Strain within mass-transport complexes (MTCs): seismic characterisation and structural restoration, offshore Uruguay

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ABSTRACT

Strain style, magnitude, and distribution within mass-transport complexes (MTCs) is important for understanding the process evolution of mass flows on continental margins and estimating their runout distances. Structural restoration and quantification of strain in gravitationally-driven margins have been shown to approximately balance, but this has not been attempted previously for an MTC. Hence, quantifying and characterising internal structural and stratigraphic variability within MTCs will help develop our understanding of strain distribution. We interpret and structurally restore a shallowly buried (c. 1500 mbsf) and well-imaged MTC, offshore Uruguay using a high-resolution (12.5 m vertical and 15x12.5 m horizontal resolution) 3D seismic-reflection survey. This allows us to characterise and quantify vertical and lateral strain distribution within the MTC. Detailed seismic mapping and attribute analysis shows that the MTC is characterised by a complicated array of kinematic indicators, which vary spatially in style and concentration. Seismic-attribute extractions reveal several previously undocumented fabrics preserved in the MTC (e.g. sub-orthogonal shear zones), which suggest multiple phases of flow and transport directions during emplacement. The MTC is characterised by a broadly tripartite strain distribution, with extensional (e.g. normal faults), translational and compressional (e.g. folds and thrusts) domains, along with a radial frontally emergent zone. Inclusion of the frontally emergent zone is important for (1) producing balanced sections in restoration calculations, and (2) estimating compressional strain, which can cause a reduction of up to 8%. Results reveal how strain is preferentially concentrated around major structures (e.g. rafted-blocks), and quantifies the strain expressed on a seismic-scale within the extensional and compressional domains. Overall, we observed a strain deficit between the extensional and compressional domains (c. 3-14%), which is attributed to a combination of variables, including distributed (i.e. sub-seismic) strain, de-watering and sediment volume changes. This work has implications for assessing MTCs strain distribution and provides a practical approach for evaluating structural interpretations.

Keywords: mass-transport deposit, submarine landslide, Punta del Este, Oriential del Plata, kinematic indicators, seismic geomorphology, deep-water depositional systems

1. INTRODUCTION

Mass-transport complexes (MTCs) are gravity-driven shear failure deposits resulting from creep, slide, slump, and debris flow processes (e.g. Dott 1963; Nardin 1979; Nemec 1990; Weimer 1990; Posamentier & Martinsen 2011). Estimation of strain distribution within MTCs is important for understanding the deformation of partially lithified sediment on continental margins. Numerous studies have demonstrated the key role that MTCs play in (1) continental margin construction, (2) petroleum systems development, and (3) geohazard prediction (e.g. Posamentier & Kolla 2003; Weimer & Shipp 2004; Moscardelli et al. 2006; Armitage & Stright 2010; Meckel 2011; Clare et al. 2017). The structures and kinematic indicators present within MTCs have been well documented by many seismic-reflection and outcrop-based works (e.g. Prior et al. 1984; Masson et al. 1993; Frey-Martínez et al. 2006; Gee et al. 2006; Bull et al. 2009; Ortiz-Karpf et al. 2016; Sobiesiak et al. 2017; Alsop et al. 2018). Yet, understanding strain distribution within MTCs has been limited by data type and quality: outcrop studies lack continuous observations from the extensional to compressional domain (Martinsen & Bakken 1990), and seismic data is limited by a lack of internal bedding preservation, imaging quality and data resolution (e.g. Frey-Martínez et al. 2006). A systematic characterisation and quantitative restoration of intra-MTC strain thus requires relatively high-resolution 3D seismic-reflection data that image the full extent of a large MTC.

In contrast, structural restoration and quantification of strain on very large gravitational margins is common (i.e. up to 500 km in dip extent; up to 6 km thick). These systems typically develop on shale or salt detachments (e.g. Hudec & Jackson 2004; Butler & Paton 2010) and demonstrate that up-dip extension, typically accommodated by normal faulting, is broadly balanced downdip by folding and thrusting (Rowan et al. 2004). Similarly, in MTCs it may be suggested that upslope extension is approximately balanced by downslope contraction (e.g. Farrell 1984; Martinsen & Bakken 1990). However, despite MTCs containing a similar overall morphology to larger gravitational margins, previous studies have been unable to quantify strain distribution across an entire MTC, mainly due to data limitations.

Hence, this study aims to interpret and structurally restore a well-imaged, shallowly buried MTC (c. 1500 mbsf) using a high-resolution 3D seismic-reflection survey. The dataset straddles the inshore Punta del Este and deep-water Oriental del Plata basins, offshore Uruguay (Fig. 1). The seismic-interpretation provides a framework for constructing a 2D structural restoration model and quantifying the lateral strain. The specific objectives are as follows: (1) assess intra-MTC strain distribution, (2) quantify extensional and compressional strain through palinspastic restoration, (3) test the hypothesis that MTC strain is best defined by a broadly tripartite strain distribution, (4) characterise vertical and longitudinal strain distributions within the MTC, (5) investigate how strain is partitioned around major structures within and beneath the MTC. Our approach will aid in detailed extraction of MTCs structural complexities and support the assessment of seal integrity of MTCs

2. GEOLOGICAL SETTING

Sedimentary basins offshore Uruguay form part of the Gondwanan break-up cycle and subsequent northward propagation of South Atlantic opening during the Late Jurassic-Early Cretaceous (Rabinowitz & LaBrecque 1979; Nürnberg & Müller 1991) (Fig. 1). Rifting occurred in two main phases: (i) an initial Jurassic phase that failed to produce oceanic crust, and which resulted in the formation of a NW-trending rift that is recorded in the nearshore Punta del Este and Argentine basins; and (ii) a second, Early Cretaceous phase, which is recorded in the distal Punta del Este, Pelotas and Brazilian basins, where it is related to formation of a NE-trending rift (Soto et al. 2011).

Four main sedimentary megasequences are identified offshore Uruguay: (i) a Paleozoic pre-rift sequence, (ii) a Jurassic-Early Cretaceous syn-rift sequence, (iii) a Barremian-Aptian transition sequence, and (iv) a Aptian-Holocene post-rift sequence (Morales et al. 2017). This study focuses on the up to 3 km thick, Neogene to Holocene post-rift sequence. In the Punta del Este basin, Neogene to Holocene deposition occurred in association with overall progradation of large (up to 1.5 km tall) clinoforms. The MTC studied here occurs downdip of these clinoforms, above a regional Miocene unconformity (Conti et al. 2017) (Fig. 2).

3. DATASET & METHODS

3.1. Dataset and seismic interpretation

The 3D pre-stack depth migrated (PSDM) seismic reflection survey used in this study covers an area of *c.*13,000 km^2. The data are SEG reverse polarity standard (European polarity, i.e. an increase in acoustic impedance = trough), have a stacking bin spacing of 15×12.5 m and a vertical resolution (limit of separability) of c.12.5 m at 2.5 km depth. A shallowly buried, and thus seismically well-imaged, MTC was selected for detailed analysis and structural restoration (Fig. 1). We mapped the base and top of the MTC, in addition to numerous internal faults and several internal reflections. Mapping enabled construction of isopach maps, extraction of kinematic indicators and calculation of MTC strain. No wells penetrate through the MTC thus we cannot constrain the lithology or precise age of emplacement.

3.2. Seismic attribute analysis

Several geometric-, amplitude-, and frequency-based attributes were used to assess the external and internal morphology of the MTC. Seismic variance (coherency) was calculated based on the Van Bemmel & Pepper (2000) edge detection method, allowing better imaging and mapping of discontinuities, such as intra-MTC faults. Seismic attributes are often sensitive to noise within the input data (REF). Hence, the raw reflectivity data was conditioned by a single layer-parallel smoothing iteration before variance attribute computation. We also used ant-tracking, a method of enhancing discontinuities in 3D seismic data, to image and map fault/fracture networks (Randen 1998; Randen et al. 2001). We also applied spectral decomposition to the raw reflectivity data; this splits the seismic signal into narrow frequency bins (i.e. low, mid and high) that, when blended together, highlight structural and stratigraphic heterogeneities (see Partyka et al. 1999). Several grid-based attributes, such as dip magnitude and root-mean squared (RMS) amplitude, were also employed to aid interpretations. In addition to grid-based surface attribute extractions, we also undertook iso-proportional slicing within the MTC to capture internal structural fabrics. This method is similar to techniques used for detailed reservoir delineation studies that provide an extra level of detail (see Zeng et al. 1998).

3.3. Decompaction and structural restoration

A kinematic restoration of the MTC was undertaken to assess longitudinal (i.e. sediment transpot-parallel) strain. Restoration was used to test the validity of the seismic interpretation (i.e. does the section balance and preserve rock volume, thickness, length, etc.) and to quantify strain distribution within the MTC (Dahlstrom 1969; Hossack 1979; Lingrey & Vidal-Royo 2015). We assume only plane-strain deformation (i.e. extension and shortening parallel to the bulk sediment transportation direction) and preservation of line-length. However, out-of-plane strain, in addition to volume loss due to vertical transport (re-suspension) of material out-of-section could occur. To help mitigate these effects, we orientated the restored sections parallel to the dominant MTC transport direction through analysis of kinematic indicators such as lateral margins (Fig. 3A). Due to the component of ductile strain within MTCs, simple shear and flexural slip methods have also been tested and compared with the line-length approach to quantify model sensitivities (Lingrey & Vidal-Royo 2015).

