Integrating Multibeam Data in the Structural 2-D Seismic Interpretation Workflow: Examples from the Mexican Gulf of Mexico*

R. Dirkx[1], K. Goldsmith[1], J. Halliday[1], and C. O'Reilly[1]

Search and Discovery Article #42182 (2018)**
Posted February 5, 2018

*Adapted from oral presentation given at AAPG International Conference and Exhibition, London, England, October 15-18, 2017

[1]TGS, Surbiton, United Kingdom (Kevin.Goldsmith@tgs.com)

Abstract

Broadband long-offset 2D seismic data, acquired and processed through 2015-2016, covering the entire Mexican Gulf of Mexico (MGOM) provide a high quality image of complexly deformed sediments, but interpreters can still experience difficulties understanding the geometry and extent of some of these structures. Multibeam data is conventionally used to identify risk at the seabed prior to installing subsea infrastructure. Here we demonstrate that the integration of multibeam data into the interpretation workflow adds significant value to the interpretation results. Whereby the high-resolution multibeam data is used to generate detailed maps of geological structures with a geomorphic expression at the seabed. The Gigante multibeam survey (approx. 500,000 km^2) covers the MGOM and extends into parts of the US GOM. The data, acquired and processed in 2015-2016, provide a high quality image of the geomorphic expressions at seabed of the various geological domains that characterize the MGOM. The geometry of the seabed in the Mexican Ridges (MR) and Salina del Istmo (SdI) areas is indicative of deformation mechanisms that were recently or are still in operation. A series of elongated linear topographic highs in the MR province formed as a result of gravitationally driven fault propagation folds. In the SdI area, the seabed is locally deformed by salt canopies and diapirs which form shorter curvilinear bumps. Digital Elevation Model (DEM) attributes, including slope, aspect, plan and profile curvatures, derived from the multibeam bathymetry data can be used to construct a workflow to automatically extract the shape and extent of these geomorphic expressions. The resultant maps give an accurate representation of the boundaries of, and trends within, present day geological domains and give information about fault, fold and salt body shape. Three key examples will be presented as case studies to demonstrate how the integration of multibeam data with 2D seismic data can be used to reliably correlate complex structures across 2D seismic lines. This improves structural interpretation confidence, as well as providing a high resolution present day analogue for guiding development of paleo-structure maps.

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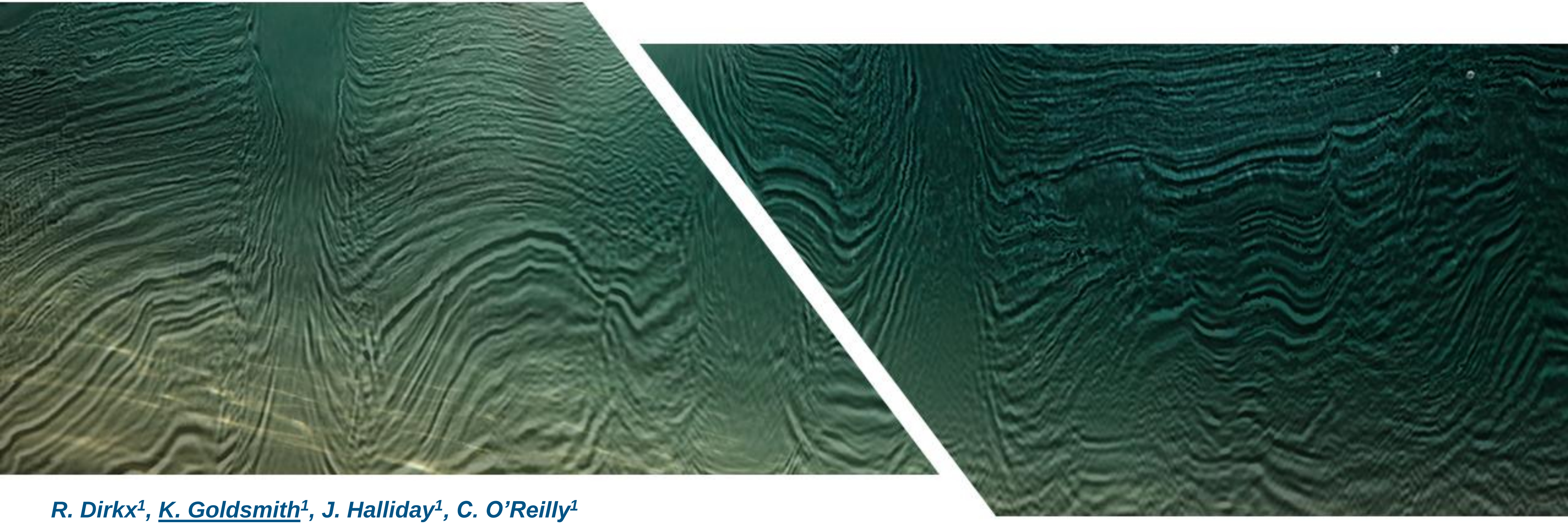


