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Sealing potential of contourite drifts in deep-water fold and thrust belts: examples from the Hikurangi Margin, New Zealand

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ABSTRACT

Contourite drifts form an important component of many deep-water sedimentary systems. Although their role as reservoirs, particularly along passive margins, is recognised, their sealing potential has been relatively understudied, especially along convergent margins. A range of contourite drifts has recently been recognised along the Hikurangi subduction margin, off the east coast of the North Island of New Zealand. Those occuring in shallower depths comprise giant elongate mounded and plastered drifts; they are mud-rich and blanket the crests and flanks of thrust-cored ridges. These drifts may seal reservoirs that principally comprise the turbiditic component of deformed trench-slope basin fill that was deposited adjacent to the ridges. The locations of modern hydrocarbon seeps appear to confirm the sealing potential of these drifts, which could trap significant hydrocarbon accumulations. The faults that underpin the ridges appear to act as primary charge pathways. Because the drifts are documented to drape the crests and flanks of the structural highs against which the reservoirs pinch out, there is a specific spatial and structural correspondence between seal, reservoir and charge pathways in this location. Such an association could be of broader economic significance if developed in convergent settings elsewhere.

1. INTRODUCTION

Contourite drift systems develop beneath persistent along-slope bottom currents (Heezen et al., 1966; Heezen and Hollister, 1971; Stow and Lovell, 1979; Hernández-Molina et al., 2008a, 2008b; Rebesco, 2005; Rebesco et al., 2014; Stow et al., 1996b, 2002, 2008, 2018; Wynn and Stow, 2002; Miramontes et al., 2019). Their deposits, contourites, are important for paleo-oceanographic and paleo-climatologic studies, for ocean hazard assessment, and in hydrocarbon exploration (Shanmugam et al., 1993; Mulder et al., 2002; Toucanne et al., 2007; Viana et al., 2007; Knutz, 2008; Laberg et al., 2016; Miramontes et al., 2018). Contourites have petroleum significance in that they may host deep-water reservoirs, may form seals, and may comprise source rocks (Viana et al., 2007). Examples of reservoirs include silt- to sand grade drifts (e.g., Gulf of Mexico [Shanmugam et al., 1993]; SE Brazil [Viana et al., 2007]; Mozambique [Palermo et al., 2014, Fonnesu et al., 2020]; and Tanzania [Sansom, 2018]), whereas mud-prone drifts (e.g., Campos Basin [Stow et al., 2002; Viana et al., 2007; Mulder et al., 2008]) are recognised as potential seals and source rocks (Moraes et al., 2007; Viana et al., 2007). Relatively short-lived, unsteady gravity currents, such as turbidity currents and debris flows, may interact with longer-duration relatively steady contour currents, either through alternations in the dominant flow type, with contour currents reworking turbidites deposits, or through the synchronous interaction of contour and gravity currents (Mulder et al., 2008; Fonnesu et al., 2020; Fuhrmann et al., 2020). Contour currents can modify gravity current deposits to different degrees, ranging from reworking turbidite bed tops to complete erosion and redistribution to form stand-alone contourites (Locker and Laine, 1992; Shanmugam et al., 1993; Howe, 1996; Masse et al., 1998; Mulder et al., 2008; Brackenridge et al., 2013; Sansom, 2018; Fonnesu et al., 2020). When contourite and turbidite systems interact, there is potential for (1) zones of enhanced reservoir quality to form as the result of flow-stripping and winnowing of detrital muds (e.g., Gulf of Cadiz [Brackenridge et al., 2013]), or (2) for seal properties to be improved depending on current orientation to the channel and sediment type (e.g., Campos Basin [Viana et al., 2007; Mulder et al., 2008]; Mozambique [Fuhrmann et al., 2020]; and Tanzania [Sansom, 2018]). The seal capacity of predominantly finer-grained drifts may, however, be compromised by the admixture of coarser-grained, relatively poorly sorted sediments, and/or by bioturbation (Faugères and Mulder, 2011).

Whereas the role of contourites as reservoirs is relatively well documented (e.g., Shanmugam et al., 1993; Viana et al., 2007; Rebesco et al., 2014) their role as seals remains relatively understudied (Duarte and Viana, 2007; Faugères and Mulder, 2011). Here, a study of the active Hikurangi subduction margin, New Zealand, is presented which extends the work of Bailey et al., (2020), which recognised the development of contourite drift systems around the margin. The shallow burial depths and relatively fine-grained nature of the documented drifts (Bailey et al., 2020) suggest low source rock or reservoir potential. Accordingly, the principal aim is to examine the seal potential of drifts; a secondary aim is to assess whether there is any spatial association between potentially sealing drifts, underlying non-contouritic sediments that may act as reservoir and charge pathways. The Hikurangi Margin case study may have analogue potential for the identification and characterisation of contourite-controlled petroleum system elements on other tectonically active margins.

2. GEOLOGICAL SETTING

The study area is located along the active Hikurangi subduction margin, offshore of the North Island of New Zealand, where the Pacific Plate subducts beneath the Australian Plate (Fig. 1; Lewis and Pettinga, 1993; Nicol et al., 2007; Davy et al., 2008). The subduction zone is predominantly characterized by the development of ENE-SWS-oriented fold-and-thrust bounded trench-slope basins (Lewis and Pettinga, 1993; Bailleul, et al., 2013) that show significant structural variation along strike (Wood and Davy, 1994; Barnes et al., 1997; 2010; Bland et al., 2015; McArthur et al., 2019); these basins partly dictate sedimentation pathways along the continental shelf and slope (Lewis and Pettinga, 1993; Foster and Carter, 1997; McArthur et al., 2019). Initiation of subduction began at ca. 27 Ma, with ongoing compression thereafter apart from a Mid- to Late Miocene episode of intermittent extension (Chanier et al., 1999; Barnes et al., 2002; Nicol et al., 2007). Rapid basement uplift in the Quaternary resulted in the modern expression of the fold-and-thrust belt (Jiao et al., 2017).

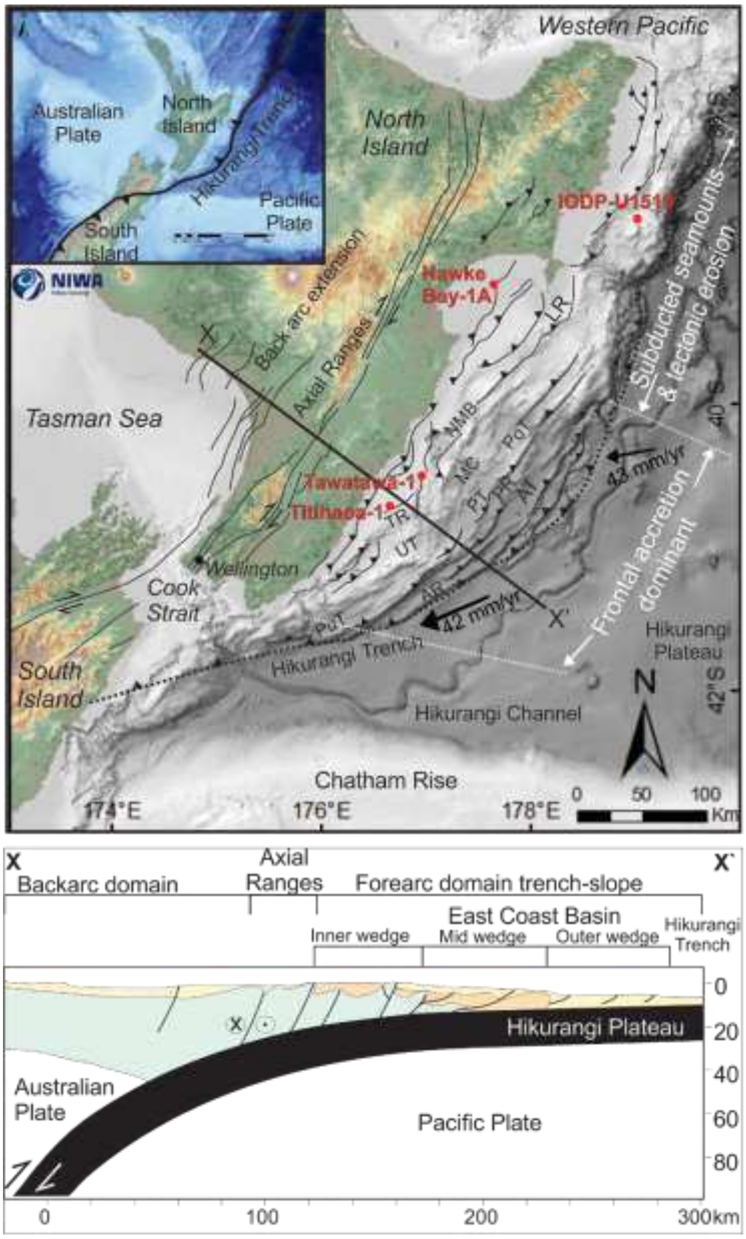


Fig. 1 Regional setting map and cross section (X-X'). Major intrabasinal features and well locations used in study (*red*): Akitio Trough (AT); Aorangi Ridge (AR); Lachlan Ridge (LR); Madden Banks (MB); Paoanui Trough (PoT); Porangahau Ridge (PR); Titihaoa Ridge (TR); Uruti Trough (UT). Modified from work by Barnes et al. (2010), McArthur et al. (2019) and Bailey et al. (2020).