Before calculating longitudinal strain, the MTC was decompacted to remove the effects of volume decrease driven by burial-related porosity reduction. Constraining pre-compaction thickness, and thus immediately post-emplacement structural geometries of intra-MTC faults and folds, allows a more accurate calculation of corrected strain magnitudes. Backstripping of the overburden was undertaken on a layer-by-layer basis (three layers in total). As input to the decompaction process we assumed initial surface porosities of 0.63 and 0.49, and rates of porosity decay of 0.51 and 0.27 Km^{-1} for shale and sandstone. This is based on the Sclater & Christie (1980) decompaction curve ($\phi = \phi_0(e^{-cz})$), where ϕ/ϕ_0 relates to present-day and surface porosities, respectively. The MTC-dominated overburden is assumed to have the same lithological characteristics as the studied, more deeply buried MTC (Fig. 4-A). The composition of the MTC (45% clay, 45% silt, 10% sand) was estimated from a shallow core sample (GeoB13860-1) taken from a seafloor MTC on the Uruguayan margin (Krastel et al. 2011). This lithological composition is comparable to MTCs observed at outcrop (e.g. Pickering & Corregidor 2005), although MTCs are, by their nature, compositionally highly variable.

The strain (e) of folded and faulted pre-kinematic strata can be approximated by summing the individual segments of a horizon ($L_0 = H_1 + H_n$) and comparing this to the present length (L_1) (1). The calculated strain is at best a minimum estimate, as only macro-scale structures are identifiable and thus restorable (i.e. sub-seismic faulting and folding cannot be explicitly accounted for using this method; e.g. Marrett & Allmendinger (1992). Thus, an mismatch in balancing of between 2-60% may be ascribed to variables that cannot be identified using seismic data; we discuss later potential ways in which we can mitigate these uncertainties (Marrett & Allmendinger 1992; Burberry 2015). Structural restoration also carries interpretation errors, with our interpretation of structures being subjective and non-unique, and likely biased towards our previous geological experiences and concepts. Variations in interpretation of fault-horizon cut-offs may also produce bed length errors of up to ±10% (Judge & Allmendinger 2011).

$$e = (L_1 - L_0)/L_0 \quad (1)$$

MTCs are typically defined by packages of chaotic reflections (e.g. Posamentier & Kolla 2003). The MTC studied here is no exception, thus it was not possible to interpret internal reflections across the entire deposit. Hence, 2D rather than 3D restoration techniques were used.

4. SEISMIC CHARACTERISATION OF THE MTC

4.1. General characteristics and nature of bounding surfaces

The studied MTC comprises low-amplitude, chaotic seismic reflections, with a high-amplitude, semi-continuous basal reflection that caps a polygonally-faulted mudstone sequence (Fig. 4). The high-amplitude basal reflection is interpreted as a basal shear surface, representing a *kinematic boundary layer* (sensu Butler et al. 2016) or zone, upon which the MTC was translated (Varnes 1978; Martinsen 1994). The basal shear surface connects updip to a headwall scarp and downdip to a frontal ramp, which define the limit of the extensional and compressional domains, respectively. Across the majority of the MTC, the basal shear surface is laterally continuous and concordant with underlying stratigraphy, except for where it cuts up through stratigraphy at the lateral margin. Locally, however, there is considerable relief (up to 460 m) along the basal shear surface in the form of steps and ramps (sensu Bull et al. 2009). Elsewhere, more subtle steps and ramps (upto 75 m relief) cut into the underlying substrate.

The top of the MTC is hummocky (vertical relief 13-65 m) and of highly variable reflectivity (Fig. 4). In areas undisrupted by later deposition, the top surface is expressed as a positive reflection, defining a downward decrease in acoustic impedance. Elsewhere, the reflection is either highly variable or undefinable with no discrete structural features (i.e. faulting or folding). Directly beneath the top surface there is a highly chaotic, weakly reflective zone, with no distinct structures visible (Fig. 4-C). The highly chaotic seismic facies can also be seen to infill topographic relief between fold-thrust structures and shear zones and rapidly thins within the frontally emergent zone. The chaotic seismic facies may represent a mud-rich debris flow (debrite), which formed during or after the MTC. We interpret the geometric irregularity and acoustic variability in the top surface reflects a combination of (1) scouring and incision of the MTC by later mass-flow events, (2) a component of high yield strength of the overlying debrite, and (3) the effect of large coherent blocks (Fig. 4-C & Fig. 6-A) (Hodgson et al. 2017).

The MTC is thickest (upto 550 m) and has the greatest relief on the top surface along the eastern and western margins, where folding and thrusting is concentrated (Fig. 3). The MTC thins significantly to the east-southeast due to incision and erosion by later MTCs, which limits identification of the eastern margin (Fig. 3-B & Fig. 5-A). These margins outlining the eastern and western boundary of the MTC are interpreted as lateral margins, where layer-normal shear would have been orientated approximately parallel to the paleo-slope (Alsop & Holdsworth 2007; Debacker et al. 2009). The lateral margins are most prominent within the compressional domain and are linked to both the headwall scarp and frontal ramp. They are up to 300 m high separating the MTC from surrounding undisrupted deposits and indicate a translation direction towards the south-east (153-118°).

We recognise four internal domains within the studied MTC: (i) an extensional domain defined by a headwall scarp and normal faults, (ii) a chaotic translational domain, (iii) a compressional domain, and (iv) a frontally emergent zone (Fig. 4-A) (cf. Posamentier & Kolla 2003; Moscardelli et al. 2006; Lamarche et al. 2008; Bull et al. 2009; Gamboa & Alves 2016). We describe these domains below.

4.2. Extensional domain

The headwall scarp bounds the updip extent of the extensional domain, being instantly recognisable in variance extraction maps as the boundary between the undeformed slope and the strongly deformed (i.e. seismically chaotic) MTC (Fig. 5-A). The headwall scarp trends NE-SW, approximately parallel to the paleo-slope and rather than having the characteristic arcuate shape (cf. Bull et al. 2009), is fragmented. Numerous NE-SW-striking (i.e. broadly scarp-parallel), gently (20-35°) SE-dipping normal faults occur immediately downdip of the scarp. Further downdip, towards the translational domain, these faults are smaller, and thus below seismic resolution, or are truly absent. An alternative interpretation is that the faults in this region are overprinted and reworked by the chaotic matrix fabric (Fig. 4-B). The extensional domain forms a relatively small section of the MTC, being 6.5-20 km in width.

4.3. Translational domain

The length and character of the translational domain is highly variable along strike (Fig. 3-B and 4-C), being narrowest (<5 km) where the extensional and compressional domains almost merge, and widest (c.18 km) near the central part of the MTC, where large blocks of continuous, often high-amplitude reflections occur. Many of these blocks are deformed by normal faults, which may also deform the underlying basal shear surface (Fig. 6-A). The NNE-SSW strike of the moderately dipping (c. 35-50°) normal faults, suggests a SE-orientated minimum compressive stress (σ_3) approximately parallel to the overall MTC transport direction. Small, arcuate fold-thrust systems occur below several of these blocks within the basal shear surface/zone (Fig. 6-A). At the base, variance and spectral decomposition extractions display the overall arcuate fold-thrust footprint, while the ant-track extractions reveal discontinuities relating to individual faults/fractures. The main mass of the block is clearly discernible as a coherent unit surrounded by a more chaotic matrix in the extractions at -150 m. At -300 m, the coherency of the block changes to fully opaque matrix facies (Fig. 6-A). This suggests the blocks were transported, rather than representing remnant blocks (Jackson 2011; Gamboa & Alves 2015; Hodgson et al. 2017). The occurrence of compressional and extensional structures in the same area may suggest polyphase deformation and a strain sequence recording acceleration (i.e. normal) faulting and translation in the basal shear zone fold-thrust system.

4.4. Compressional and frontally emergent domains

The compressional and frontally emergent domains characterise the downdip termination of the MTC (Frey-Martínez et al. 2006). In this example, the MTC climbs up the frontal ramp and becomes emergent, passing downdip into chaotic seismic reflections interpreted as a debrite. The compressional domain is highly deformed with a well-imaged fold-thrust system and shear zones

The fold-thrust system is the defining feature of the compressional domain (Figs. 4-D, 5-B, 5-D). In map view, the domain is radial, with the fold-thrust system trending 015°-195° in the east to 100°-280° in the west. The thrusts typically dip 30-40° (some up to >60°) towards the NW (i.e. updip). Displacements range from 12.5 (minimum vertical resolution) to 175 m and vary along strike, with relays (fault-linkage) forming between individual thrust segments (Fig. 6-B). The thrusts detach downwards onto the basal shear surface and can affect the entire vertical extent of the MTC, particularly towards the frontal ramp. The thrusts are flanked by and dissect hangingwall anticlines and footwall synclines. These folds are gentle-to-open, non-cylindrical, and verge downdip towards the frontal ramp (Fig. 6-B). Folds are more open above the thrust tips, and tighter where they have been dissected by their related thrust; we infer this geometry records an initial phase of fault-propagation folding and open fold formation that was superseded by thrust propagation and fold dissected.

