cm thick, but may be tens of metres thick	Typically chaotic, very poorly-sorted, massive conglomerates. Bed bases are typically sharp and erosive, often scouring tens of centimetres. A subtle cross-stratification is observed rarely in a minority of beds. Beds are typically laterally very variable in thickness and discontinuous and may be observed to laterally grade into thin sandstones (Lee et al., 2002). May show normal, inverse or no grading from pebbles to boulders, which range from spherical to angular and spheroidal to elongate. Clasts represent a wide range of lithologies, including older ECB lithologies, such as Whangai, Wanstead and Weber Formation and may also show a subordinate proportion of 'intraformational' sandstone, carbonate or mudstone clasts. Outsized rafts of material up to 12 m long have been encountered. Clasts typically represent less than 50% of the bed, which is matrix-supported. The matrix typically consists of a poorly sorted granular to very fine grained sandstone, often with a bioclastic component. Wood debris was also rarely found	These matrix-supported, polymict conglomerates, associated with marine strata and containing bioclastic debris in the matrix are interpreted to represent the products of submarine debris flows. Different beds may show different concentrations of clast types, in some localities being almost monomict, indicating derivation from local highs comprised of a single lithology. Delteil et al. (2006) considered these to represent mass-failures of steep bedrock margins
LF9 – Clast-supported	Pebble to boulder sized clasts set within granular	Typically chaotic, very poorly-sorted, massive conglomerates. Bed bases are typically sharp and erosive, often scouring tens of	These clast-supported, polymict conglomerates associated with marine strata are interpreted to

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polymict conglomerates	to fine grained matrix; beds are up to 240 cm thick	centimetres. A subtle cross-stratification was observed rarely in a minority of beds, which are normally laterally restricted to a few tens of metres. May show normal, inverse or no grading from pebbles to boulders, which range from spherical to angular and spheroidal to elongate. Clasts may show imbrications. Clasts represent a wide range of lithologies, including older ECB lithologies, such as the Weber Formation marls. Clasts typically represent upward of 70% of the bed, showing clast contacts, and the assemblage is considered to be clast-supported. The matrix typically consists of a poorly sorted granular to very fine grained sandstone, often with a bioclastic component. Wood debris was also rarely found	represent the products of submarine debris flows. These may be interpreted to represent the traction carpet of high-density turbidity currents (R2–R3 of Lowe, 1982) and include the Packspur Conglomerate, which Neef (1992) interpreted to have filled a submarine channel. Different beds may show different concentrations of clast types, in some localities being almost monomict, indicating derivation from local highs comprised of a single bedrock lithology
LF10 – Bioclastic grits	Granular to fine grained; beds up to 100 cm thick, but typically <10 cm	Pale yellow to beige, often weathering orange beds of very coarse material, primarily comprising a poorly sorted mixture of siliciclastic, bioclastic and glauconite grains of highly variable proportions. Mud-clasts are also common, typically less than 5 cm long, but up to 50 cm. Exotic pebbles are a rare inclusion. Bed bases are typically sharp, erosive and may display scour marks. Beds are variably massive, show coarse laminations or planar cross-stratification. Beds are often very laterally variable in thickness, grain size and persistence, often seen to be pinching and swelling along dip. Bioclastic material includes fragments of molluscs, foraminifera, bone material (primarily fish, but also cetacean), corals and other marine organisms. Although rare, terrestrial material, including wood fragments may also be found in these beds. These beds may occur in isolation within mudstone intervals, or more commonly immediately below much finer grained LF3, LF4 and LF6, or very rarely in normally graded beds	These coarse, bioclastic beds are interpreted as the deposits of gravity flows originating from local shallow marine environments, reworking material from marine shelves to deposit them in relatively deep-water. Their common association with very fine grained material may be interpreted in one of two ways: (i) these beds were triggered simultaneously with finer siliciclastic rich events; or (ii) they represent a missing grain-size portion in normally graded events. The observation of beds grading normally through medium and fine with decreasing bioclastic content implies that the latter was the dominant process
LF11 – Sand injectites	Medium to fine grained; <2 m thick	Massive, well-sorted sandstones, which may show grading towards margins. May occur as small, simple elongate fingers adjacent to sandstones or as significantly larger sheets and pipes cross-cutting stratigraphy. The host stratigraphy often shows signs of brittle deformation all around these units	The highly discordant and irregular nature indicates that these are injected sandstones. The brittle nature of their associated deformation and the mudstone clasts implies that host lithologies were already lithified when the injection occurred

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Table 2. Seismofacies of the Madden Canyon

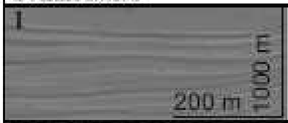
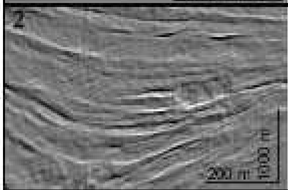
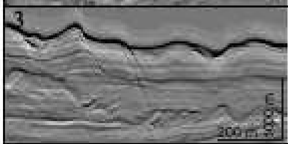
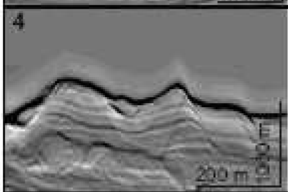
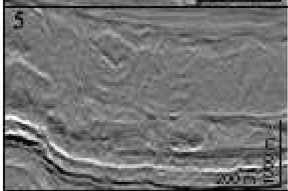
Seismofacies	Amplitude & dimensions	Interpretation
1 	Low amplitude, laterally continuous (where not truncated). Tens to hundreds of meters thick, but thousands to tens of thousands wide.	These are interpreted to represent background, mud dominated sediments (sensu Vinnells et al., 2010).
2 	High to very high amplitude, laterally extensive but discontinuous and mounded bodies. Tens of meters thick although variably pinching to zero, being up to 3500 m wide.	These relatively discontinuous lenses are interpreted to represent sediment infilling an older stage of the canyon. The geometry of these units resembles isolated shelf-margin clinoforms described by (Johannessen and Steel, 2005).
3 	Variable amplitude fill of incisions tens to hundreds of meters deep, by hundreds to thousands of meters wide, although typically less than 500 m wide.	These relatively small incising features with variable fill are interpreted as the fill of submarine channels (Mayall et al., 2010).
4 	Alternating high and low amplitude bands of laterally thinning material hundreds thinning to tens of meters, often showing wave-forms with wavelength of hundreds to thousands of meters. Found laterally to seismofacies 3.	This banded seismofacies, found adjacent to SF3 is interpreted as overbank levees (Posamentier and Kolla, 2003).
5 	Chaotic fill of irregular packages tens to hundreds of meters thick, often thousands of meters wide. Rarely coherent rafts or deformed packages of banded, high and low amplitude material can be seen.	These irregular, chaotic geobodies are interpreted to represent mass-transport complexes (Posamentier and Kolla, 2003).
6 	Alternating high and low amplitude packages seen to be thickening towards the core of troughs and onlapping at margins.	These are interpreted as sand- and mudstone rich deposits filling sub-basin in the form of ponded turbidites (Prather et al., 1998)