Since the Early Miocene, large volumes of sediment have been dispersed to the marine environment (Carter et al., 1996; Carter and McCave, 2002; Carter et al., 2004). Some has been transported to remote offshore basins via the continental-scale Solander, Bounty and Hikurangi Channels (McCave and Carter, 1997; Carter and McCave, 2002; Carter et al., 2004; Fernandez et al., 2018); much of the rest has been transferred offshore via direct or tortuous canyons and channels (e.g., Lewis and Barnes, 1999; Mountjoy et al., 2009;

McArthur and McCaffrey, 2018), ultimately to be captured in the trench-slope basins or the trench (e.g., Lewis and Pettinga, 1993; Bailleul, et al., 2013, McArthur et al., 2019). However, using 2D seismic and bathymetric datasets Bailey et al., (2020) documented, for the first time, the presence of volumetrically-significant contourite drifts along the Hikurangi Margin (Fig. 2). Drifts were best imaged in intervals immediately below the mudline, occurring in three principal associations:

1. An upper slope drift association of giant elongate mounded (GEM) drifts (ca.150 km long, 50 km wide, up to 1100 m thick, and in water depths ca. 200 – 1,500 metres) and plastered drifts (ca. 300 km long, 8 km wide, < 600 m thick, and in water depths 500 – 1,500 m deep), located upon and lateral to major intrabasinal thrust-cored highs (e.g., the Lachlan Ridge).
2. A spatiotemporally discontinuous association of confined hybrid drifts (up to ca. 500 m long, < 2 km wide, up to 500 m thick, and in water depths ca. 1,600 – 2,500 m deep) that occurs along the mid-to-outer slope domain of the subduction wedge, recording the interaction of along-slope and downslope currents within trench-slope basins.
3. A trench assemblage of hybrid drifts in water depths >2,500 m which records the local interaction of abyssal bottom currents with sediment wave fields up to ca. 100 km long, 30 km wide and 1 km thick that result from turbidity current overspill from the trench axial Hikurangi Channel.

Of particular interest here are the GEM and plastered drifts, which are interpreted to have developed under the influence of the shallow Wairarapa Coastal Current (WCC) and the deeper East Cape Current (ECC) (Carter et al., 2002; Chiswell et al., 2015), that flow to the ENE and WSW, respectively, sub-parallel to the axis of the major slope structures (Fig. 2; Bailey et al., 2020).

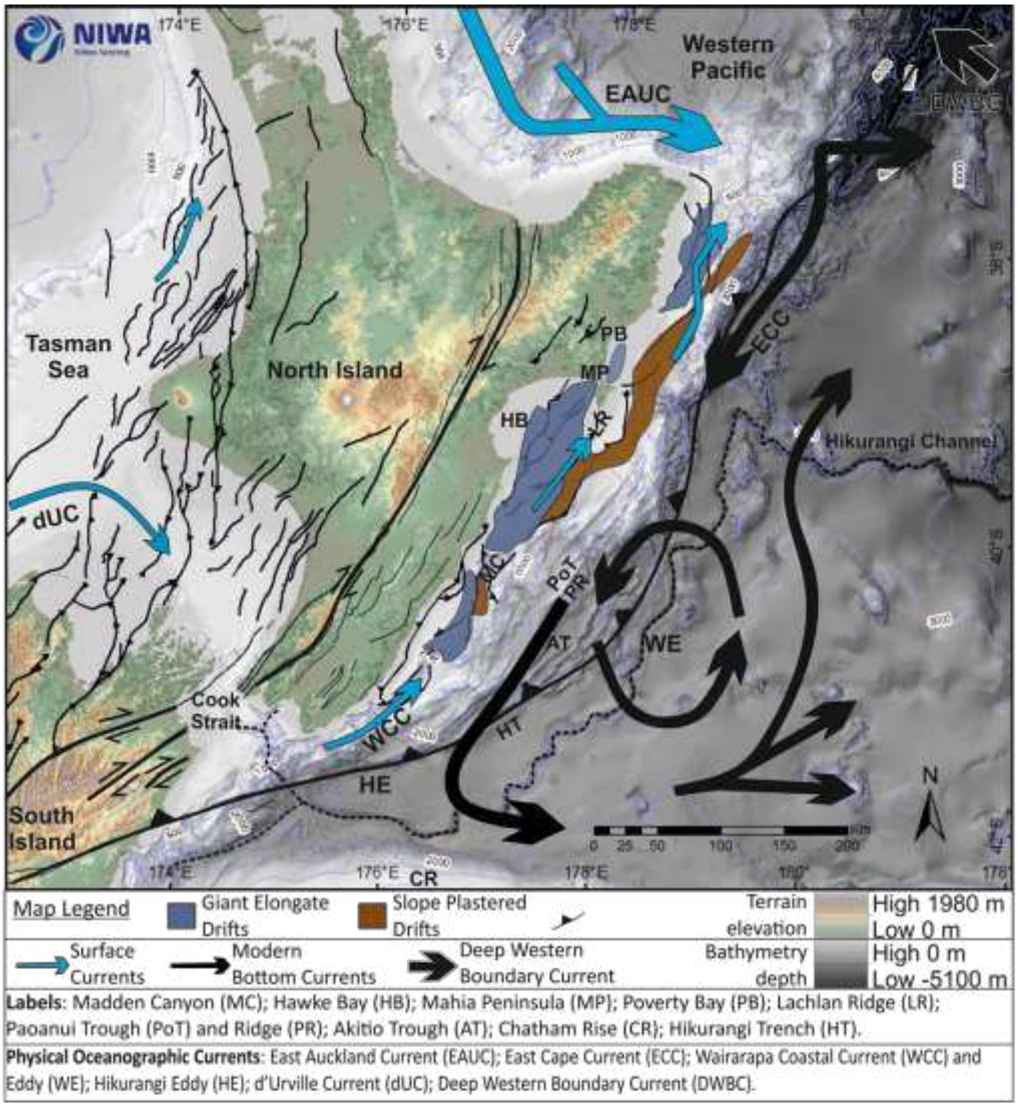


Fig. 2 Distribution map of contourite drifts along the margin overlain by regional oceanographic currents. Modified from work by Carter and McCave (2002); Lewis and Pantin (2002); Carter et al. (2004); Chiswell et al. (2015); Mountjoy et al. (2018); Stevens et al. (2019); Bailey et al. (2020). Bathymetry courtesy of NIWA.

3. DATA AND METHODS

The data for this study includes: (i) high-resolution bathymetry measured on a 100 by 100-metre grid, (ii) >15,000 line-kilometres of two dimensional seismic data, (iii) limited wireline log data from three wells that penetrate the subduction slope, and (iv) a hydrocarbon seep and show database. Bathymetric data of the modern seafloor is accessible from the National Institute of Water and Atmosphere Research, New Zealand (NIWA). The seismic dataset comprises six 2D seismic surveys covering the east coast of New Zealand (Table 1), with open source data provided by New Zealand Petroleum and Minerals (NZPM) and recently acquired data provided by WesternGeco (Fig. 3). Open access well data, including composite logs and final well reports, were provided by NZPM and the IODP from three penetrations (Fig. 3); coverage is limited over the study area, and the associated wireline logs and records of ditch-wall cuttings samples are incomplete, typically starting below the interval of interest. Modern hydrocarbon seep data are accessible from the NZPM database (New Zealand Petroleum and Minerals, 2016) and previous studies (*e.g.,* Barnes et al., 2010; Malie, 2017; Malie et al., 2017; Higgs et al., 2019; Watson et al., 2019).