Two sets of shear zones are recognised, trending longitudinally (c.130°-310°) and sub-orthogonally (c. 050°-230°) to the slope (Fig. 5-B & Fig 5-D). The longitudinal shears are imaged on the top surface as narrow zones (100-150 m) infilled by chaotic seismic facies, interpreted as the overriding debrite. We infer these shear zones record the junction between segments of the MTC where differential transport velocities have produced strike-slip motions (Masson et al. 1993; Gee et al. 2005). The sub-orthogonal shears produced 'V'-shaped depressions within the MTC, with the associated zones dipping upslope to the NW (Fig. 6-B). These depressions are up to 600 m wide and spaced at 2-6 km intervals along the western margin of the MTC (Fig. 5-B). At the base of the sub-orthogonal shears, bedded segments are juxtaposed against one another, whereas the depressions are filled from above by chaotic seismic facies (debrite). These shears probably reflect differing flow velocities within the basinward translating MTC (Bull et al. 2009). More specifically, individual segments appear to have interacted with the lateral margin and frontal ramp at different times during MTC emplacement. This may have caused segments (I) to (III) (see inset map Fig. 5-B) to decelerate intermittently, producing a component of right-lateral (dextral) internal shearing. Therefore, in addition to layer-normal shear, we also interpret a component of oblique compression against the western lateral margin to account for the modified fold-thrust system (Strachan & Alsop 2006; Sharman et al. 2015).

Beyond the frontal ramp and in the distal reaches of the lateral ramps, the seismic character of the MTC changes abruptly, from well-defined, albeit folded and thrusted reflections, into only chaotic reflections. We relate this change to a modification in transport dynamics from a confined to an unconfined system, allowing the MTC and overriding debrite to spread-out over the paleo-seafloor (Frey-Martínez et al. 2006; Armandita et al. 2015). This reduction in confinement was associated with increased disaggregation and deformation of bedding, hence the downdip transition to debrite. As well as unconfined flow over the frontal ramp, spill-over of the flow occurred where fold-thrusts curve towards the margin in an upslope direction (Fig. 6-C).

4.5. Classification and transport direction

Based on its geometry and scale (c. 500-150 m thick, 50 km long, 2400 km^2), the MTC is classified as a *frontally emergent* (Frey-Martínez et al. 2006), *attached* MTC (*sensu* Moscardelli & Wood 2015). Furthermore, the Moore & Sawyer (2016) flow factor measure, which is a proxy for relative mobility, suggests the MTC has a low-medium mobility based on the hummocky top surface, well developed fold-thrust belt, and longitudinal shear zones. This would suggest an approximate transportation and deformational process spanning slump-slide rather than full plastic flow (Posamentier & Martinsen 2011).

We have shown that the MTC displays predictable albeit variable strain distributions, defined by a relatively narrow, updip extensional domain, a transitional domain of variable width, and a relatively wide, downdip compressional domain including frontal and some lateral emergence. We have used the associated kinematic indicators in combination with the regional basin setting to estimate the overall transport direction 118°-162°; i.e. broadly SE. This analysis informs where we select our dip-sections for structural restoration, which we describe in the following section (Fig. 3-A & Fig. 4).

5. STRUCTURAL RESTORATION

Structural restoration was undertaken on two dip-oriented sections positioned orthogonal to the transport direction and dominant fault strikes; as discussed above, our assumption of broadly plane strain should thus be valid (Fig. 4). The sections are positioned near the western margin (Section 1) and centre (Section 2) of the MTC and were chosen due to the high-quality seismic imaging within the compressional domain and the relatively completeness of preservation (i.e. no later erosion by MTCs or submarine channels) (Fig. 3). In principle, strain within the MTC should approximately balance (i.e. extension = contraction) if the system is kinematically self-contained.

5.1. Model set-up and decompaction

The geometric input model to the restoration is based directly on the seismic-scale geometry of the studied MTC, consisting of a 12-20 km wide extensional domain, a wide 20-30 km compressional domain, and a 1-2 km wide translational area lacking seismic-scale structures (Fig. 7). The input model consists of the basal shear surface, top surface, several intra-MTC surfaces, normal faults (updip), and thrusts (downdip). As there are no translational structures in Section 1 that could be measured, a boundary (denoted E/C) was used in the model to mark the estimated mid-point between the compressional and extensional domains. In Section 2 we focus solely on the compressional domain due to the poor-imaging and lack of clear structures within the extensional domain. Hence, for Section 2 we aimed to understand the depth dependency of strain in the compressional domain, rather than evaluating longitudinal balancing. Two definitions of the compressional domain were considered: (1) H_C, which includes the frontally emergent, debrite-dominated zone; and (2) $H_{C\text{-}f}$, which excludes this zone (Fig. 7). This distinction enabled quantification of the effects frontal emergence and distal ramps have on section balancing (e.g. Hudec & Jackson 2004).

The decompacted sections show a similar overall morphology to that presently observed, with minor geometric variations amplifying the extensional domain features to the north-west where overburden is thickest. After decompaction, the MTC increased in cross-sectional area by 27% (14.5 km^2 to 18.2 km^2) and 23% (19.4 km^2 to 24.5 km^2) for Sections 1 and 2, respectively.

5.2 Results

The present length of the extensional domain in Section 1 is 13.9 km, whereas the restored length, depending on the method used, is 12.0-12.3 km, equating to 13-16% of extension (Table 1). For Section

1, a single intra-MTC reflection ($H3_C$) was interpreted through the compressional domain; the present-day length of this reflection is 32.3 km, whereas the restored length is 39.1-39.8 km, equating to 17-19% of horizontal shortening (Table 1). When the frontally emergent zone ($H3_{C-f}$) is excluded, the horizontal shortening increases to 25-26%. Section 1 thus approximately balances, with the mismatch between of 3-14% (i.e. shortening strain<extensional strain) being within the bounds of expected error (± 2-40%) (Burberry 2015). The discrepancy increases when the frontally emergent zone is excluded, which is expected as only the most highly strained-area of the section is restored.

For Section 2, two internal horizons were interpreted: a lower horizon, $H3c_i$, and an upper horizon, $H3c_{ii}$. The present length of $H3_{Ci}$ is 24.0 km, restoring to 31.8-32.8 km and thus yielding a horizontal shortening of 24-27%. When the frontally emergent zone ($H3c_{ii}$) is included in the restoration the horizontal shortening is 14-15%, increasing to 16-18% when this zone is excluded ($H3c_{ii-f}$). Although no observation can be made on the balancing of Section 2, vertical strain partitioning could be inferred between $H3_{Ci}$ and $H3_{Cii-f}$. The lower ($H3_{Ci}$) has been shortened significantly more (24-27%) than the upper ($H3_{Cii-f}$) suggesting something intrinsic to the MTC that resulted in this apparent partitioning of strain.

Overall, the structural restoration of Section 1 provides some validity to the interpretation of the MTC. Nevertheless, the shortening is not fully balanced by extension. This suggests accommodation through other strain components, which cannot be accounted for using conventional structural restoration methods. Drawing comparisons with frontally emergent MTCs, including or excluding the frontally emergent zone in the restorations has significant implications for section balancing. Although no discrete macro-structures are visible in the zone it may be that sub-seismic structures are present and are accommodating extra strain. This can be demonstrated by comparing $H3_{Cii}$ to $H3_{Cii-f}$ (Table. 1), where strain in the frontally emergent zone accommodates c.13% of the total shortening experienced by the compressional domain. Inclusion of the frontally emergent zone in calculations of compression is significant; to produce an approximately balanced seismic-scale MTC (Table. 1) a certain percentage of shortening needs to be accommodated by this zone. Therefore, results that include the emergent zone are more realistic, even though a volume is partitioning away from the main MTC body it is still accommodating strain.

6. DISCUSSION

This section considers the MTC structure and emplacement mechanism, and discusses the advantages, limitations, and implications of the restoration approach for understanding intra-MTC strain.

6.1. Mode of MTC emplacement

The occurrence of radial spreading fold-thrust structures, the distribution of extensional-translational-compressional domains, the presence of stratified blocks and the relatively low degree of disaggregation suggest the MTC formed through slump-slide processes (e.g. Dott 1963; Nardin 1979; Merle 1989; Posamentier & Martinsen 2011).

The relationship between the MTC and its capping debrite may indicate: (1) the debrite is younger and thus genetically unrelated to, and simply fills relief created by the MTC, (2) the debrite and MTC are coeval, and/or (3) debrite deposition initiated *in-situ* failure of underlying sediments and formation of the MTC. The following observations support the latter interpretation: (1) thrust-related hangingwall anticlines in the distal domain are not eroded at the base of the capping debrite, (2) the close correlation between debrite thickness and MTC depressions (e.g. fold-troughs and shear zones), (3) rapid thinning of the debrite beyond the frontally emergent zone, and (4) no continuous erosional features such as grooves or striations are observed at the base of the MTC suggesting a limited run-out distance (Figs 4-6).

Hence, deformation within the MTC was probably initiated by an overriding debris flow, which produces increased loading and localisation of shear stress on a mechanically weak zone (Fig. 8). This is consistent with similar observations from the field (e.g. Van der Merwe et al. 2009; Van Der Merwe et al. 2011) and from other seismic-based examples (e.g. Schnellmann et al. 2005; Watt et al. 2012), which all suggest shear coupling-type models. Initial triggering mechanisms for the debris flow are beyond the scope of this study. However, the basal shear surface of the MTC may have coincided with a low shear strength sediment layer produced by shallow gas. This is consistent with present-day signs of shallow gas, both below and above the MTC, in the form of a bottom-simulating reflector, bright spots and pockmarks (see supplementary material).