R. Dirkx[1], K. Goldsmith[1], J. Halliday[1], C. O'Reilly[1]

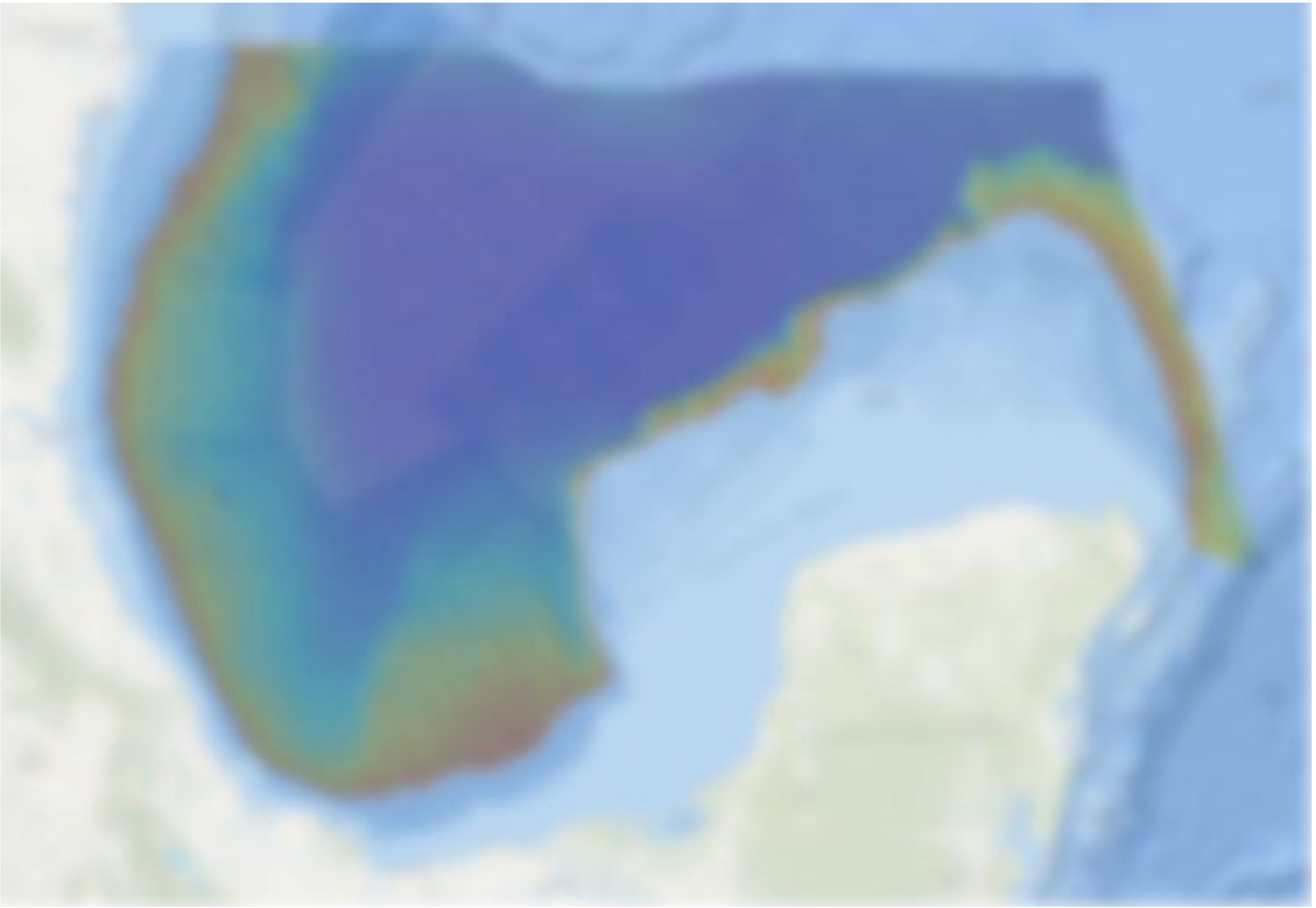
[1]TGS, 1 The Crescent, Surbiton, Surrey, KT6 4BN, United Kingdom