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Table 3. Details of attached active margin canyons and detached canyons documented across the globe								
Canyon name	**Location**	**Margin type**	**Head distance from shore (km)**	**Water depth head (m)**	**Width of canyon head (km)**	**Length canyon (km)**	**Water depth terminus (m)**	**Authority**
Hendrickson (detached)	New Jersey Slope, Atlantic Ocean, offshore USA	Passive	153	250	2	31	2500	Pratson et al., 1994
Lindenkohl (detached)	New Jersey Slope, Atlantic Ocean, offshore USA	Passive	140	200	4	50	2700	Pratson et al., 1994
Tortuga Canyon-1 (detached)	Ebro Margin, western Mediterranean	Passive	Unknown	Unknown	2	At least 8	Unknown	Bertoni and Cartwright, 2005
Madden (detached)	East Coast Basin, Pacific Ocean, offshore New Zealand	Active	15	1400	9	95	2200	This study
Kings (detached)	East Coast Basin, Pacific Ocean, New Zealand	Active	At least 50 km	At least 700	At least 6	At least 11	Unknown	This study
Opouawe (detached)	East Coast Basin, Pacific Ocean, offshore New Zealand	Active	13	80	2	60	2600	Mountjoy et al., 2009
Central (detached)	Cascadia, Pacific Ocean offshore Oregon, USA	Active	95	1300	0.1	2	2000	McAdoo et al., 1997
Aoga Shima (detached)	Izu–Bonin forearc, Pacific Ocean, offshore Japan	Active	18	1000	5	150	6000	Klaus & Taylor, 1991
Barbados A (detached)	Barbados Prism, Offshore Venezuela, Caribbean Sea	Active	ca 360	1300	5	250	3500	Huyghe et al., 2004
Astoria	Washington Slope, Pacific Ocean, offshore USA	Active	17	100	3.7	115	2000	Nelson et al., 1970
Kushiro	Kuril Trench, Pacific Ocean, offshore Japan	Active	10	90	3	233	7000	Noda et al., 2008
La Jolla	California margin, Pacific Ocean, offshore USA	Active	1	100	2	54	1000	Normark, 1970
Milazzo	North-eastern Sicilian margin, Mediterranean Sea	Active	0.4	50	7	79	2490	Gamberi et al., 2017
Monterey	California margin, Pacific Ocean, offshore USA	Active	0	45	12	470	3300	Greene et al., 2002
San Antonio	Central Chile Forearc, Pacific Ocean, offshore Chile	Active	0	100	15	150	5400	Laursen & Normark, 2002

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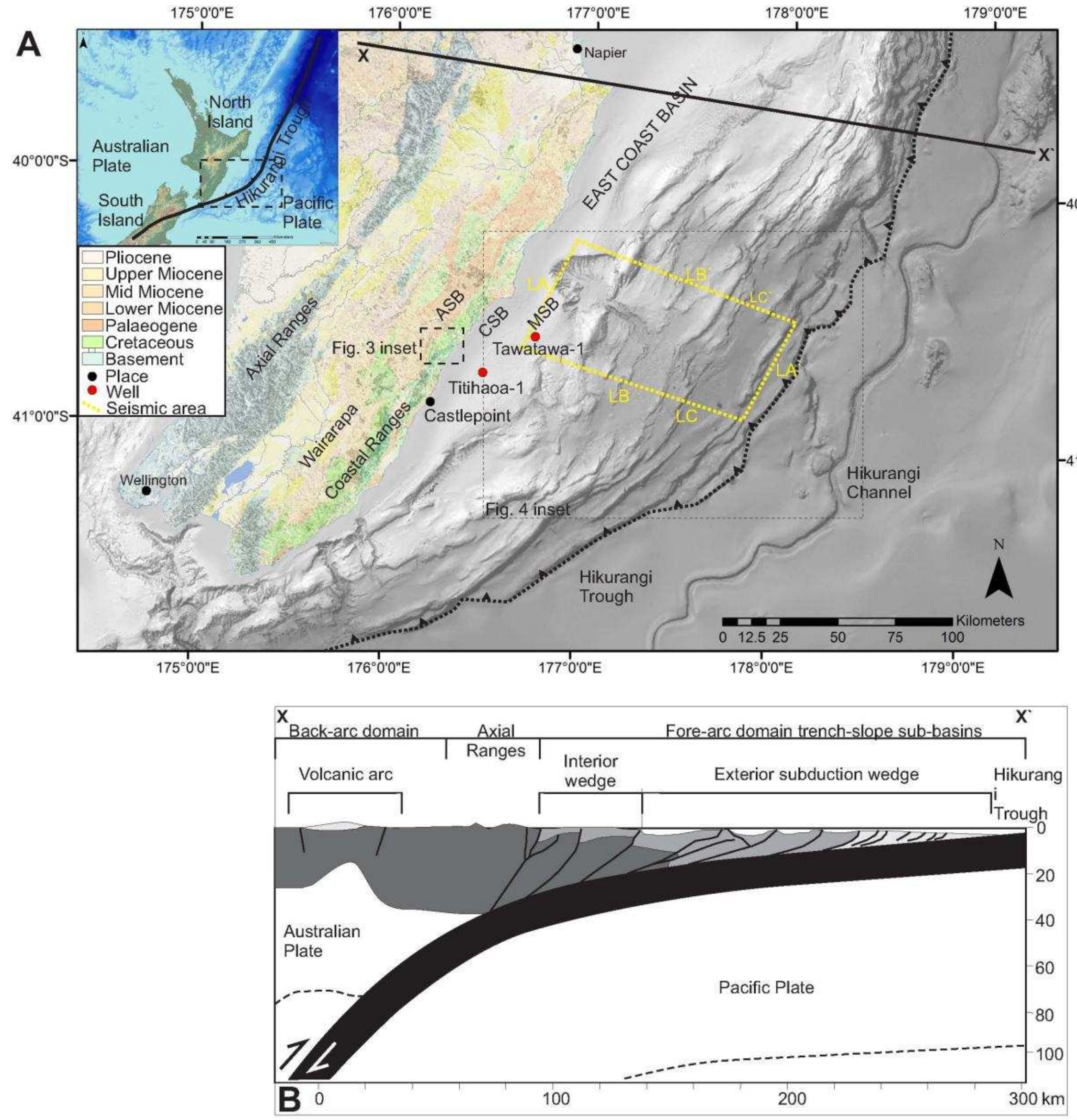

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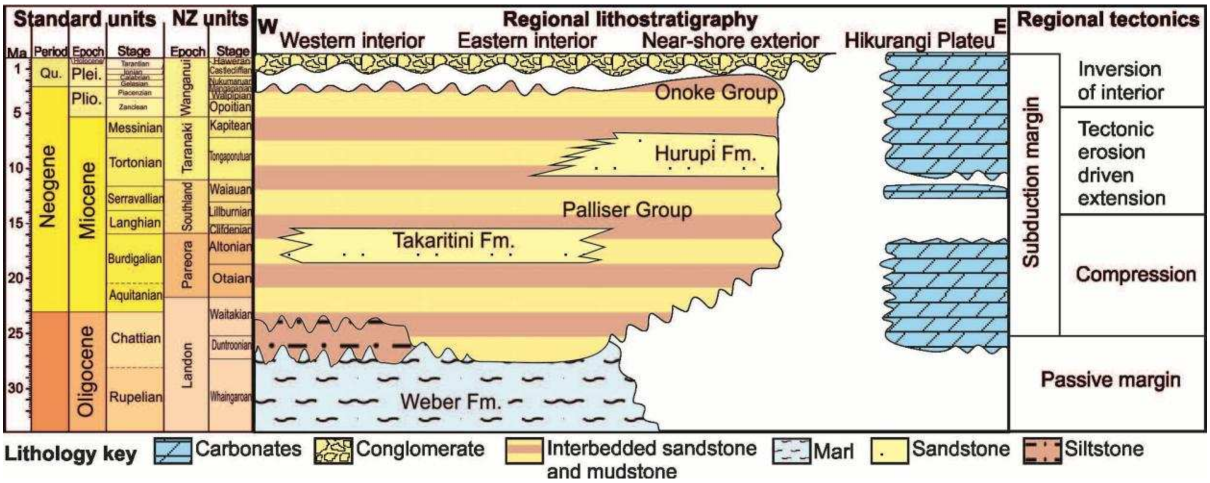