6.2. Intra-MTC strain features

We have demonstrated that seismic-scale structures in MTCs can be extracted using modern attribute techniques. This approach has allowed us to document two previously unrecognised types of intra-MTC structures using seismic-reflection data: (1) internal shearing in the form of sub-orthogonal shear zones, and (2) fold-thrust systems within the basal shear zone beneath rafted-blocks.

Longitudinal shear zones have been attributed to variations in MTC transport velocities (Masson et al. 1993; Gee et al. 2005; Bull et al. 2009). The results from the MTC studied here suggests that emplacement was more complex than simple single-celled models suggest (see Farrell 1984). In addition to the more common longitudinal shear zones, there is a second sub-orthogonal set, which supports internal shearing linked to transport velocity variations, but this time oblique to the bulk sediment transport direction. This second set of shear zones seems to be intimately linked to the orientation of the western lateral margin (Fig. 5-B). Typically, lateral margins impose transtensional strain in areas of depletion (i.e. extensional domains) and transpressional strain in areas of volume increase (i.e. compressional domains) (Varnes 1978). Fleming & Johnson (1989) identified similar orientated ‘cracks’ along the lateral margins, when observing subaerial landslides in Utah, USA. However, to our knowledge, no such seismic-scale shear of this type has been documented. One interpretation may be that the sub-orthogonal shear zones record transpression within the compressional domain and could be classified as a form of riedal shear or extensional fracture. This provides evidence for a strike-slip/oblique slip component through the compressional domain of the MTC and shows that tri-partite strain distribution may be an oversimplification.

Another new observation is the development of minor fold-thrust systems beneath rafted blocks (Fig. 6-A). Alves (2015) shows how large, rafted blocks may interact with basal shear surfaces, typically forming seismic-scale grooves (furrows) and scours. Field observations at the base of rafted blocks often show small-scale foliation and soft-sediment shear structures and, at a larger-scale, folding and injectites (Alves 2015; Hodgson et al. 2017). However, structures modifying the basal shear surface can be >100 m in height and extend across the aerial-footprint of a rafted-block recording the transportation pathway. Our observations support the notion of a basal shear zone of distributed strain, rather than distinct surface and correlates approximately with Alves & Lourenço (2010) block to basal shear zone thickness ratio (c. 0.2), approximately 0.22 for the block in Fig. 6-A. Our results suggest that previously observed rafted blocks in other 3D seismic-reflection case studies may also have modified the basal shear surface to create similar discrete structures (e.g. Hodgson et al. 2017). However, limitations to the spatial resolution of seismic-reflection data may, in the past, have prevented clear imaging of these structures. Furthermore, in the field there is a risk that the fold-thrust systems underneath rafted-blocks could be misinterpreted as compressional domains within smaller MTCs. Therefore, we suggest that distributed strain in *attached*-MTCs is substantial enough to create upto 100 m thick zones of intense, predominantly contractional strain.

The identification of these intra-MTC structures demonstrates the way in which strain can be concentrated in discrete areas. This also illustrates why structural restoration results cannot be used in isolation to capture entire MTC strain characteristics. The detailed seismic attribute work presented here, including iso-proportional slicing, demonstrates the extra level of detail and spatial understanding of MTCs that is unparalleled, certainly when compared to isolated outcrops.

6.3. Structural restoration and missing strain components

Updip extensional and downdip compressional strain within the MTC approximately balance when including the frontally emergent zone. Compressional strain accommodates approximately 3 to 6% more strain, which is at least partly attributed to limitations of the restoration method. In addition, other aspects also have the potential to produce underestimated strain magnitudes and need to be considered further: (1) sub-seismic faults and folds, (2) volume loss due to lateral compaction, (3) porosity reduction and dewatering, and (4) strain overprinting

Restoration techniques

Variations in results between restoration methods line-length and flexural slip are insignificant in the compressional domain as both procedures preserve line length (Lingrey & Vidal-Royo 2015; Fossen 2016). Simple shear shows a greater discrepancy with less compression between domains in Section 1, likely reflecting its inability to preserve line length and poor handling of steeper-dips. These results also show that definition of the lateral extent of the MTCs has a large impact on the compressional domain and, hence, whether or not a section can be balanced. Inclusion of the debrite-dominated material basinward of the frontal ramp is a key factor for MTC strain balancing. This suggests that a “foreland” type strain zone is apparent beyond the defined boundary of the MTC. Therefore, characterisation of the terminal emergent wedge of a frontally emergent MTC is critical for successful restoration. Otherwise, results may suggest insufficient compression.

There are several limitations imposed by palinspastic restoration and the line-length, flexural slip and simple shear methods. Line-lengths, and hence cross-sectional areas, are unlikely to be preserved in MTCs due to penetrative strain. For example, in order to understand deformation in the distal contractional domain, in particular the impact of so-called ‘cryptic’ lateral compaction may require the application of area sensitive methods, such as area-depth-strain (ADS) (e.g. Schlische et al. 2014). Additionally, physical and numerical models may allow more rigorous boundary conditions (e.g. porosity distributions) to be defined on the transformation of MTCs from semi-lithified sediments (e.g. Wang et al. 2017).

Sub-seismic strain

Despite the relatively high vertical and lateral resolution of our seismic-reflection dataset (12.5 by 12.5-15 m), not all intra-MTC structures can be imaged, most notably (1) discrete, albeit sub-seismic fractures and folds, and (2) more distributed, cryptic features associated with penetrative strain (e.g. intergranular deformation). Hence, the estimations of extension and compression represent minima values, since the restoration models only capture seismic-scale deformation. Although sub-seismic strain (penetrative strain) cannot be quantified in this MTC, there are numerous studies which have attempted this (Kautz & Sclater 1988; Marrett & Allmendinger 1992; Walsh et al. 1996; Burberry 2015; Dalton et al. 2017)

Penetrative strain typically accommodates between 2-30% of overall shortening in horizontal shortening-related analogue models (Koyi et al. 2004; Burberry 2015). The amount of penetrative strain decreases away from thrust belts (Craddock & van der Pluijm 1989), with the magnitude of layer-parallel shortening increasing with depth (Koyi 1995). In physical models, the increase in shortening with depth (c.19%) is accommodated by (1) a decrease in bed-length, (2) an area-loss through lateral compaction in deeper layers, (3) layer-normal thickening of shallower layers, and (4) increased displacement on thrusts (Koyi 1995; Koyi et al. 2004; Groshong et al. 2012). We make similar observations in the up to 550 m thick MTC studied here, with strain increasing with depth from $H3_{ii\text{-}f}$ (18%) to $H3_{i}$ (27%), at least in Section 2. This suggests similar depth dependant layer-parallel shortening, perhaps related to one or a combination of the processes listed above. Physical models only record grain-grain displacement and, therefore, penetrative strain estimates are only considered a minima of that occurring in natural systems (Burberry 2015). The mechanisms of penetrative strain within the MTC are likely to include the following: (1) grain-grain displacements, (2) dewatering, minor folding and faulting, and (3) other minor structures only observable in the field (e.g. Sobiesiak et al. 2017). Similar studies of high-porosity (40-70%) sediments at similar depths (i.e. 700 mbsf) experience horizontal ductile shortening of c. 12% before the formation of discrete structures (Henry et al. 2003). It is not possible to quantify the degree to which lateral porosity and fluid loss within the MTC without calibration from well data. However, we can assume that some component related to these mechanisms is being overlooked on a seismic-scale study. Therefore, we may expect penetrative strain in the compressional domain of the studied MTC to be larger than that estimated by physical models.

It is well known that seismic-reflection based restoration studies may underestimate true strain; for example, these data may underestimate 15-60% of the true extensional strain occurring in rift basins (Marrett & Allmendinger 1992; Walsh et al. 1996). This error is generally ascribed to seismic-resolution limitations, most notably (1) "small" fault populations, which contribute significant amounts to extension, and (2) ductile strain components of extensional faults, which are commonly overlooked. Similar missing extensional components are expected in this MTC. Assuming normal fault populations follow fractal size distributions, it is possible to estimate the missing extensional strain using the heave and number of observable faults (Marrett & Allmendinger 1992; Knott et al. 1996). Using this relationship, we can estimate extension of sub-seismic extensional faults (h_{sf}) by measuring heaves on the observable faults (h_{lf}), where N = number of faults and C = characterises the relative numbers of sub-seismic to observable faults (Marrett & Allmendinger 1992).

$$h_{sf} = h_{lf}\frac{C}{1-C}(N+1)\left(\frac{N}{N+1}\right)^{1/N} \quad (2)$$

The above equation is very sensitive to the linear relationship between N and displacement, and hence variations in exponent C. When using 3D-seismic reflection data, Gauthier & Lake (1993) found that, in most cases, C = ~1, ranging from 0.8-1.5. For Section 1, we estimate between 17-40% additional extension from sub-seismic faulting, assuming C = 0.9-1.1, h_{lf} = 1.88 km and N = 13. This value is in line with other estimates of missing extensional strain and eloquently demonstrates the limitations of palinspastic restoration.

With the recognition of missing strain components, we are inevitability underestimating shortening and extension. This inference may suggest that the MTC interpretation is less balanced than Table 1 suggests. However, we could extrapolate these missing components (compression 30%+, extension c. 17-40) to assume that if, on a seismic-scale, the MTC broadly balances we may suggest that on a sub-seismic scale the system also balances. Further, detailed fieldwork and modelling (physical and numerical) may be required to validate sub-seismic balancing. However, balancing of extensional and compressional domains seems a reasonable hypothesis to propose.