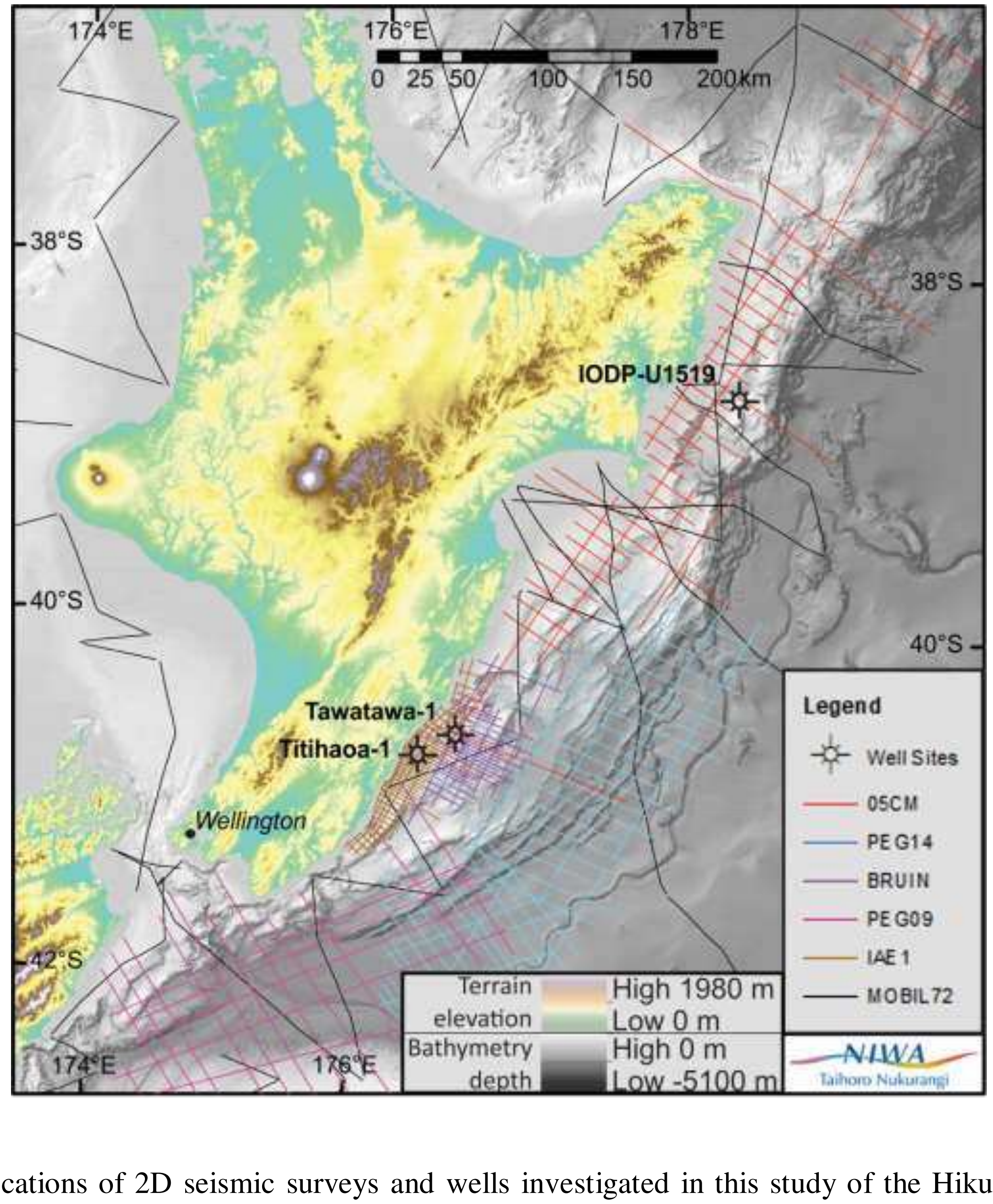


Fig. 3 The locations of 2D seismic surveys and wells investigated in this study of the Hikurangi Margin. Bathymetric data courtesy of NIWA.

Table 1 (A) Seismic survey coverage and data quality of the Hikurangi Margin. Data courtesy of New Zealand Petroleum and Mineral (NZPM) and WesternGeco. (B) Well coverage and sampling intervals.

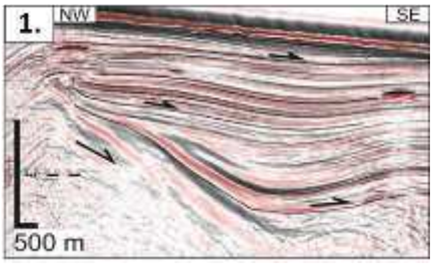
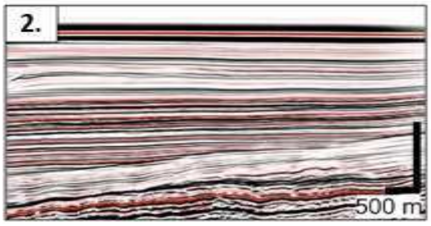
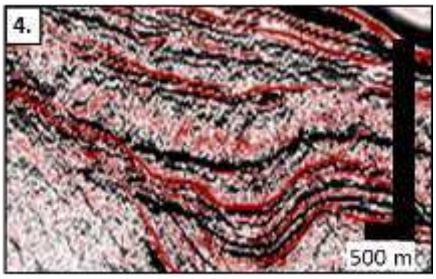
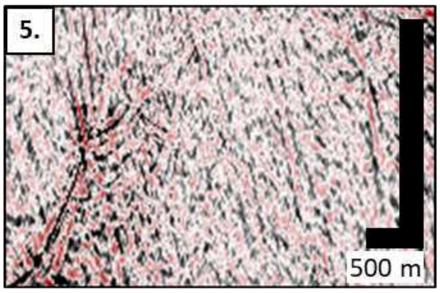
A	Survey Name	Acquisition Year	Depth Interval	Access Provided By	Sample Interval	Vertical Resolution	Frequency	Polarity
	MOBIL72	1972	TWT (ms)	NZPM	4 ms	20 ms	20-30 Hz	SEG Negative
	IAE1	1990	TWT (ms)	NZPM	4 ms	10 ms	40-50 Hz	SEG Negative
	05CM	2005	TWT (ms)	NZPM	4 ms	12 ms	30-40 Hz	SEG Negative
	BRUIN	2005	TWT (ms)	NZPM	4 ms	8 ms	40-60 Hz	SEG Negative
	PEG09	2009	TWT (ms)	NZPM	4 ms	12 ms	30-40 Hz	SEG Negative
	PEG14	2014	TVDSS (m)	WesternGeco	3 ms	15 m	0.04-0.08 m^{-1}	SEG Negative

B	Well Name	Year	Total Depth (TD)	Wireline Coverage	Core Interval Recovered	Operator	Data source
	Titihaoa-1	1995	2741 m	600 m-TD	NA	Amoco NZ	Biros et al., 1995
	Tawatawa-1	2004	1560 m	231m-TD	NA	Tap Oil Ltd.	Tap Oil Ltd. 2004
	Site U1519	2018	640 m	0 m -TD	108–163.6, 250–288.4, and 520–640 mbsf	IODP	Saffer et al. 2018

Bailey et al., (2020) followed McArthur et al., (2019) in recognising five broad classes of non-contouritic seismofacies (muddy shelf clinothems, (hemi-) pelagic muds, mass-transport complexes (MTCs), turbidites, and seismic basement), plus a sixth, contouritic, seismic facies, whose characteristics were used to frame the present analysis (Table 2). The contouritic class was subdivided into six individual drift types by Bailey et al., (2020), whose three principal associations - in shallow, mid-slope and abyssal depth ranges – were mapped along the margin.