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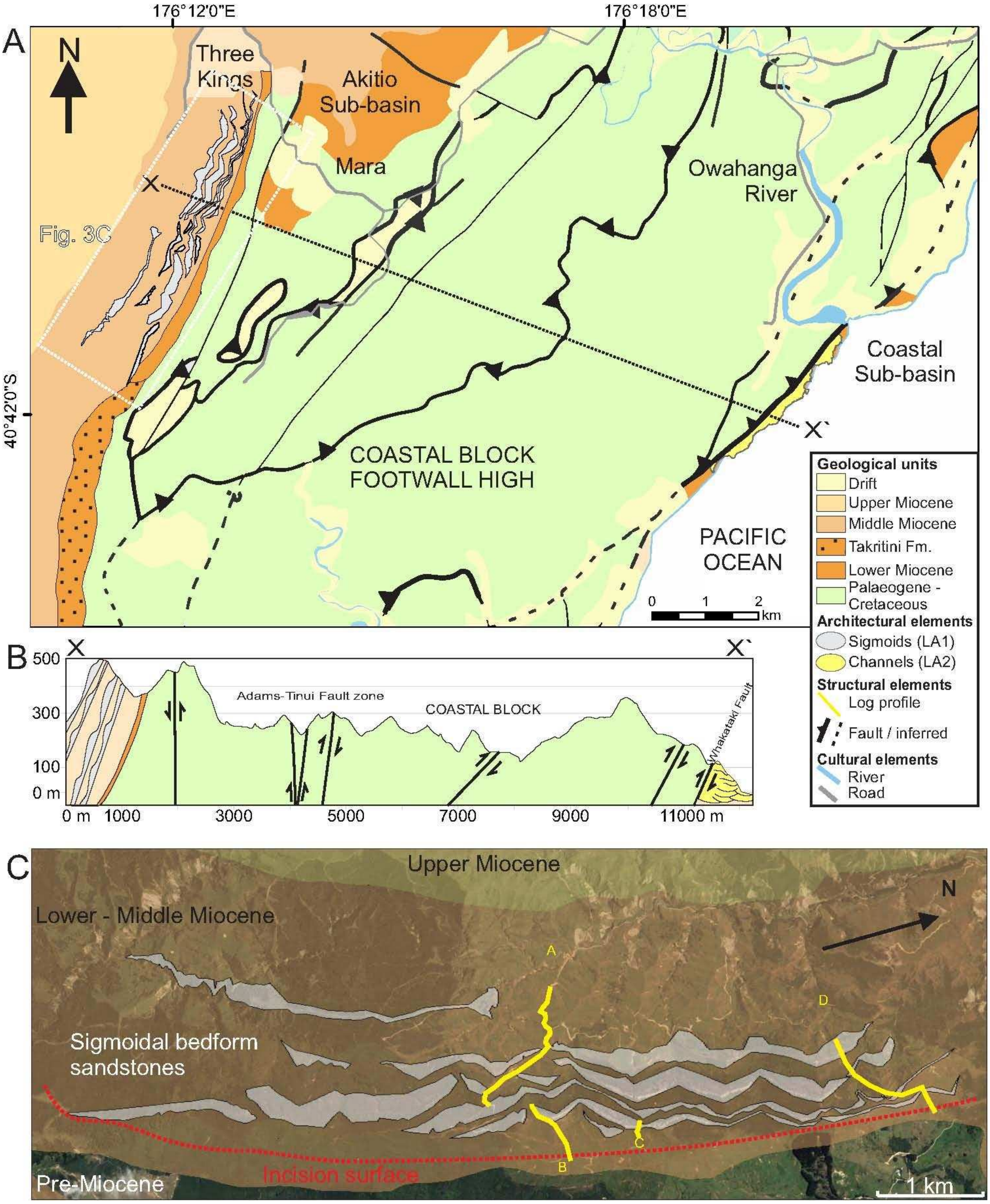

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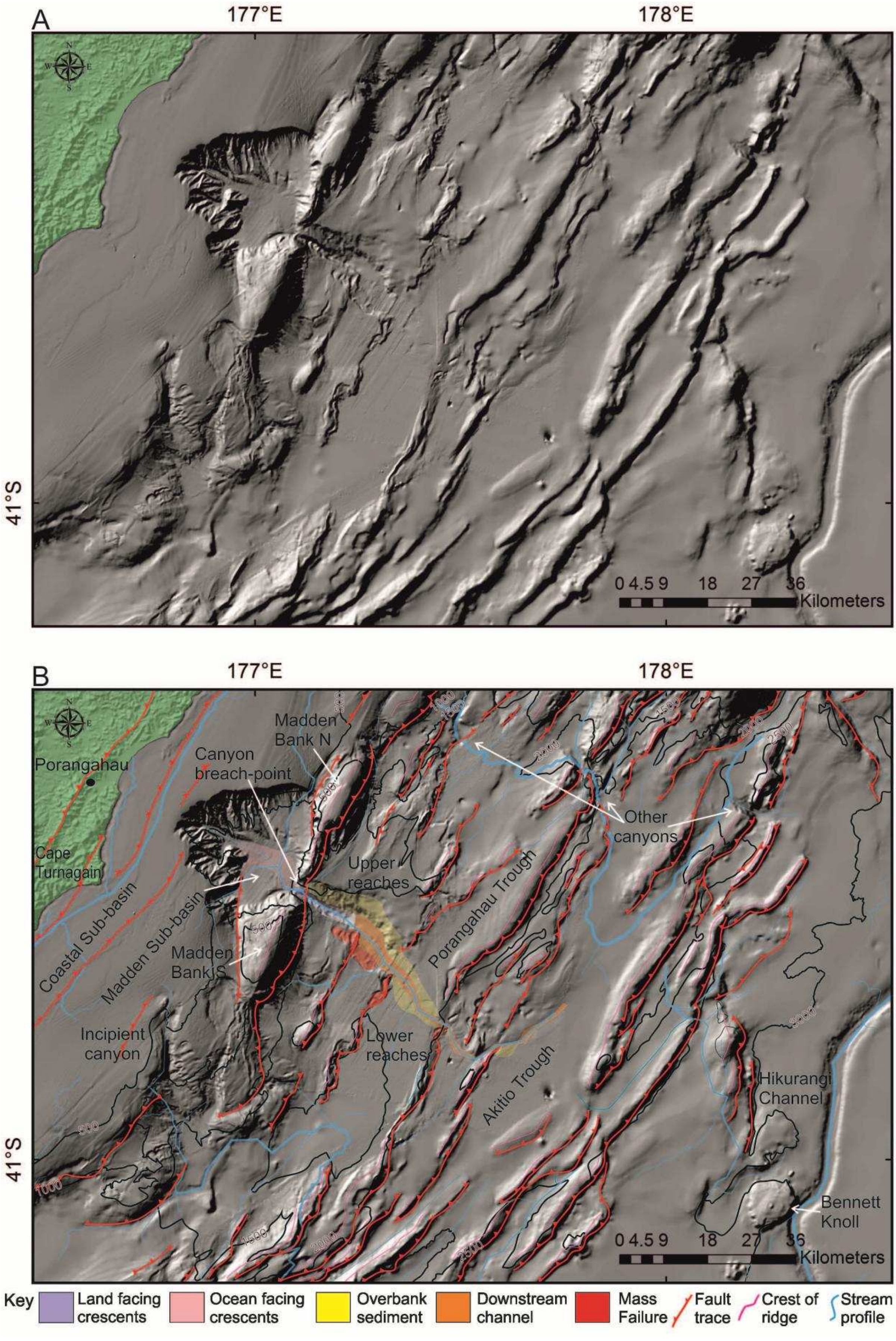