Overprinting, polyphase deformation and cell flow models

Classic single-cell dislocation models describe the idealised case of a single MTC sheet, referred to as a "cell", propagating downslope, with up-dip extension balanced by down-dip contraction (Lewis 1971; Farrell 1984). The model suggests an initial point of failure along a weak detachment layer where compression develops downslope and extension develops upslope of this point (Farrell 1984). This concept is useful for gaining a first-order understanding of MTCs gross-structure but, as many field studies have shown, is oversimplified (e.g. Martinsen & Bakken 1990).

Our MTC displays many of the features proposed by single-celled models such as (1) downslope thrust patterns, and (2) basinward fold-vergence. However, as Farrell (1984) notes in the original model, a component of "anti-dislocation" (i.e. propagation of strain through the MTC as it ceases translation) may cause overprinting of primary structures. The overprinting would come about due to the termination of shear failure on the basal shear surface occurring at either the head or toe of the MTC. Practically this would mean (1) if the toe ceased first then contractional strain would propagate upslope, or (2) if the head ceased first then extensional strain would propagate downslope, until the full mass of the MTC has come to rest. This leads to the formation of additional structures such as shear fractures, dilatational (mode 1) fractures, and thrusts that overprint the originally formed structures (e.g. Alsop & Marco 2011). Explanations for this added structural heterogeneity have focused on the theory of multi-cell models, where a large, first-order MTC cell is composed of many transient secondary-order flow cells that locally interact and overprint related features (Alsop & Marco 2014). Similarly, identification of polyphase deformation/accumulation of multiple event from seismic-field integrated studies (e.g. Ogata et al. 2014) shows added intricacy when compared to the single-celled model assumption.

We suggest towards the eastern part of the MTC, compressional overprinting fabrics may have been preserved within a predominately extensional domain, as the fold-thrust system is seen much further updip. In addition, the longitudinal and sub-orthogonal shear zones represent velocity variations and potentially cell boundaries within a larger first-order MTC. Therefore, although extensional-translational-compressional sequences are often most appropriate when assessing MTC at a seismic scale, strain-overprinting should be considered together with structural restoration results. One potential way to account for this complexity would be to treat each cell as a separate structural restoration case. Identifying any strain discrepancies between and within cells could then be compared to the overall single-celled model.

7. CONCLUSIONS

(1) A structurally-complex Neogene MTC has been identified on the lower slope within the deep-water passive margin sequence, offshore Uruguay. A shear coupling type emplacement model is proposed, where an overriding debris flow(s) produced increased loading and localisation of shear stress on a mechanically weak zone, which subsequently underwent shear failure.

(2) 3D seismic-reflection data, including several seismic attributes, enabled kinematic indictors to be determined from the following features: rafted-blocks, lateral margins and fold-thrust systems. In addition, two previously undocumented seismic kinematic indicators were identified: (1) sub-

orthogonal shear zones, and (2) the formation of fold-thrust systems within the kinematic boundary zone beneath rafted-blocks. Characterisation of the MTC enabled a paleo-slope and transport direction to be identified and the correct orientation of structural restoration models to be constrained.

(3) This is the first study to undertake structural restoration, including quantification of intra-MTC strain, within a single, completely preserved MTC. The results reveal that, on a seismic-scale, the MTC approximately balances, with 13-16% extension and 17-18% (c 25% without the frontally emergent zone) compression. A depth-dependant layer-parallel shortening is identified within the compressional domain that is consistent with other fold-thrust system models. One major uncertainty of the restoration models is the missing components of sub-seismic/penetrative strain that are likely contributing significantly to shortening and extension.

(4) Using conventional seismic-analysis and classification the MTC could be split into a broadly tri-partite strain distribution with extensional, translational and compressional domains. However, after undertaking detailed seismic extractions and appreciating the limited nature of the translational domain, it is concluded that a bi-partite strain distribution, with an appreciation of strain overprinting processes, may be a more accurate way to describe many MTCs.

(5) The assumption of a structurally balanced MTC is a simple high-level concept. However, proving this based on natural examples is difficult due to a combination of the complex and often polyphase deformation history, and dataset limitations.

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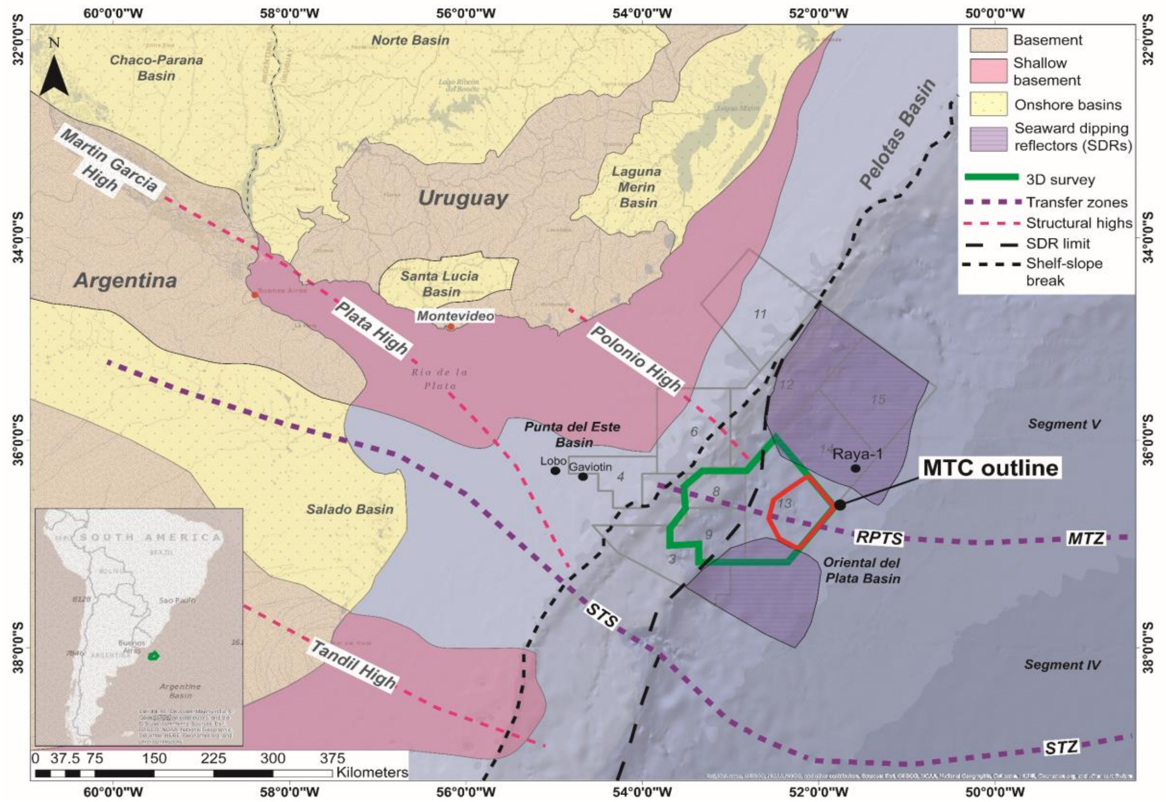

Figure 1: Study area offshore Uruguay, onshore/offshore basins outlines and structural highs from ANCAP and Soto et al. (2011), landward limit of seaward dipping reflectors from Franke et al. (2007), note current licence blocks and Lobo and Gaviotin wells, dataset (green) and study area (red) outlines, Raya-1 location from spectrumgeo.