In the work reported here each drift association was assessed in regards to its impact upon petroleum system properties. Variance and amplitude property analysis were used to investigate seismic facies and fluid anomalies within and around the documented drifts (*sensu* Sangree and Widmier, 1979, Wang, 2000, Upadhyay, 2013). In order to characterize drift seal potential, the distribution of modern hydrocarbon seeps and shows along the margin was compared to the distribution map of mud-dominated drifts. Faults and fractures were mapped and their sealing potential assessed, together with their potential to act as primary fluid migration pathways for hydrocarbon charge; the role of stratigraphic carrier beds as secondary charge pathways was also investigated. Where possible, data from the three wells that penetrate the subduction wedge were used to characterise the sediment type of the drifts in terms of their reservoir potential (sand-dominated drifts) versus seal potential (mud-dominated drifts). Note that the commercial wells were targeting significantly deeper intervals at and below their total depth, hence data collected in the finer grained drift intervals and their immediate subcrop was not specifically calibrated for prospect analysis.

Table 2. Seismic facies of the Hikurangi Margin. Images courtesy of WesternGeco.

Seismofacies (SF)	**Amplitude and dimensions**	**Interpretation**
	High amplitude, high frequency reflectors that either grade into or downlap more distal reflectors, creating wedge shaped packages, tens to hundreds of metres thick, and tens of kilometres in length.	Clinoforms stepping off shelf, which are interpreted to represent silty to muddy sediments. Progradational to retro-gradational geometries may be related to sea-level or tectonic variations.
	High amplitude, moderate to high frequency, laterally continuous reflectors, tens to hundreds of metres thick, kilometres to tens of kilometres wide, with internally coherent reflectors. Seen fill and to onlap structural highs within trench-slope basins and on the subducting plate.	Interpreted to represent background sedimentation, principally mud dominated, pelagic to hemipelagic sediments (*sensu* Vinnels et al., 2010), but could also include the distal deposits from turbidity currents.
	Mixed amplitude and frequency, chaotic, typically laterally discontinuous packages tens to hundreds of metres thick and kilometres wide. May be internally homogenous or exhibit coherent blocks.	Interpreted as gravity-driven mass-transport complexes (MTCs) (*sensu* Posamentier and Kolla, 2003). Seen to be shed from growth structures and fill trench-slope basins. Their composition is likely variable.
	Variable amplitude and frequency of coherent reflectors that show varying lateral continuity, some are sheet-like and continuous across basins, onlapping their margins; others occur in mounded or lenticular packages hundreds to thousands of meters wide.	These are interpreted as the products of turbidity currents, producing sheets, lobes and channel fills (*sensu* Prather et al., 1998). They may be sand-rich and represent the principle reservoir facies on the margin (McArthur et al., 2019).
	Transparent to high amplitude, chaotic reflectors seen at depth and within the cores of structural highs; often penetrated or bounded by thrust and normal faults and may display fluid anomalies.	Interpreted as seismic basement, which may include true basement and heavily deformed syn-subduction strata, exhibiting both thick and thin skinned faults (*sensu* Lewis and Pettinga, 1993).
6. Contourites	*See Section 4.1 for detailed descriptions, interpretations and facies associations of the characteristic drift types found along the margin.*	

4. UPPER SLOPE DRIFT ASSOCIATION

Following an initial screening of drift associations, the study focused upon the upper slope assemblage of GEM and plastered drifts, principally due to their scale and the quality of data that enabled impacts on sealing potential to be reliably identified, together with assessments of charge pathway and reservoir presence. The principal characteristics of these drift types, identified by Bailey et al., (2020) are summarised below, augmented with additional facies observations.

4.1 Giant Elongate Mounded (GEM) Drifts

Seismic Observations: Documented examples of the GEM drift type occur across the continental shelf, the shelf-slope break, and the upper slope of the margin, spanning water depths of 200 to 1,500 metres (Fig. 2; Bailey et al., 2020). Overall, they generally form smoothly varying sediment packages, approximately 150 km long, 50 km wide, and up to 1100 metres thick (Fig. 4; Bailey et al., 2020). The internal architecture of the drifts is expressed as moderate- to low amplitude, commonly sub-horizontal reflectors, albeit with dips steepening prior to down- or onlap onto older reflectors that represent non-contouritic seismic facies (Bailey et al., 2020). The internal reflectors stack shoreward (to the NW) with strikes parallel to that of the Lachlan Ridge (NE-SW). These drifts may be locally disrupted, firstly by high amplitude erosional disconformities that form internal macro-scale wedges, and secondly by the occasional development of lateral incisions hundreds to thousands of metres wide (Bailey et al. 2020).

Facies: Stepped fining upward signatures through the GEM are revealed by data from wells Titihaoa-1 and Tawatawa-1 (Fig. 6A and B). Predominantly siltstone deposits at the base transition to overlying fine-grained (mudstone–dominated) facies in the upper ca. 1,000 meters of each well; this transition develops from the Latest Miocene through the Plio-Pleistocene (Fig. 6A and B; Crutchley et al., 2016). In the Titihaoa-1 well lithologies remain relatively fine-grained across the transition into the drift; in the Tawatawa-1 well the base of the drift is interpreted to coincide with a change from influxes of coarse-grained sediments, interpreted as gravity current deposits, to the fine-grained system – contourites – implying that these drifts are composed primarily of siltstone and mudstone, albeit possibly reworking coarser substrate intervals immediately after initiation, depending on the nature of the local substrate (see section 5.2 below).

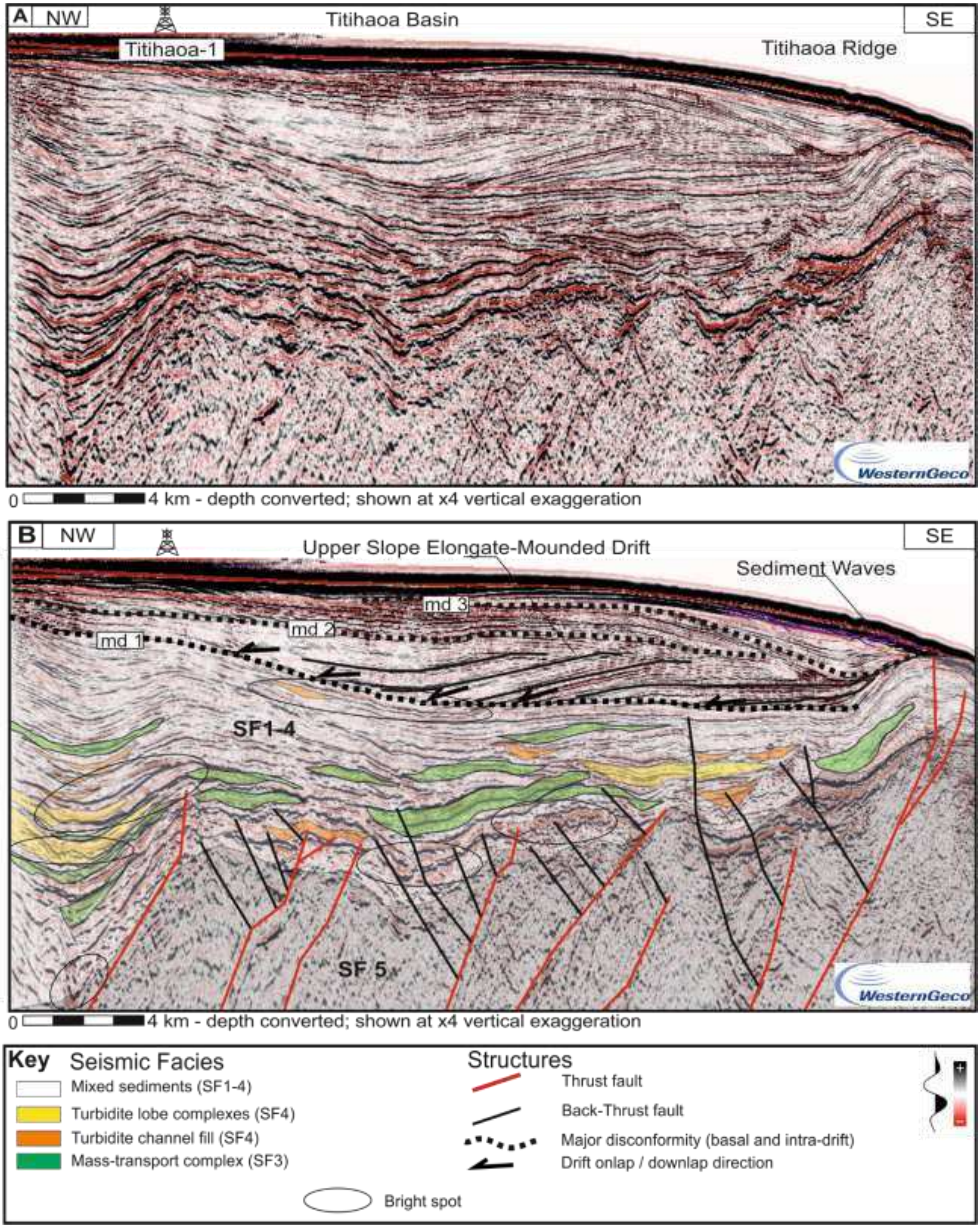


Fig. 4 (A) Non-interpreted and (B) interpretation of the giant elongate mounded (GEM) drift located along the upper slope. Here, the drift is penetrated by well Titihaoa-1, where (C) shows drift facies, bio-stratigraphic age boundaries, and pre-drift reservoir facies separated by a major disconformable (md) surfaces. Drift interpretation modified from Bailey et al. (2020). Note vertical exaggeration 4x.