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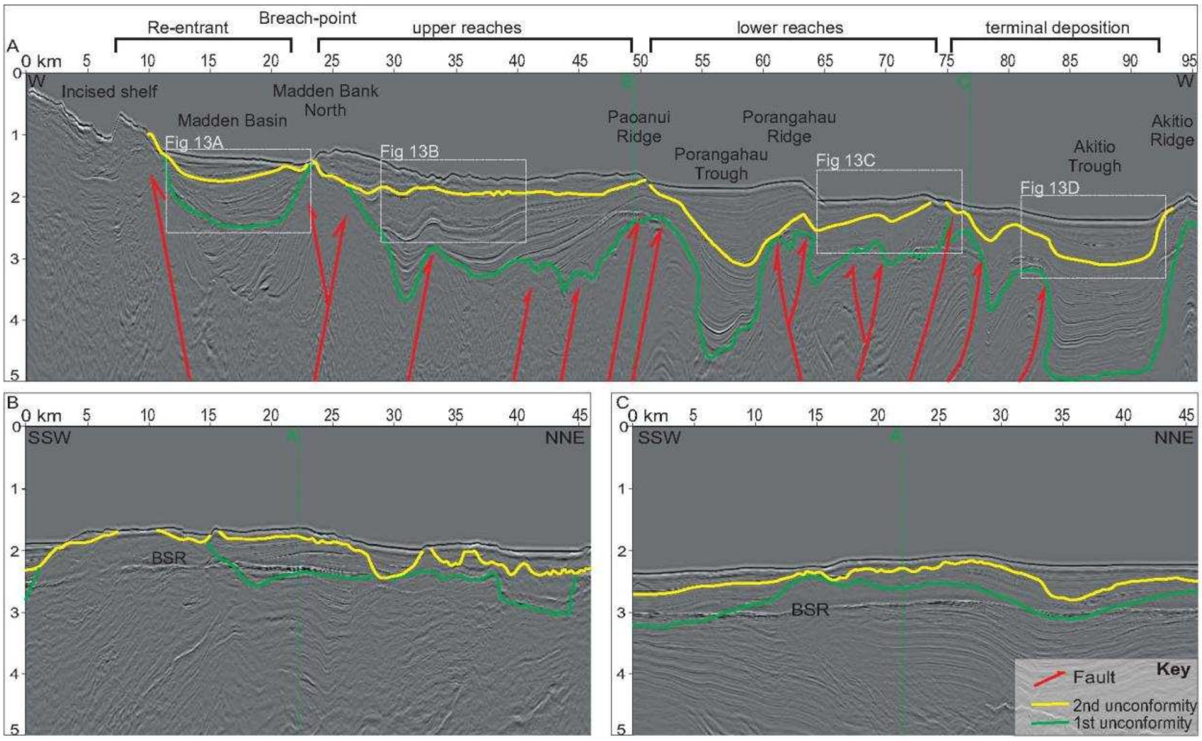

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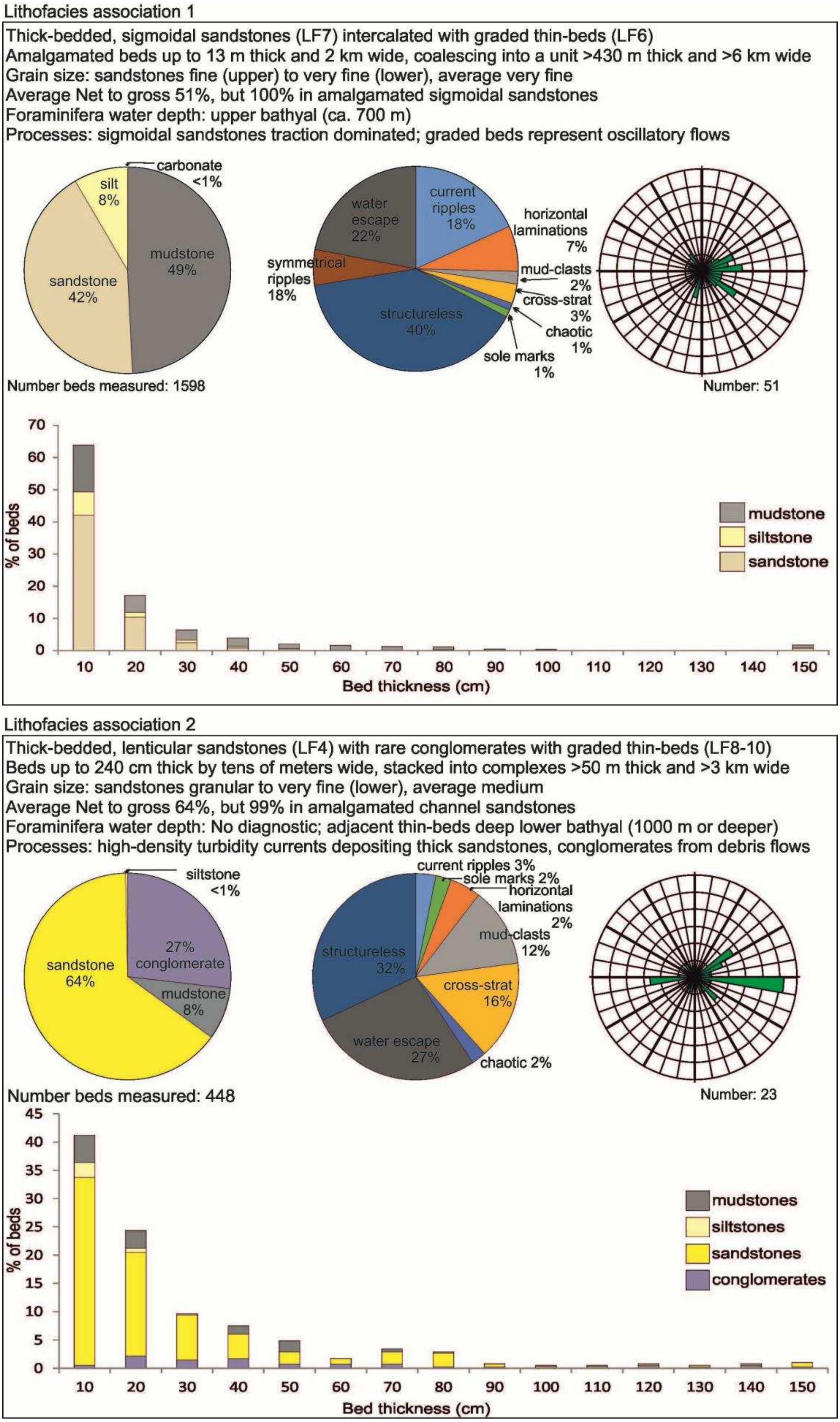