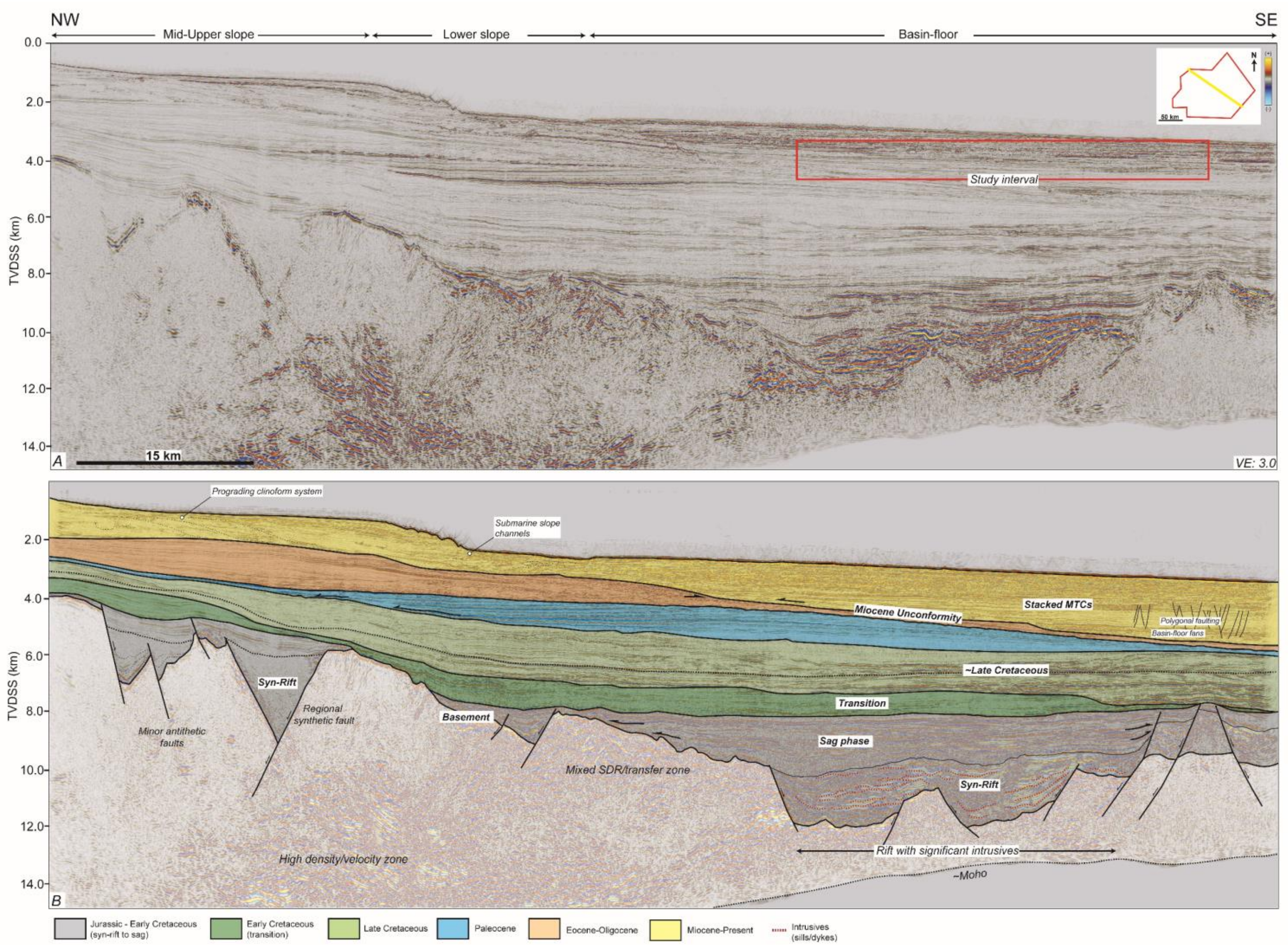

Figure 2: (A) Dip seismic section, (B) geosection, through the central Uruguay margin spanning the continental to transitional crust with significant volcanic components including SDRs, a high density underplating zone and intrusives. Stratigraphic ages are estimated from Morales et al. (2017) and ANCAP. Note the study area, located down-dip from a large prograding clinoform system.

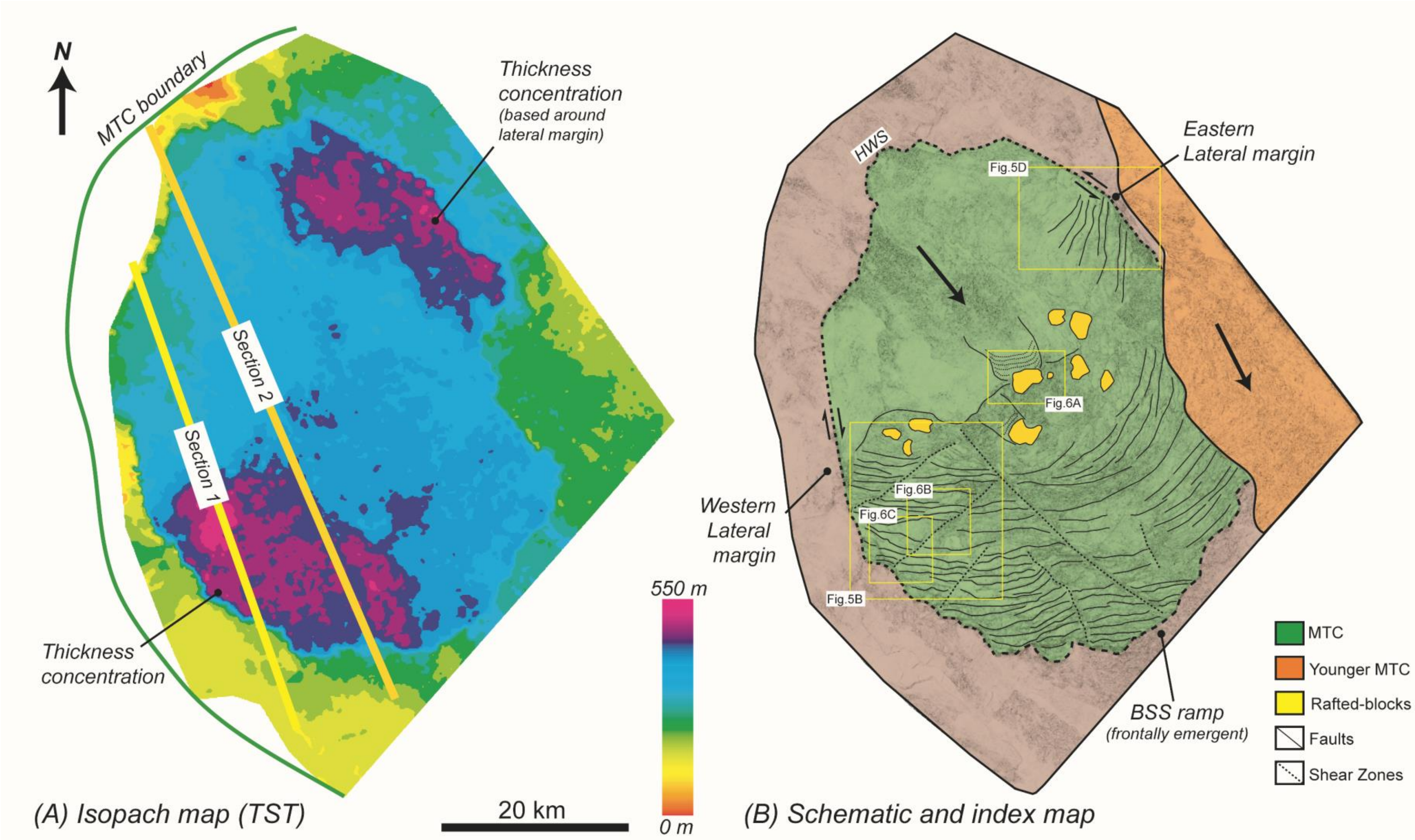

Figure 3: (A) Isopach map displayed in true stratigraphic thickness, between the basal shear surface (BSS) and top surface. Note Sections 1 and 2 which are the dip sections chosen for structural restoration, (B) Schematic and index map of main structural elements within the MTC and reference locations for later figures.

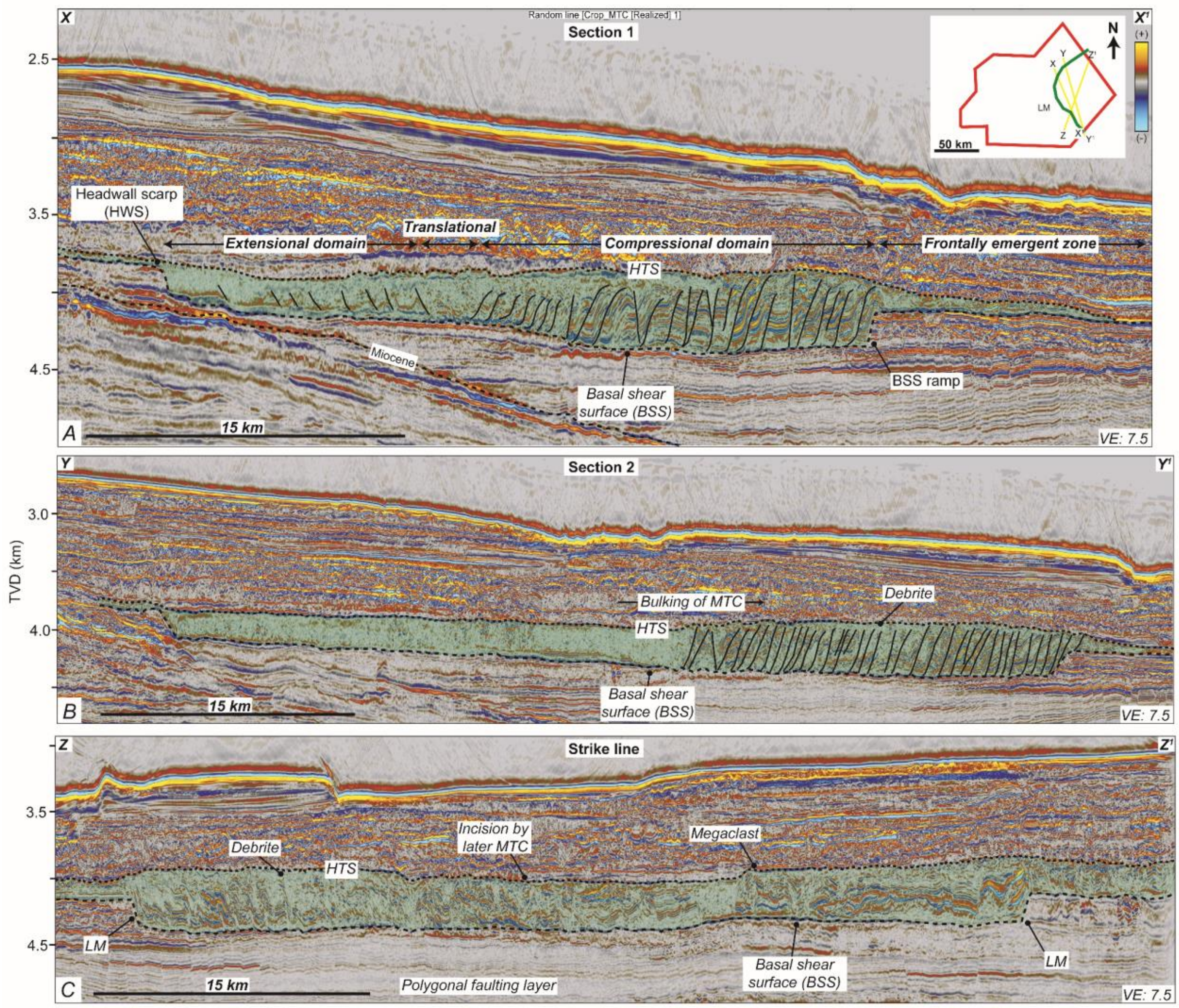

Figure 4. (A) Dip seismic Section 1, used for structural restoration, note the well-defined extensional and compressional domains (B) Dip seismic Section 2 used for structural restoration located more centrally within the MTC, note the overlying chaotic debrite (C) Strike seismic section highlighting distinct lateral margins, megaclasts and incision of the top surface, HTS = hummocked top surface, LM = lateral margins. Amplitudes have been compressed to account for washout from very high amplitude gas charged sediment above the study interval