4.2 Slope Plastered Sheeted Drift

Seismic Observations: This drift type occurs widely across the upper slope domain (i.e., water depths from 500 to 1,500 m) along the central and northern shelf-slope break, effectively blanketing an area some 300 km long, 8 km wide (Fig. 5; Bailey et al., 2020). In seismic data, these drifts present as thin sheets of reflectors (<0.5 sec (TWT), c. <600 m thick), oriented parallel or subtly sub-parallel to the mudline, with laterally continuous, sigmoidal to sub-horizontal reflectors overlying thrust-cored ridges of seismic basement (SF-5). Internally, moderate- to high amplitude, generally seaward-dipping reflectors stack along the gentle slope and smooth the bathymetric topography. Where drifts thin prior to termination, internal seismic facies at the drift boundaries (at both upper and lower slope surfaces) image as high amplitude reflectors, often with apparently erosional lower contacts (Fig. 5; Bailey et al., 2020).

Facies: Data from the IODP well 375, site U1519, indicate the presence of coarser-grained (sandy siltstone to silty sandstone) deposits at the base, transitioning to overlying fine-grained (mudstone – dominated) facies in the upper 300 metres, creating a Pleistocene through to Recent overall fining upward signature (Fig. 6C; Saffer et al., 2018). The IODP well records a change from influxes of coarse-grained sediments, interpreted as gravity current deposits, to the fine-grained system, implying that these drifts are composed primarily of silty mudstone deposited under a gentle flow regime (Saffer et al., 2018; Bailey et al., 2020).

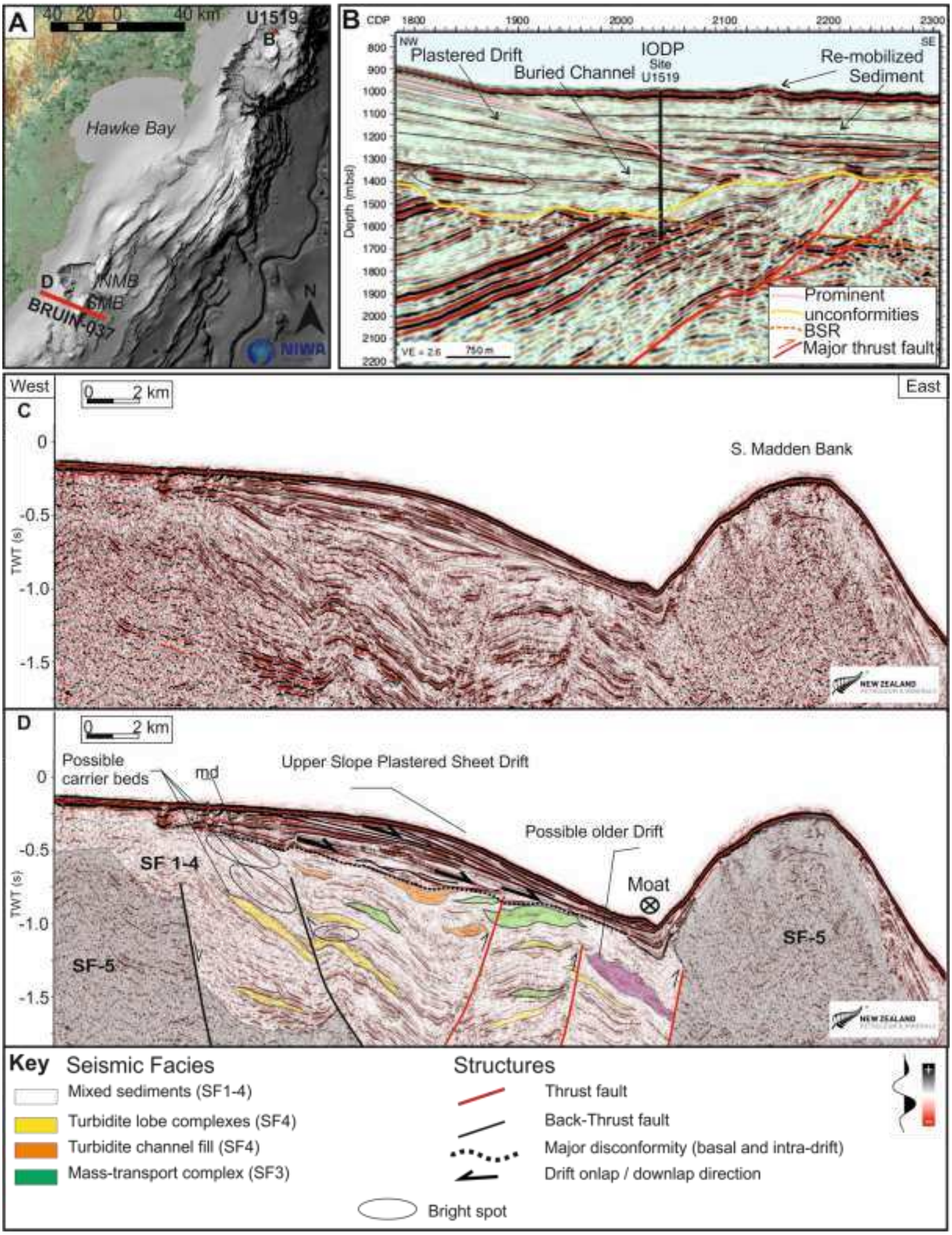


Fig. 5 (A) Location map; (B) interpreted line 05CM-04, with IODP Site 1519 indicated; (C) uninterpreted and (D) interpretation of the plastered drift (see inset map for location of line Bruin-037). Seismic interpretation illustrates a major basal disconformity (md) that records the initiation of the drift and deformed pre- and syn-kinematic stratigraphy (SF 1-4). Approximately 4x vertical exaggeration applied to accentuate depositional gradient of South Madden Bank (modified from Bailey et al. (2020).