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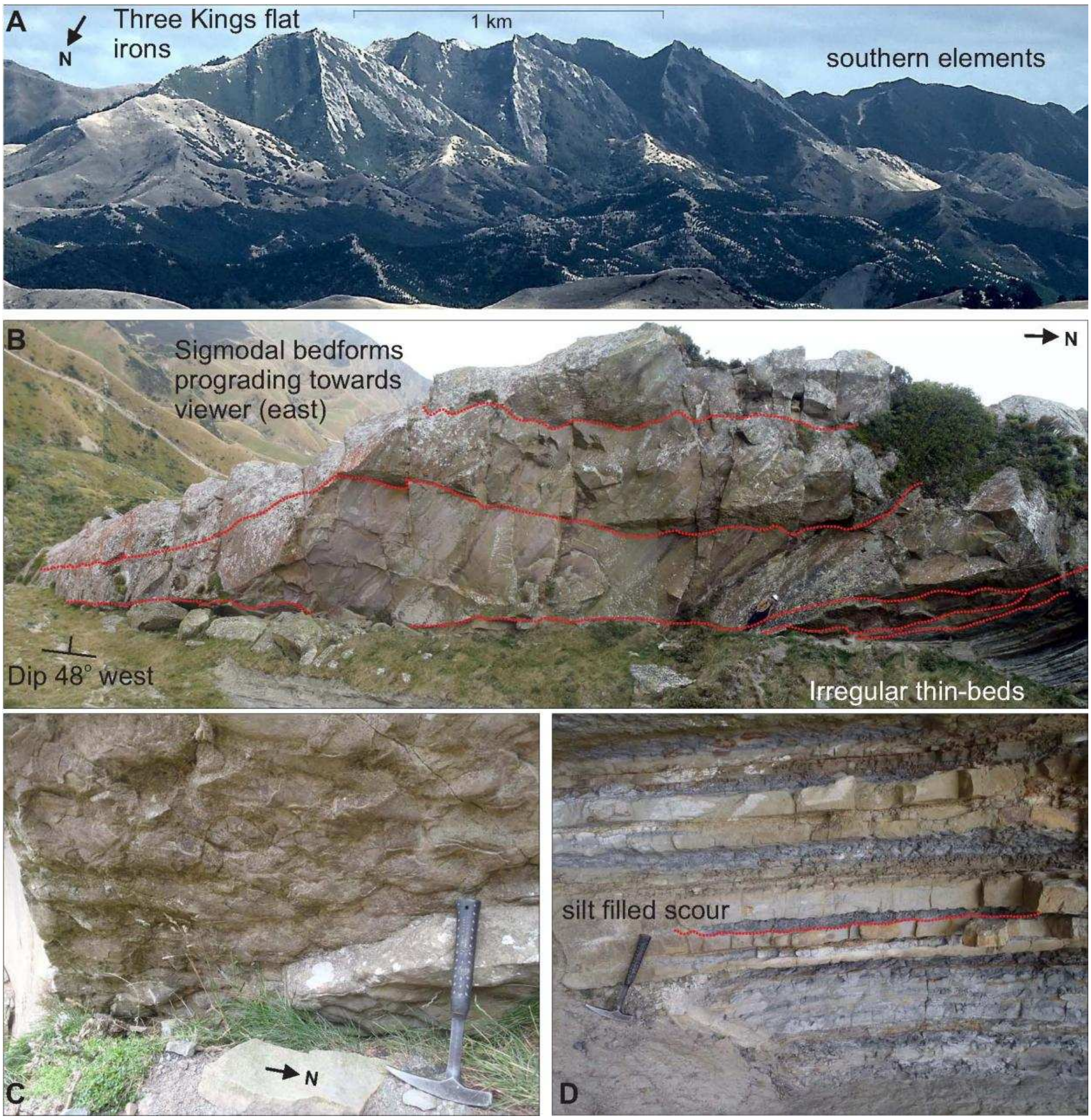

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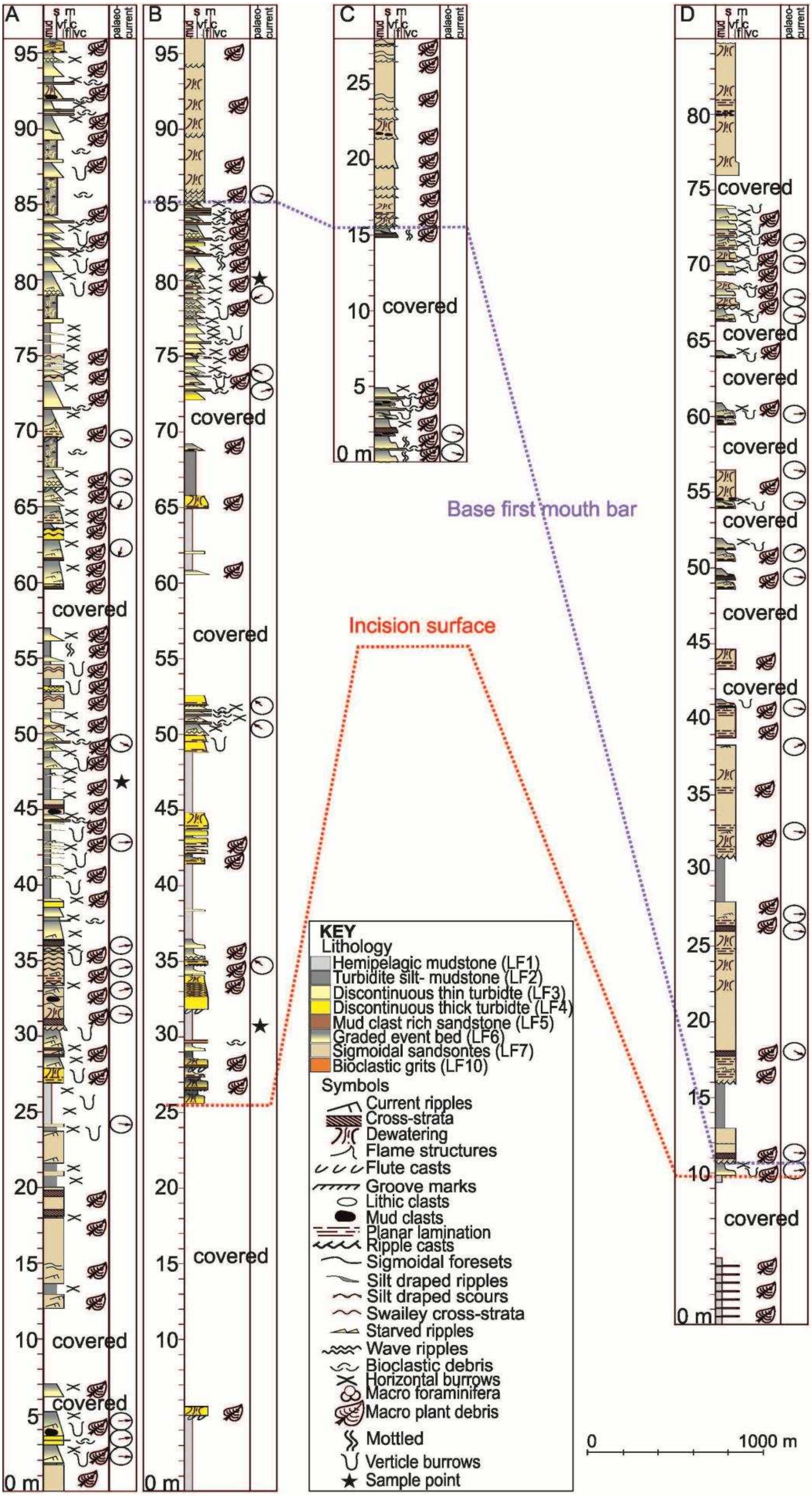