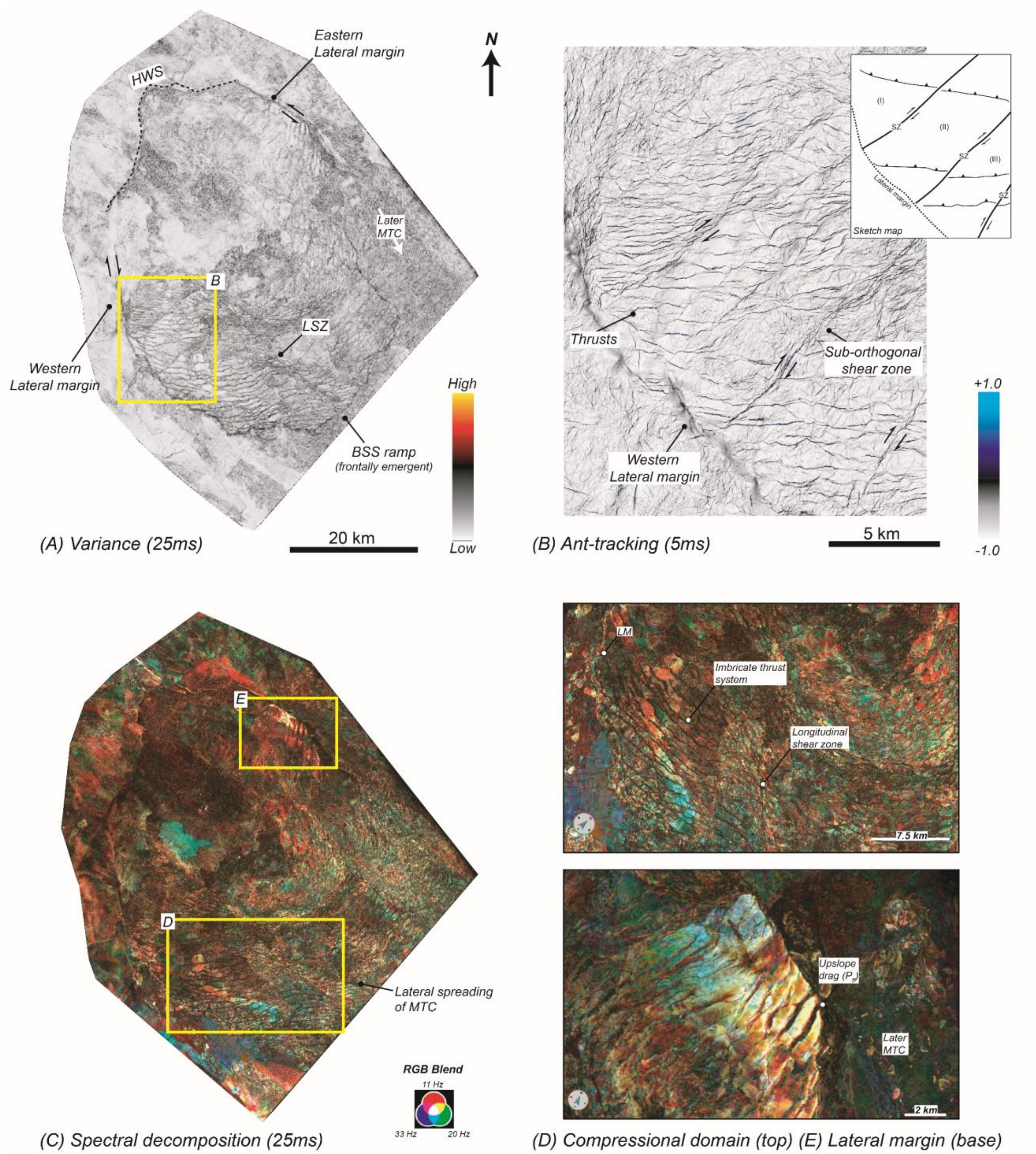

Figure 5: (A) Variance extraction from the basal shear surface over a 25ms window, delineating the lateral margins, frontally emergent ramp and longitudinal shear zone (LSZ), (B) Ant-track extraction from the basal shear surface over a 5ms, imaging the interaction between the western lateral margin and sub-orthogonal shear zones, (C) Spectral decomposition extraction from the basal shear surface over a 25ms window, note locations of D and E, (D) Compressional domain imaging imbricate thrust systems, (E) Eastern lateral margin imaging upslope drag and erosion by a younger MTC.

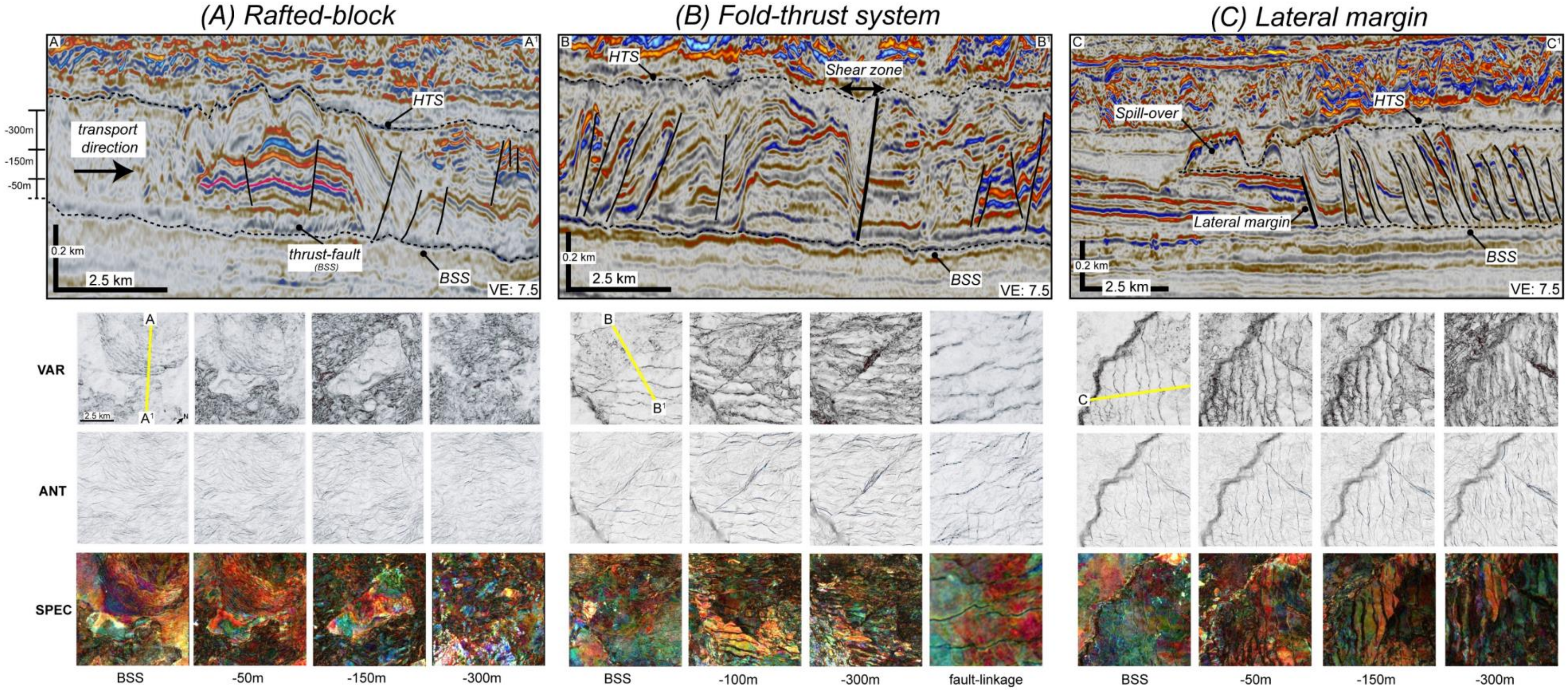

Figure 6: Iso-proportional variance (VAR), ant-track (ANT) and spectral decomposition (SPEC) extractions between the BSS and top surface (HTS), (A) Seismic dip line displaying rafted-block, BSS thrust faults and intra-block normal faults, BSS to -300 above demonstrating the through going nature of the fault systems, (B) Seismic line through MTC thrust-fault system and orthogonal shear zone seen to detach onto the BSS, fault linkage (relay ramps) imaged between thrust faults, (C) Seismic line highlighting the abrupt western lateral margin, note the irregular nature of the thrust as they interact with the lateral margin