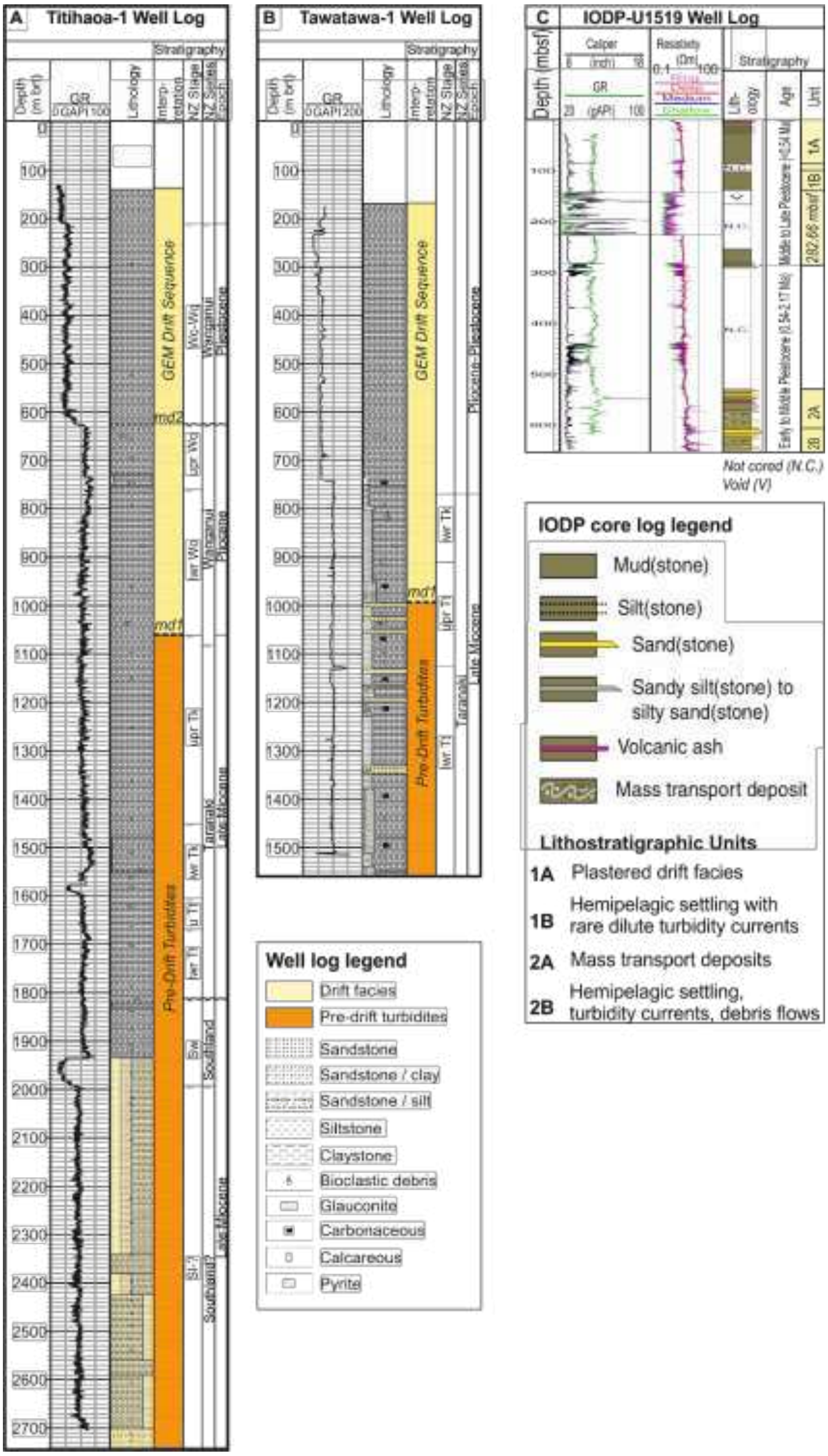


Fig. 6 Composite well logs from the margin that have penetrated drifts. (A) Titihaoa-1 modified from Biros et al. (1995). (B) Tawatawa-1 modified from Tap Oil Limited (2004). (C) IODP, site U1519 well log illustrating drift facies and age (modified from Saffer et al., 2018). Lithologies interpreted from wireline log suites (gamma ray, reseistivity, neutron density, spontaneous potential, neutron porosity and sonic logs), supplemented by cuttings, sidewall cores, and conventional core data in IODP, site U1519. Locations shown in figure 3. md - major disconformable (md) surfaces.

5. SEEP DISTRIBUTION, DRIFT SUBCROP COMPOSITION AND FLUID PATHWAYS

5.1 Seep Distribution

A number of offshore seeps are active on this margin (Barnes et al., 2010; Malie, 2017; Malie et al., 2017; Higgs et al., 2019; Watson et al., 2019). Their presence enables the sealing potential of drifts to be evaluated by assessing the spatial relationships between seeps and drifts. Accordingly, the mapped locations of the GEM and plastered drifts documented along the east coast and outboard of Hawke Bay by Bailey et al., (2020) are compared with those of modern seeps as documented in the NZPM seep and show database. The comparison shows a significant negative correlation (Fig. 7). Active seeps, shows and flares documented along the upper and middle slope do not occur in areas where thick, fine-grained GEM or plastered drifts are present on the seafloor (e.g., Fig. 7 inset A); they are seen either in areas remote from drifts, where they commonly align sub-parallel to the crests of thrust-cored ridges, or they occur along drift margins. Similarly, pock marks near drifts occur almost exclusively on their margins (e.g., Fig. 7 inset C), the one exception being along the trace of the thrust fault that underpins the Lachlan Ridge (Fig. 7 inset B). The implications of these observations are discussed below.

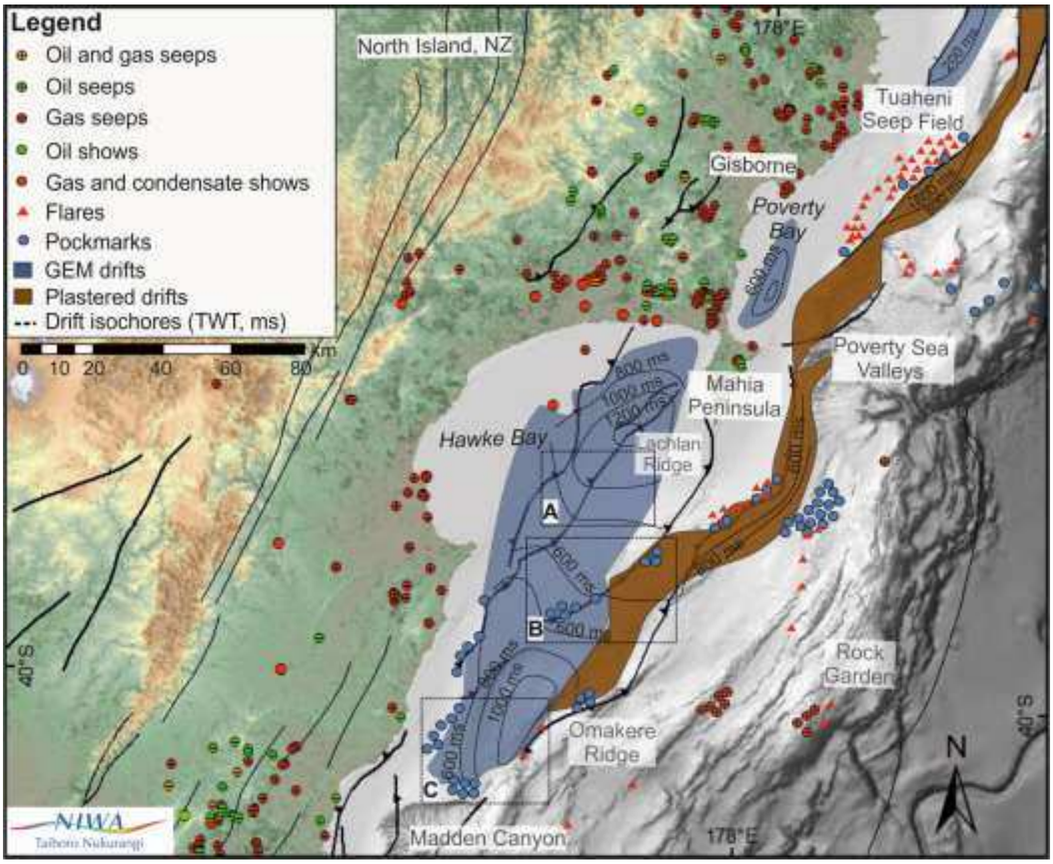


Fig. 7 Hydrocarbon seep map illustrating drift seal potential and possible spill points located at the drift margins. Inset boxes highlighting (A) a drift-buried thrust-cored ridge and corresponding seal; (B) a surface-breaching thrust with associated pock marks; and (C) drift margins populated by pockmarks and flares. Seep map modified from NZPM and updated from recent works by Malie (2017) and Watson et al. (2019). On- and offshore structures sourced from NZPM. Bathymetry courtesy of NIWA.

5.2 Drift Subcrop Composition

The commercial wells were not targeting a drift play, but rather deeper targets within the crests of buried anticlines (Fig. 4). Hence the strata penetrated by the wells below the drifts is dominantly that deposited adjacent to and over structural highs, i.e. unlikely to be reservoir (Fig. 6). However, analysis of seismic data in basin fill adjacent to the drilled structures yields insights to facies underlying the drifts.