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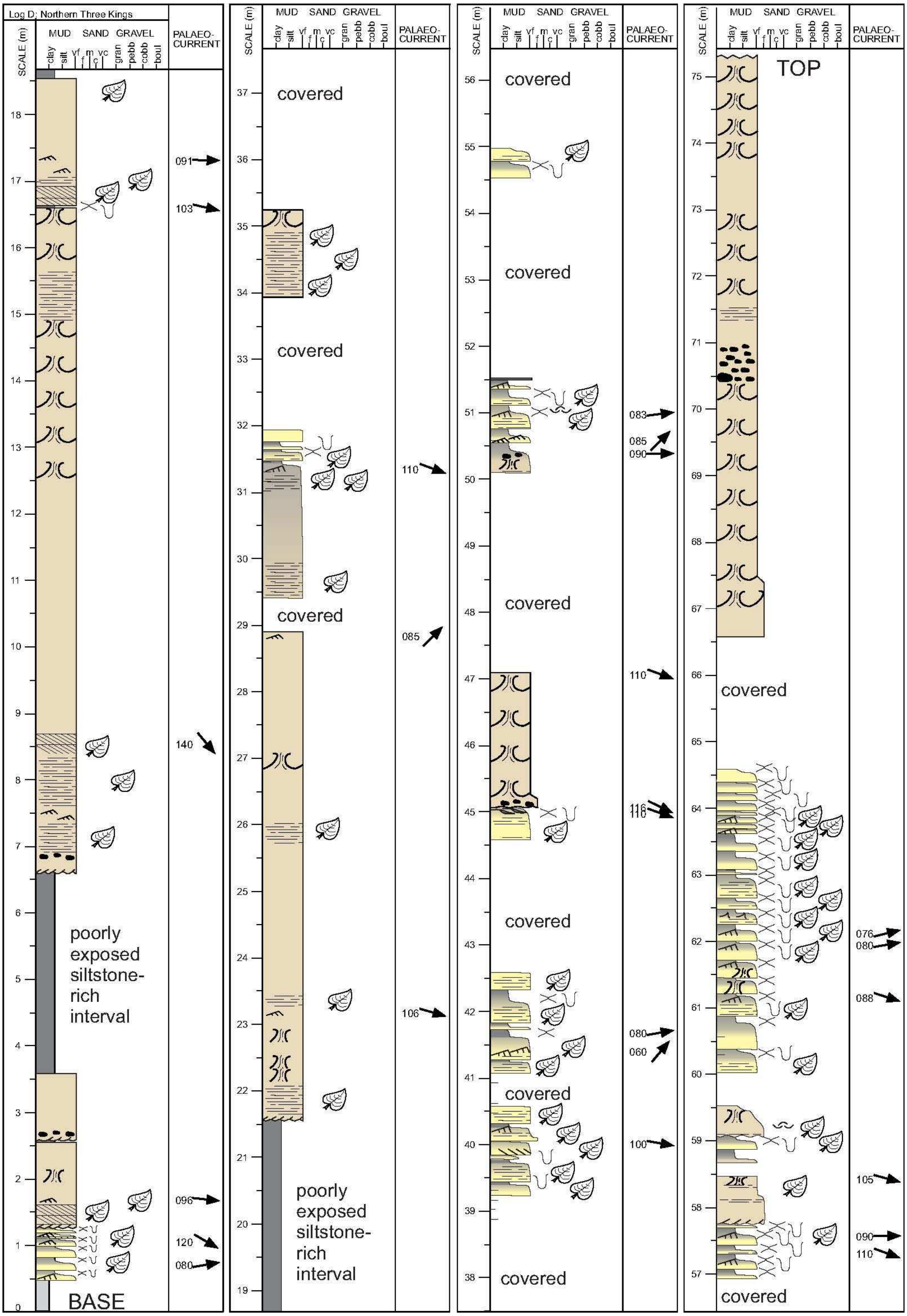

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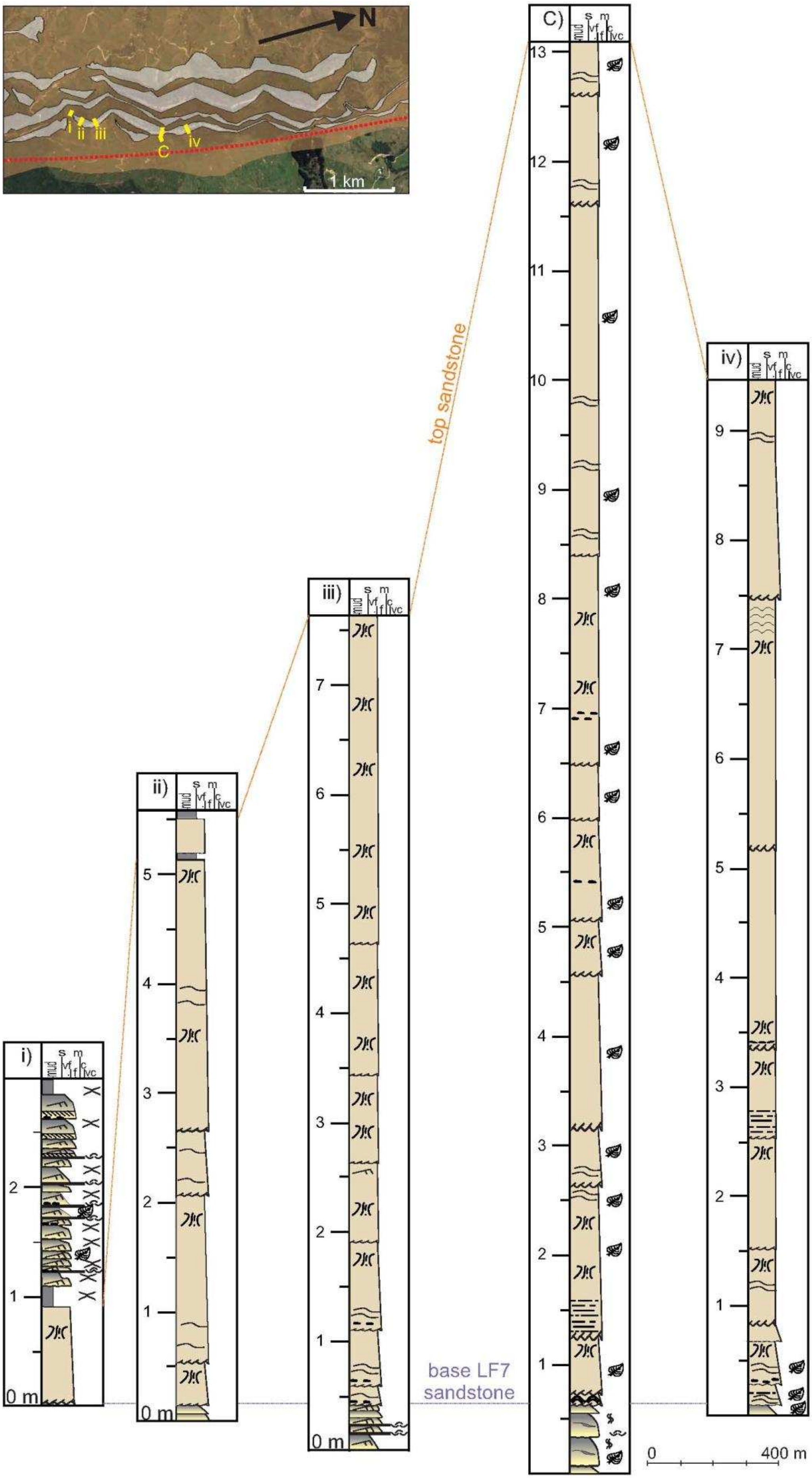

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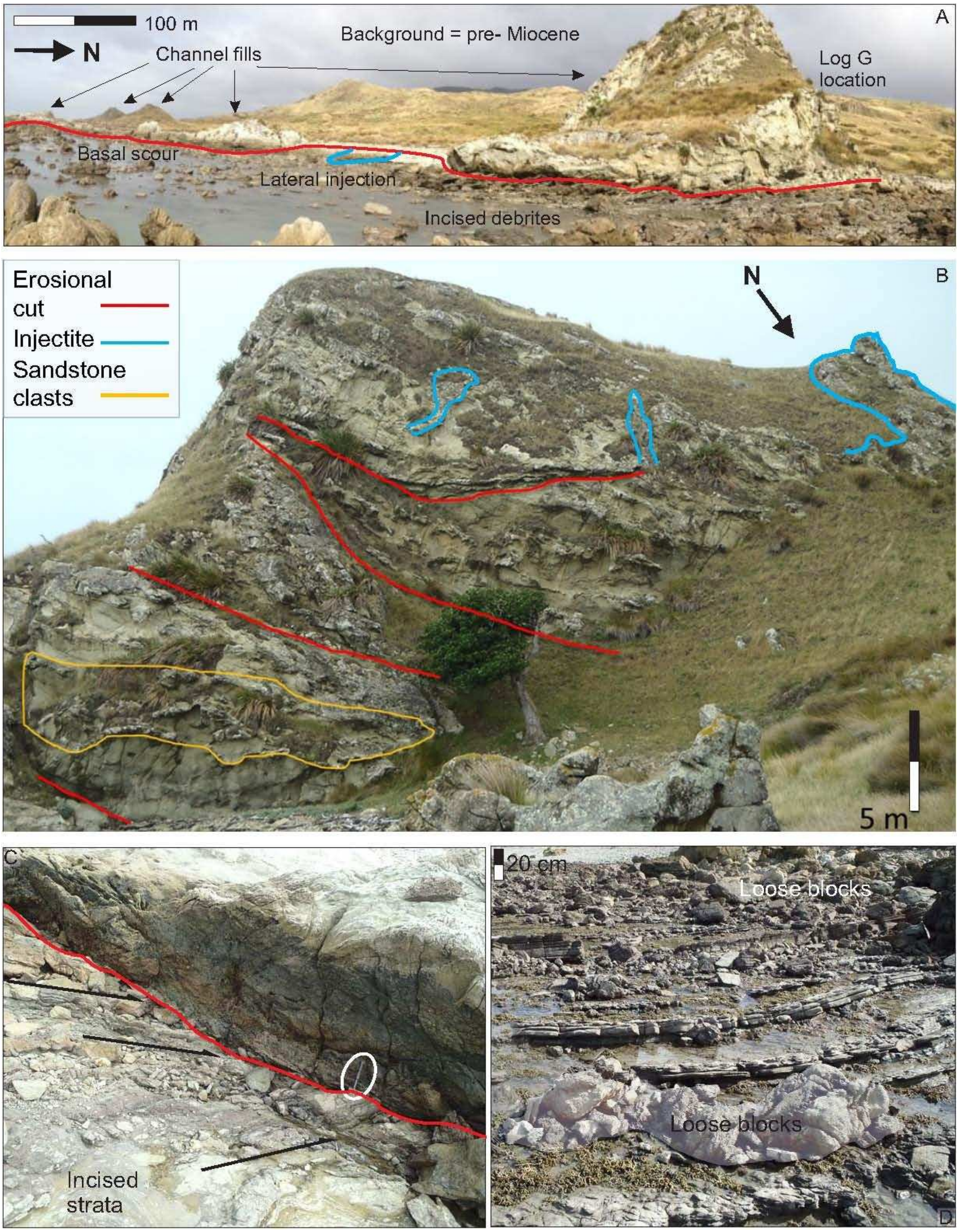