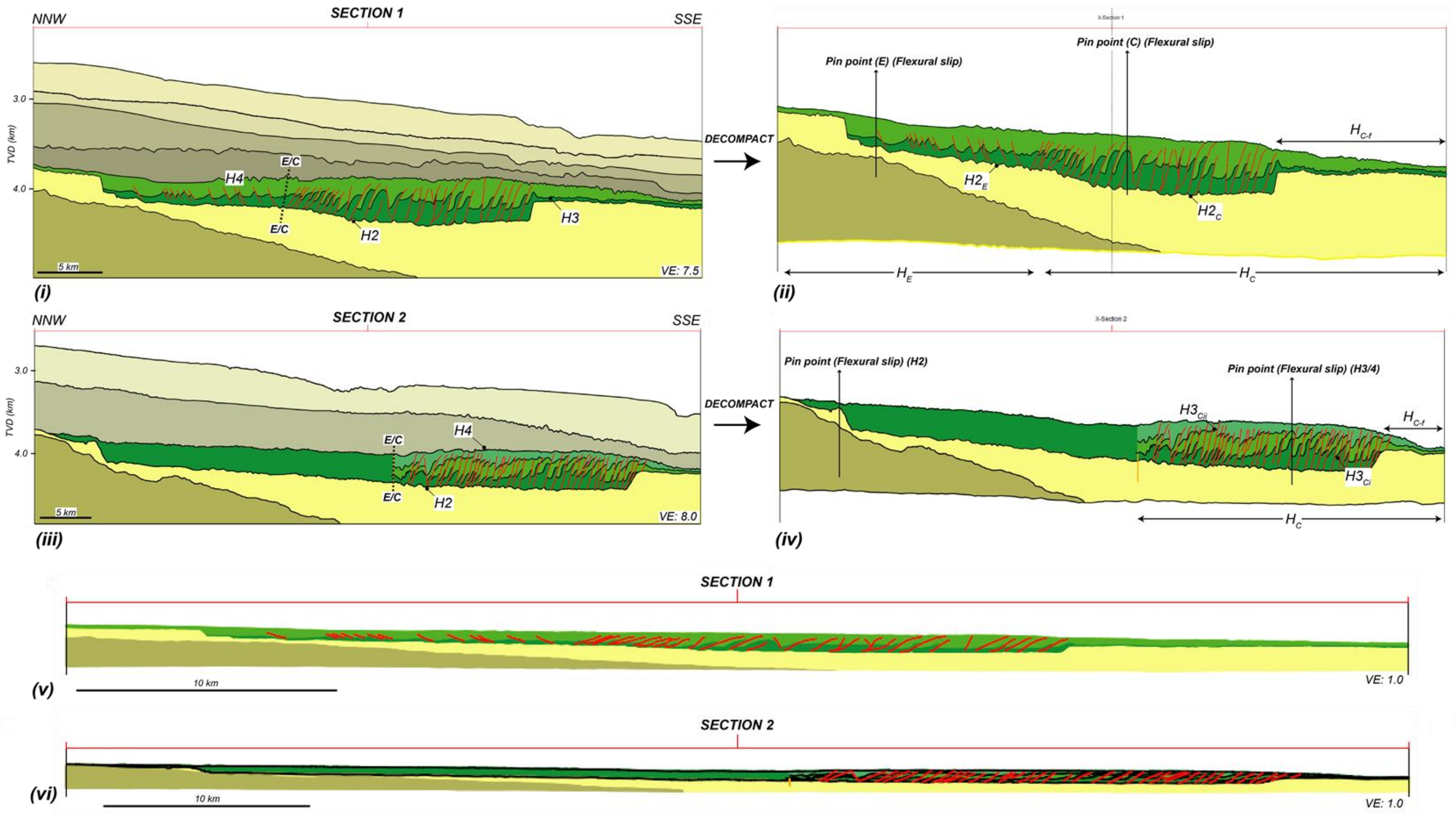

Figure 7: Decompacted structural restoration models, (i) section 1 present day section, (ii) section 1 decompacted section, (iii) section 2 present day section, (iv) section 2 decompacted section. Section 1 sits near the western lateral margin of the MTC, section 2 crosses centrally through the main MTC body, note pin points used for flexural slip calculations, (v/vi) Vertically exaggeration 1.0.

Table 1: Results of structural restoration, (+) extension, (-) compression

Restoration Method	***Horizon***	***Present-length (m)***	***Restored-length (m)***	***Missing length (m)***	***Strain (e)***
Section 1					
Line-length	H2	51600	52024	424	*-0.8*
	H3	46206	51827	5621	*-10.8*
	H4	51600	51708	108	*-0.2*
	$H3_{E}$	13900	12002	-1898	*15.8*
	$H3_{C}$	32345	39824	7480	*-18.8*
	$H3_{C-f}$	20585	27983	7398	*-26.4*
Simple/vertical shear (90 deg)	H2	51600	51602	2	*0.0*
	H3	46206	51058	4852	*-9.5*
	H4	51600	51598	-2	*0.0*
	$H3_{E}$	13900	12218	-1682	*13.8*
	$H3_{C}$	32345	39152	6808	*-17.4*
	$H3_{C-f}$	20585	27359	6774	*-24.8*
Flexural slip	H2	51600	52024	424	*-0.8*
	H3	46206	51826	5620	*-10.8*
	H4	51600	51708	108	*-0.2*
	$H3_{E}$	13900	12316	-1584	*12.9*
	$H3_{C}$	32345	39825	7481	*-18.8*
	$H3_{C-f}$	20585	27982	7397	*-26.4*
Section 2					
Line-length	H2	65000	65675	675	*-1.0*
	H4	63800	64404	604	*-0.9*
	$H3_{Ci}$	24058	32894	8836	-26.9
	$H3_{Cii}$	30028	35404	5376	-15.2
	$H3_{Cii-f}$	23963	29056	5093	-17.5
Simple shear (unfold 90 deg)	H2	65000	65028	28	0.0
	H4	63800	63836	36	-0.1
	$H3_{Ci}$	24058	31812	7754	-24.4
	$H3_{Cii}$	30028	34922	4894	-14.0
	$H3_{Cii-f}$	23963	28593	4630	-16.2
Flexural slip	H2	65000	65681	681	-1.0
	H4	63800	64460	660	-1.0
	$H3_{Ci}$	24058	32895	8837	-26.9
	$H3_{Cii}$	30028	35404	5376	-15.2
	$H3_{Cii-f}$	23963	29057	5094	-17.5

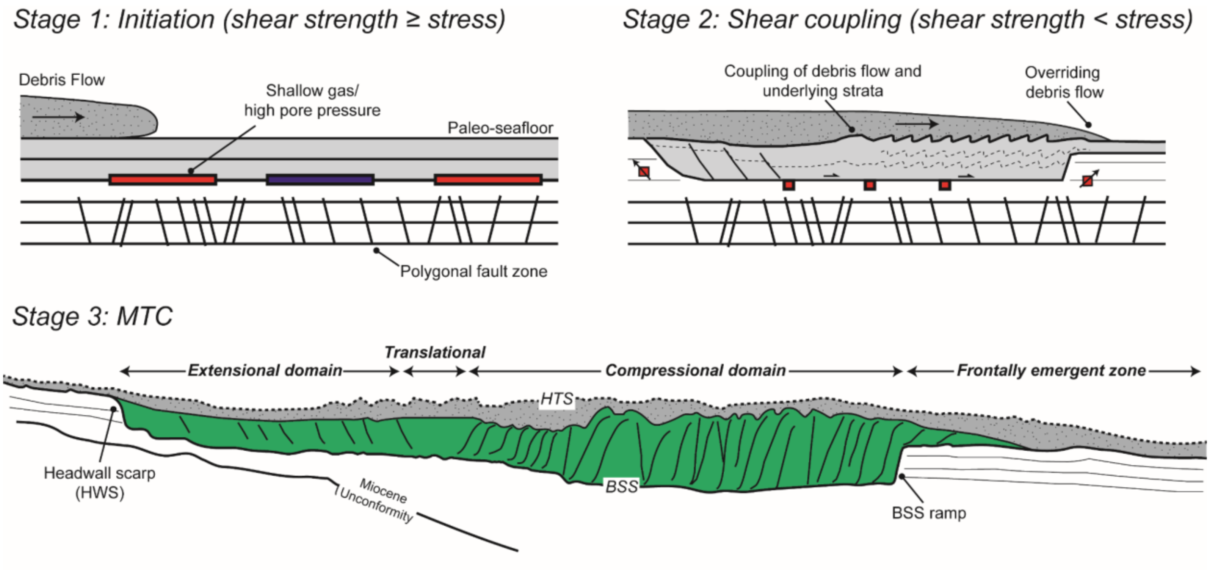

Figure 8: MTC emplacement model, stage 1 initiation through overriding debris flow producing localisation of shear stress on a mechanically weak likely shallow gas filled zone, stage 2 in situ failure of underlying sediments through shear coupling, stage 3 failure of underlying sediments has produced significant extensional and compressional domains.