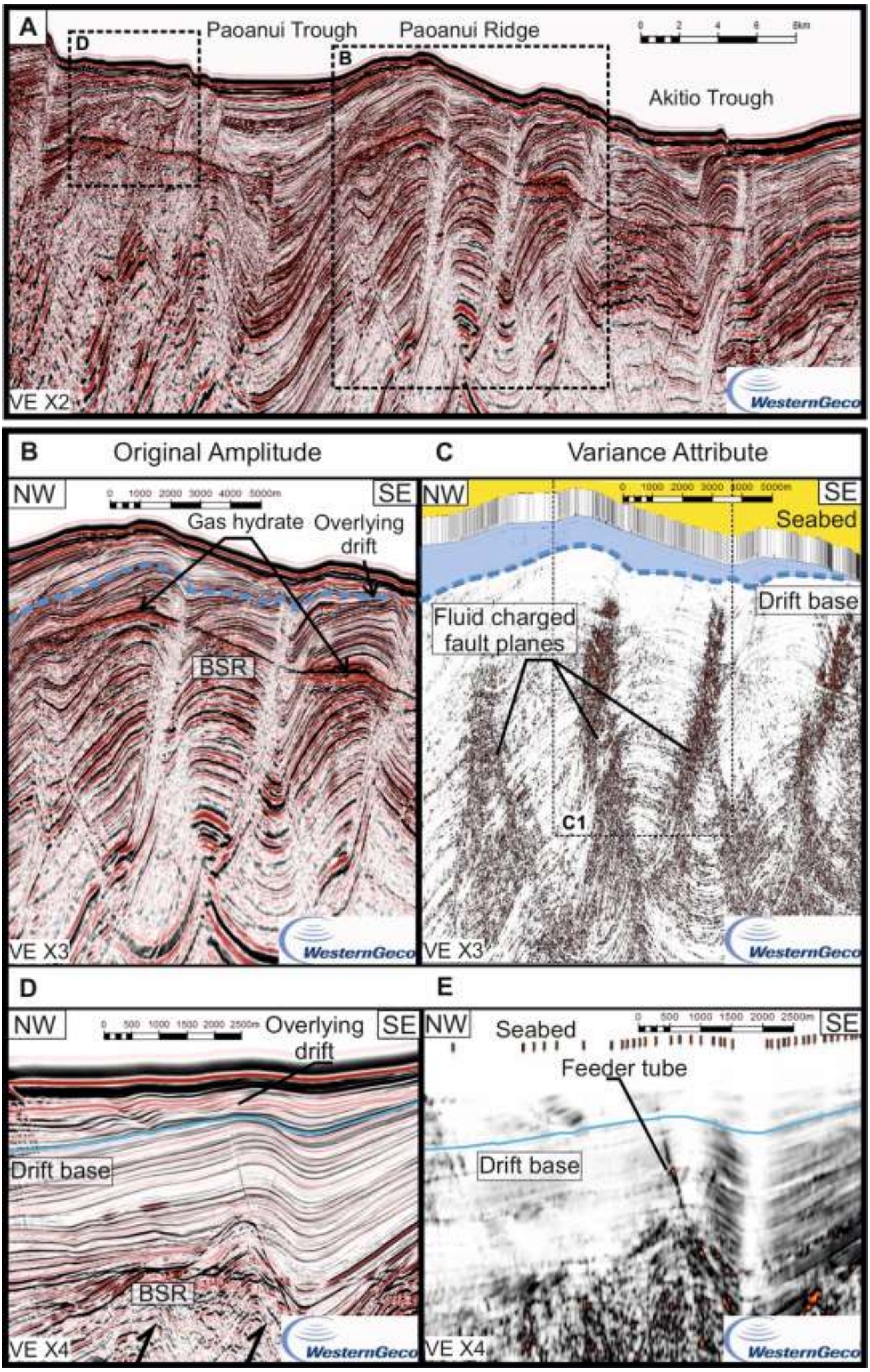
Giant Elongate Mounded (GEM) Drifts: Immediately beneath GEM drifts deformed pre- and syn-subduction strata comprise local "basement" and fault-controlled basin fill composed of MTCs and turbidites, respectively (McArthur et al., 2019; Table 2). The tops of both the thrust faults and associated trench-slope basin fill are erosionally truncated, such that fine-grained drift material is interpreted to onlap and to downlap upon older strata (Fig. 4); the subcropping intervals are heterogeneous, such that different discrete elements (channel fill, MTD, etc) or undifferentiated basin fill may be at or close to the transition into the overlying drift. Fluid anomalies are clearly visible within the older pre- and syn-subduction strata (ca. 2,500 m TVDSS), where bright spots occur along fault planes and up-dip of the sediments comprising the trench-slope basin fill (Fig. 4); see section 5.3, below.

Slope Plastered Sheeted Drifts: Similarly to GEM drifts, the bases of plastered drifts unconformably overlie deformed pre-subduction "basement" and syn-subduction basin fill strata dominated by gravity-flow deposits such as MTCs and turbidites (McArthur et al., 2019). The fine-grained drift material accretes from west to east over the fault-controlled topography, erosionally truncating and smoothing the tops of the basin fill and bounding thrusts (Fig. 5). The resultant unconformity is interpreted to mark the initiation of drift development (Faugères et al., 1999; Bailey et al., 2020). Fluid anomalies within the deeper (>1.0 sec [TWT]) pre- and syn-subduction strata clearly illustrate fault planes that are fluid charged, as are stratigraphic intervals in the otherwise low- to -moderate amplitude, often transparent, seismic facies (SF 1-4).

5.3 Fluid Pathways

Previous studies in the Hawke Bay area have documented the presence of gas chimneys and fault-related fluid conduits within the Middle to Late Miocene and the Pliocene – Holocene sequences (Hollis et al., 2005; Campbell et al., 2008; Barnes et al., 2010; Plaza-Faverola et al., 2014; Malie, 2017; Malie, et al., 2017; Erdie et al., 2018). In this study, analysis of the primary amplitude data confirms the presence of fluid charged fault planes and stratigraphic carrier beds within the upper 3,000 m (TVDSS) of the mid-slope domain of the margin (Fig. 8). These seismic anomalies are interpreted to represent fluid migration pathways. The primary charge occurs along fault surfaces ducting hydrocarbons derived from deeper source rocks; stratigraphic carrier beds within the trench-slope basin fill act as secondary transmission conduits, transmitting fluids from faults at the basin depocentre laterally and upward within the fault-controlled anticline (Fig. 8B and C; Barnes et al., 2010; Plaza-Faverola et al., 2014; Crutchley et al., 2016). An additional secondary charge pathway may entail flow along coarse grained sediments at the base of drifts, when such intervals are developed. The BSR and hydrate accumulations are observed to be accentuated below the anticlines; associated extensional fractures and small-offset faults, interpreted to be related to anticlinal flexure, often penetrate the overlying sediment to breach the seafloor (Fig. 8D and E; Barnes et al., 2010). However, these imaged fluid conduits may also terminate against the base of the mud-dominated drifts because the location of both GEM and plastered drifts is related to the bathymetric highs created by the thrust activity (Fig. 8).

Fig. 8 Attribute analysis of Hikurangi Margin thrust-cored ridges overlain by drifts. (A) Uninterpreted regional line showing locations of insets B and D in relation to the Paoanui Trough and Ridge and the Akitio Trough (see Fig. 1 for location). (B) Original amplitude shows hydrocarbon indicators with bright and dim spots across faults. (C) Fluid charged fault planes and spill points observed using variance attribute analysis. (D) Original amplitude and (E) variance attribute illustrate the termination of fluid charged extensional fracture beneath a drift, which buries the structural high of a thrust-cored ridge. Scales depth converted, shown with approximately 2x, 3x and 4x vertical exaggeration applied to A, B-C and D-E respectively. Note: pock marks are absent above the drifts (Fig. 7).



6. DISCUSSION

Contourite drifts have only recently been recognised on the Hikurangi Margin (Bailey et al., 2020). Based on their size and location, this study has evaluated whether the GEM and plastered drifts might act as reservoirs, seals or as source rocks. Analysis of seismic attributes and well log data confirms that these drifts are predominantly fine-grained, indicating that they lack the potential to form high-quality conventional reservoirs (Crutchley et al., 2016; Saffer et al., 2018; Bailey et al., 2020). Further, shallow burial of the documented drifts and lack of evidence for drift development at the depths required for hydrocarbon generation and maturation suggests that contourite drifts have only low source rock potential on this margin. Therefore, the principal focus of this study has been on the potential of contourites to act as seals; a linked analysis considers the relative spatial distribution of drifts, charge pathways and reservoirs.