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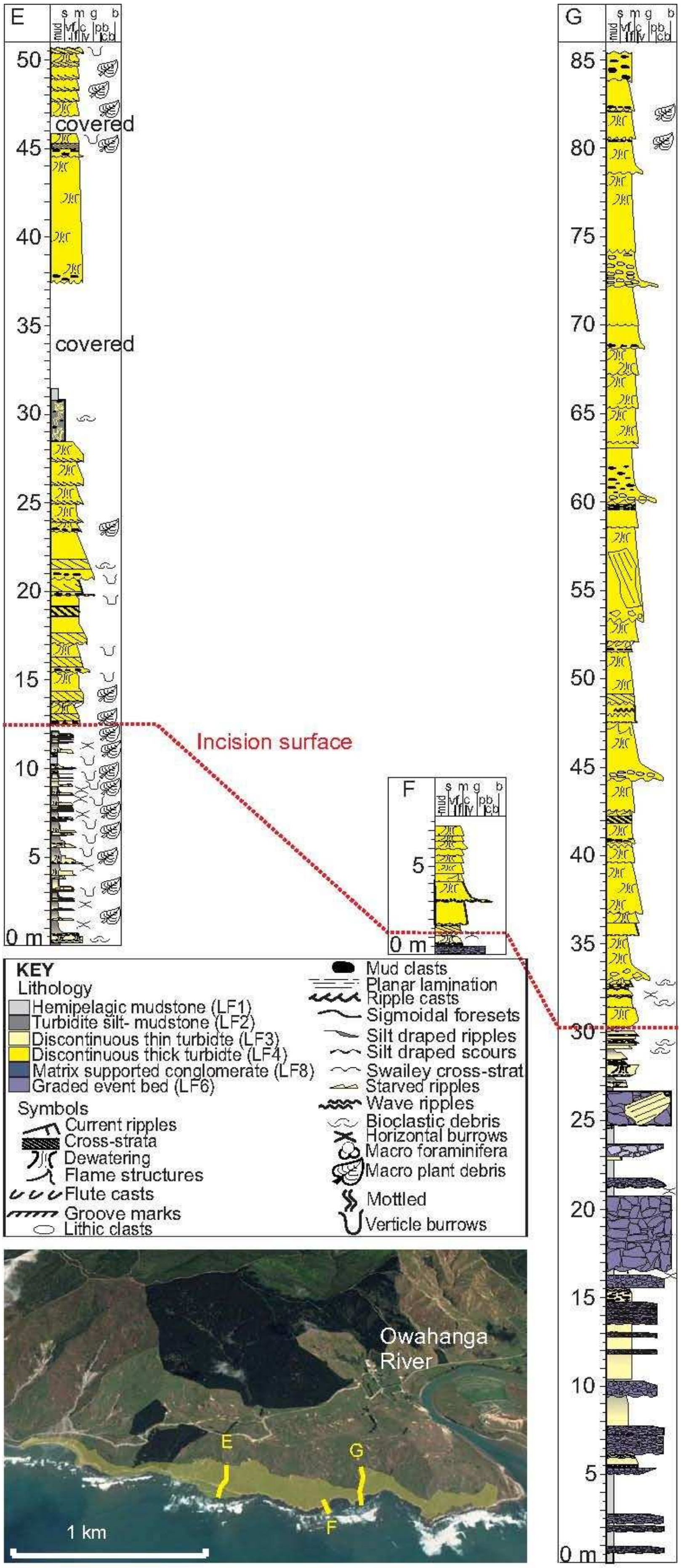

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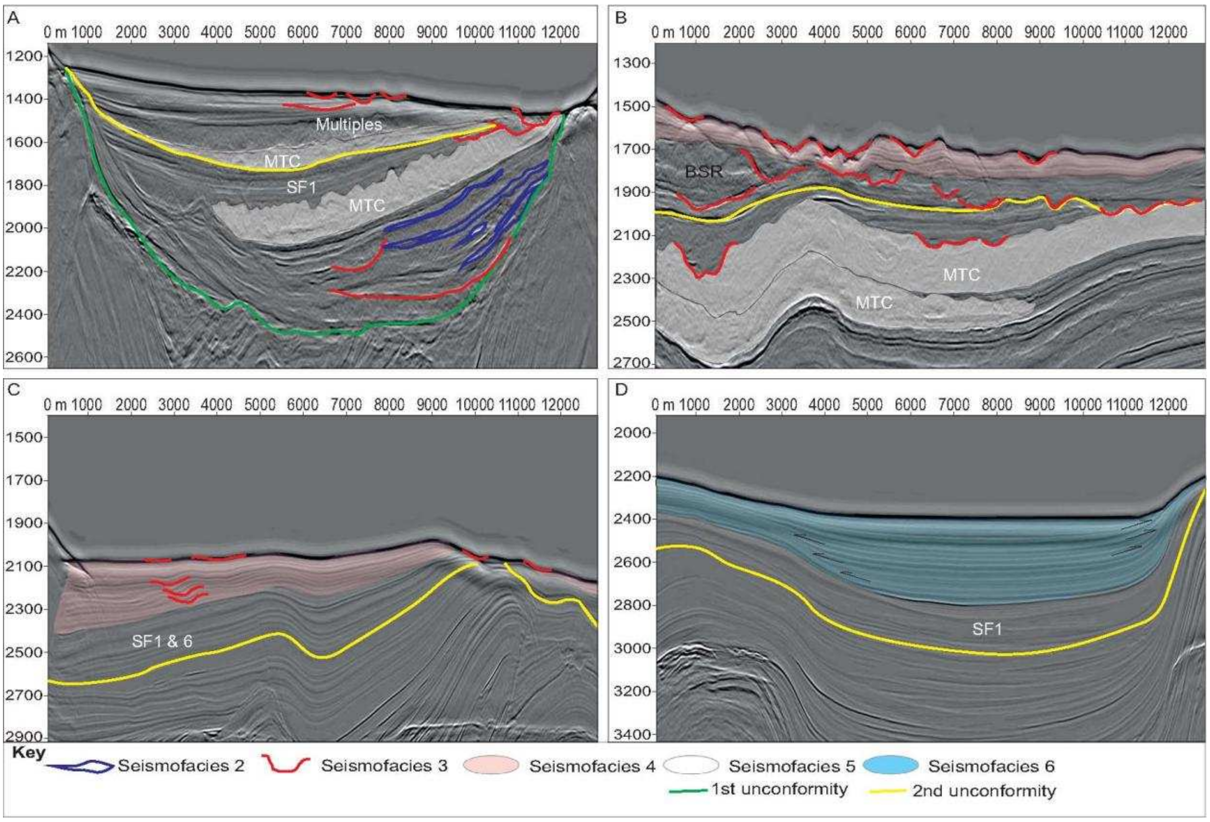