18 October 2017

Introduction

- Recently acquired broadband long-offset 2D seismic data in the Mexican Gulf of Mexico provide a high-quality image of complex sub-surface geological structures
- TGS are attempting to establish a unified, regional stratigraphic framework for the entire Mexican Gulf of Mexico (MGoM) through the interpretation of 192,000 km 2D Gigante PSDM seismic data
- Gigante seismic survey ties into TGS surveys in the US GOM and is ideally suited to creating a catalogue of structural styles, depositional characteristics, and trap and play types throughout the MGOM (GCAGS, PETEX 2016)
- Multibeam data is conventionally used to identify risk at the seabed prior to installing subsea infrastructure – TGS have experience in developing proprietary workflows
- This paper demonstrates that the integration of multibeam data into the interpretation workflow adds value to the interpretation results and presents novel methods in an attempt to provide new insights

Gigante: A Comprehensive Geoscience Database

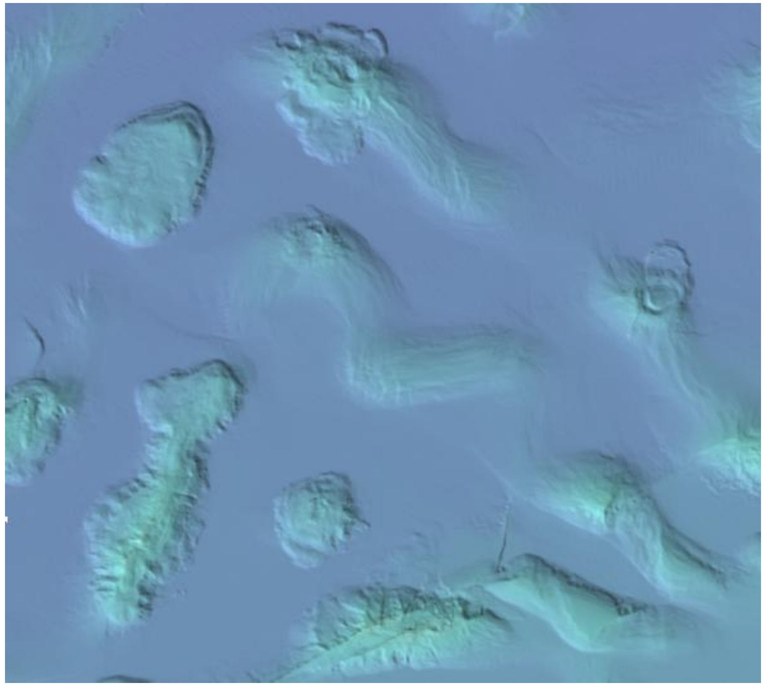


Note: high resolution image subject to confidentiality

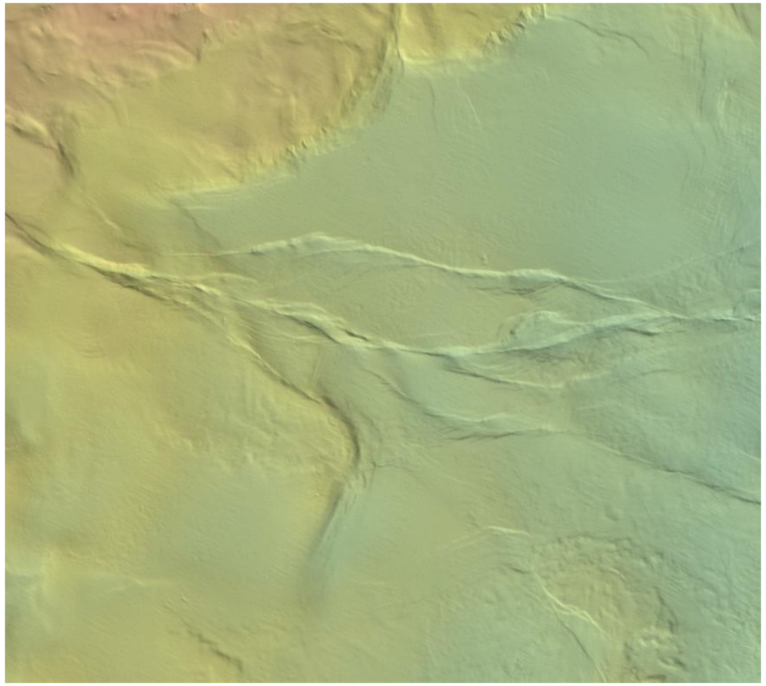
- **192,000 km 2D PSDM Seismic**
- 605,000km^2 Multibeam & Back-scatter data
- Complimented with 1098 cores & geochemistry

Multibeam – High Resolution Imagery

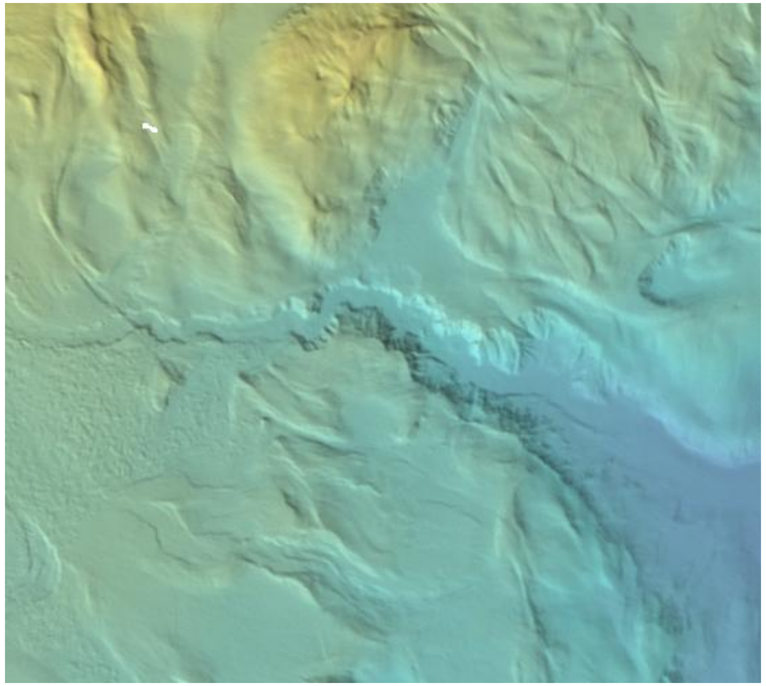
It reveals a complex seafloor environment with structural and geomorphic detail including salt knolls, mini basins, fault escarpments, gas and fluid escape features and submarine channelling and slumping.