6.1 Seal Potential of Contourites

Comprehensive studies of fine-grained drifts along passive margins (e.g., Campos Basin [Moraes et al., 2007]; Tanzania [Sansom, 2018]) concluded that contourite intervals (10s to 100s of m thick, c. 1,000 m wide) had the potential to form important seals and flow baffles, hindering fluid migration where fault planes and stratigraphic carrier beds terminate against them. It was acknowledged, however, that because the studied drifts could be heterogenous, containing coarser, relatively poorly sorted sediments, and be extensively bioturbated, their seal capacity might be compromised (Faugères and Mulder, 2011). Accordingly, the shallow drifts along the upper slope of the Hikurangi Margin were investigated with respect to their seal potential. The seismic facies and well data indicate that on this margin these drift types are mud-dominated, and thus likely sealing. In addition, recent seismic studies show that these shallow Plio-Pleistocene drifts may grow to be 700 – 1,100 metres thick (Fig. 8; see also Bailey et al., 2020), which could further enhance their seal potential.

Both on the Hikurangi Margin and elsewhere documented seeps and associated features are most commonly associated with seabed fault breaches related to primary thrust fault displacement and secondary extensional fracturing and faulting associated with active propagation of the underlying subduction wedge (Barnes et al., 2010; Fischer et al., 2013; Plaza-Faverola et al., 2014); evidently the hemipelagic or other surficial sediments in these locations are not able to seal hydrocarbon flow pathways. However, a significant negative correlation is seen between the locations of active seeps along the upper and middle slope and those of the thick, mud-dominated GEM and plastered drifts, regardless of the presence of faults (Figs. 7 and 8). This negative correlation supports the interpretation that such drifts may act as seals (Fig. 7A). In particular, the occurrence of a subset of seeps adjacent to the lateral margins of drifts suggest a possible relationship to the position of spill points; this interpretation would imply that the trapping volume beneath the drifts is filled (Fig. 7B and C). Although no active seeps are documented, the presence of pock marks along the trace of one fault (Fig. 7 inset B) could indicate intermittent leakage of gas following episodes of faulting (cf. Pettinga, 2003). In addition, it should be noted that a gas hydrate layer is observed to accumulate below the documented drifts (Fig. 8); hydrates may form a local barrier to gas migration, and potentially enhance local seal along the base of the drift (Barnes et al., 2010). Nevertheless, large drifts, such as the GEM have the capacity to form a top seal to accumulations of significant hydrocarbon volumes (Fig. 8).

6.2 Drifts and Charge Pathways

The thrust-cored structures of the upper subduction wedge both underpin the intrabasinal highs and act as the primary charge pathways for subsurface fluids (Barnes et al., 2010; Plaza-Faverola et al., 2014; this study); carrier beds within the basin fill that are truncated by the drifts are here interpreted to act as secondary charge pathways. As the GEM and plastered drifts are documented to drape these structural highs (Bailey et al., 2020), there is a close relationship between charge, reservoir and seal in this setting (Figs. 8 and 9). Depending on the subcrop composition, the basal drift facies may constitute zones of winnowed turbidite deposits, potentially comprising narrow lenses of enhanced reservoir or carrier bed facies parallel to the drift (Fig. 9). Charge pathways below these drifts may be disturbed by the presence of the gas hydrate layer, but this topic requires further work.

6.3 Implications for Prospectivity

This study of the Hikurangi Margin has found evidence of structural and combined structural-stratigraphic trapping above thrust-cored bathymetric highs, sealed by associated contourite drift development preferentially located above likely charge pathways. Notwithstanding the risk of biodegradation (e.g., Wenger et al., 2002), these findings are likely to positively support prospectivity assessments along this and other compressional margins. This configuration may even constitute a new play type, in which combined structural and stratigraphic traps, with reservoirs comprising deformed turbiditic basin fill, possibly augmented by its contour current - winnowed remnants, pinch-out up-dip onto thrust-cored anticlines and are sealed by overlying mud-rich drifts (Fig. 9). The faults that underpin the anticlines may constitute hydrocarbon migration and charge pathways into overlying reservoirs. Recognition of this play may rejuvenate assessments of late-life prospectively in mature basins or indicate prospectivity in unproven frontier areas. However, examples of documented drifts on convergent margins are notably smaller, less continuous, and develop more intermittently than drifts on passive margins (Reed et al., 1987; Chen et al., 2019; Bailey et al., 2020), which may impact on seal continuity and reservoir volumes in convergent settings. Further studies are recommended to investigate whether the spatial co-occurrence of sealing drifts and charge pathways documented on the Hikurangi Margin is seen elsewhere, and at what scale.

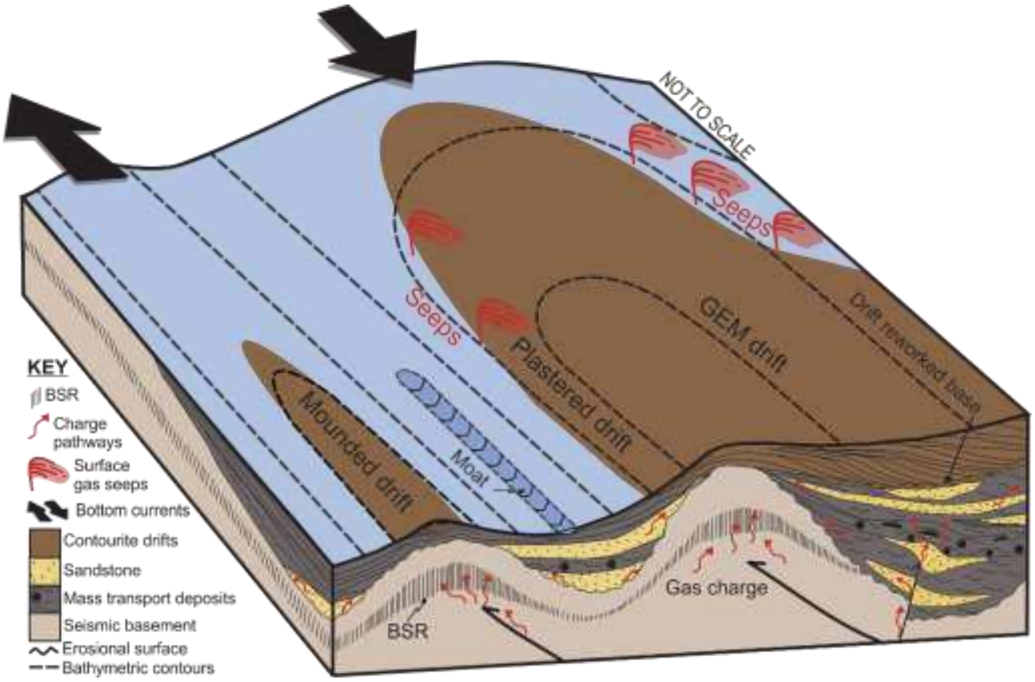


Fig. 9 Schematic model of a typical Hikurangi Margin seep site offset by contourite drift development. Fluid migration pathways including the primary structural conduits and secondary stratigraphic carrier beds charge a volumetrically significant reservoir comprising deformed basin fill that is sealed by mud-rich drifts located on top of and behind the thrust-cored ridges. Seep locations indicate the reservoir spill points. Note: wells, which target ridge crests, are associated with lower probability of intersecting reworked turbidites or in-situ sand-rich turbidites.

7. CONCLUSIONS

This study has focused on the seal potential of giant elongate mounded (GEM) and plastered contourite drifts developed along the Hikurangi subduction margin of New Zealand. These contourites are mud-rich and blanket the crests of thrust-cored ridges and adjacent basins in this setting. The size, composition and distribution of the drifts, their relationship with underlying turbiditic sedimentary systems and with thrust-related bathymetric highs indicates the contourites may form seals to fluid migration. The distribution of modern seeps is offset with that of the GEM and plastered drifts; seeps predominantly occur in the absence of these drifts, or along their margins. This pattern confirms that the drifts may act as seals. In the study area there is a spatial and structural correspondence between drift location and charge pathways; the faults that core the ridges appear to act as primary pathways, with secondary stratigraphic carrier beds charging the turbiditic fill of the basins that flank the ridges. If developed elsewhere, the spatial association of charge pathway, reservoir and seal may prove especially valuable when de-risking hybrid contourite – turbidite reservoir prospects and may rehabilitate prospective plays within drift-buried anticlines that had previously been considered breached.

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