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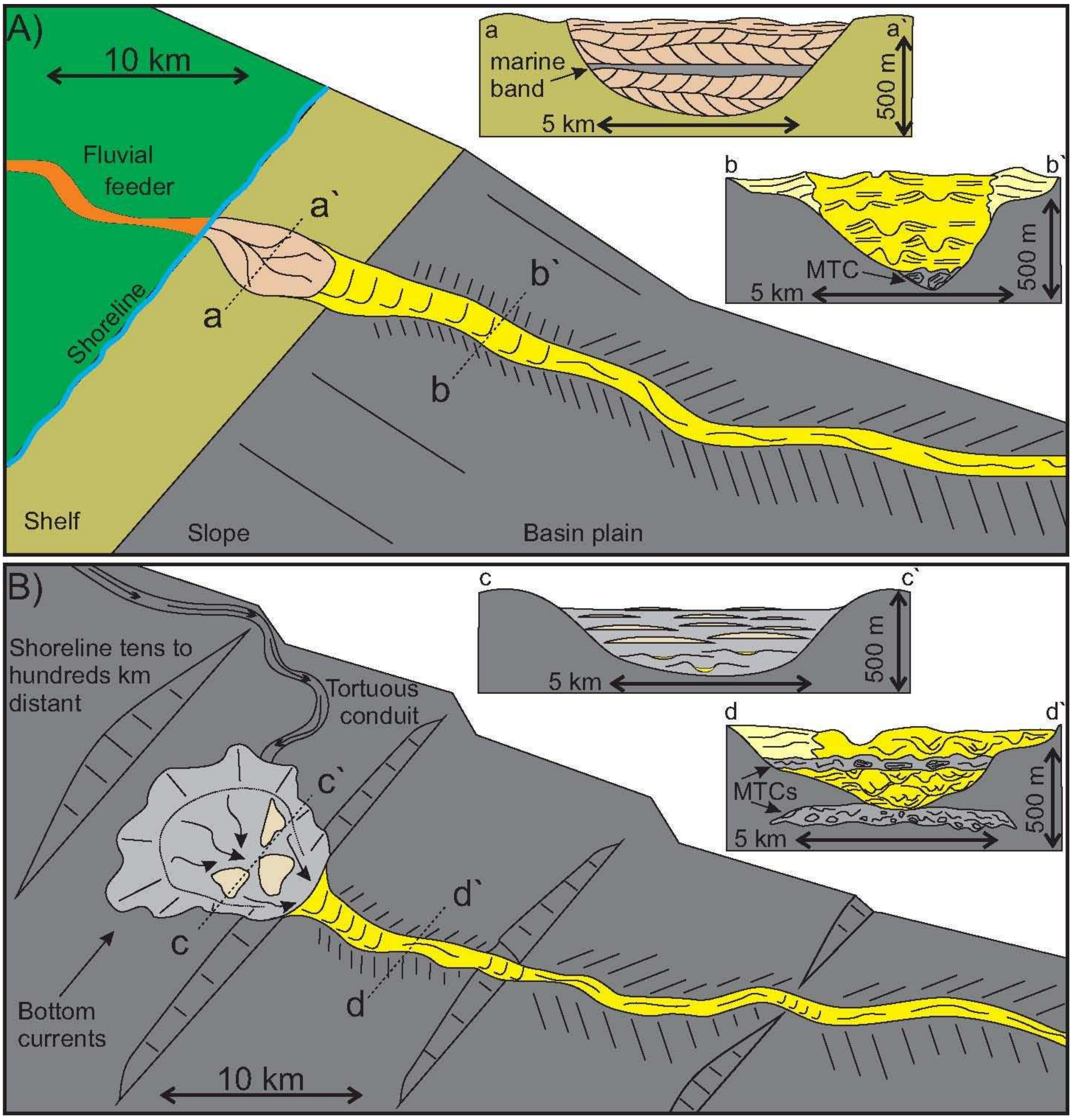

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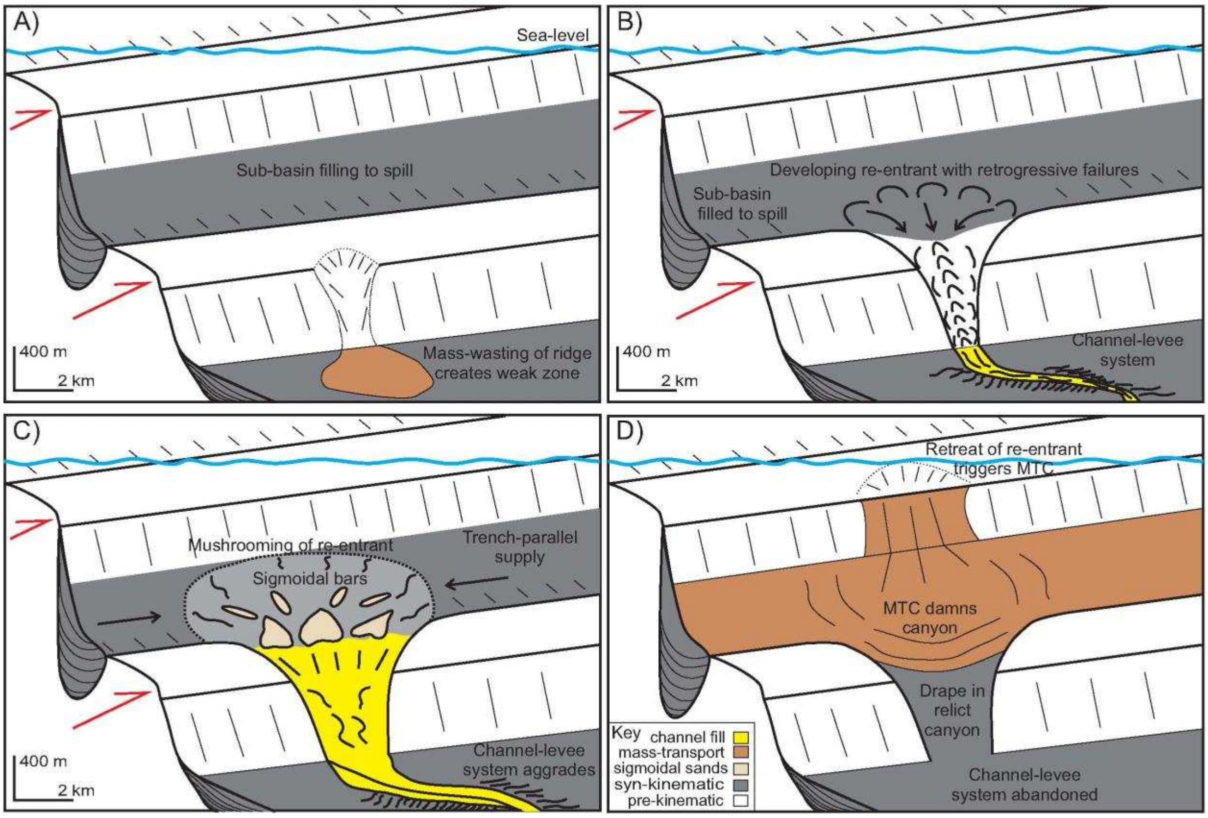

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