Salt Knolls
Subsurface salt features

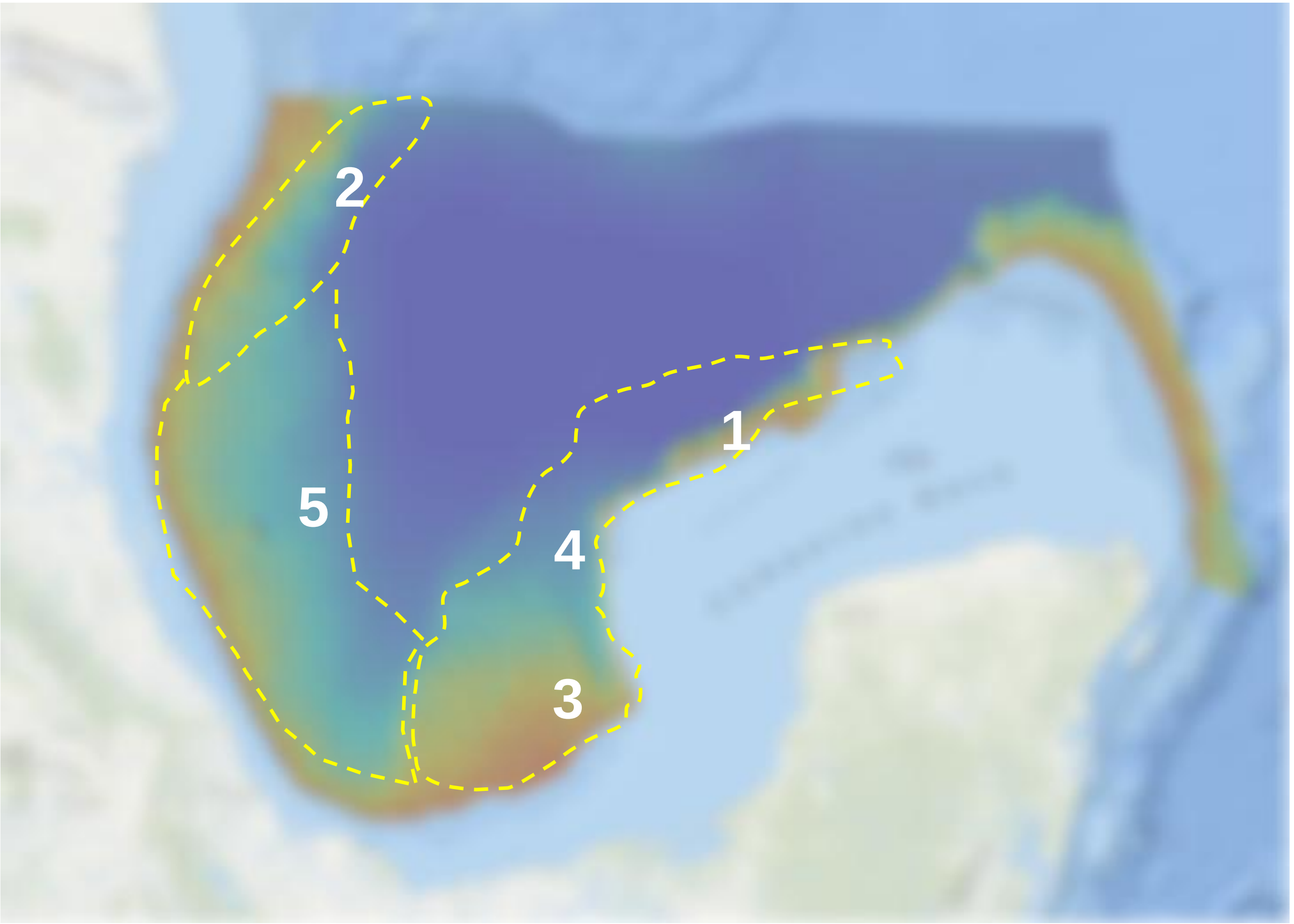


High-angle Faulting
Fault Escarpments



Submarine Canyon

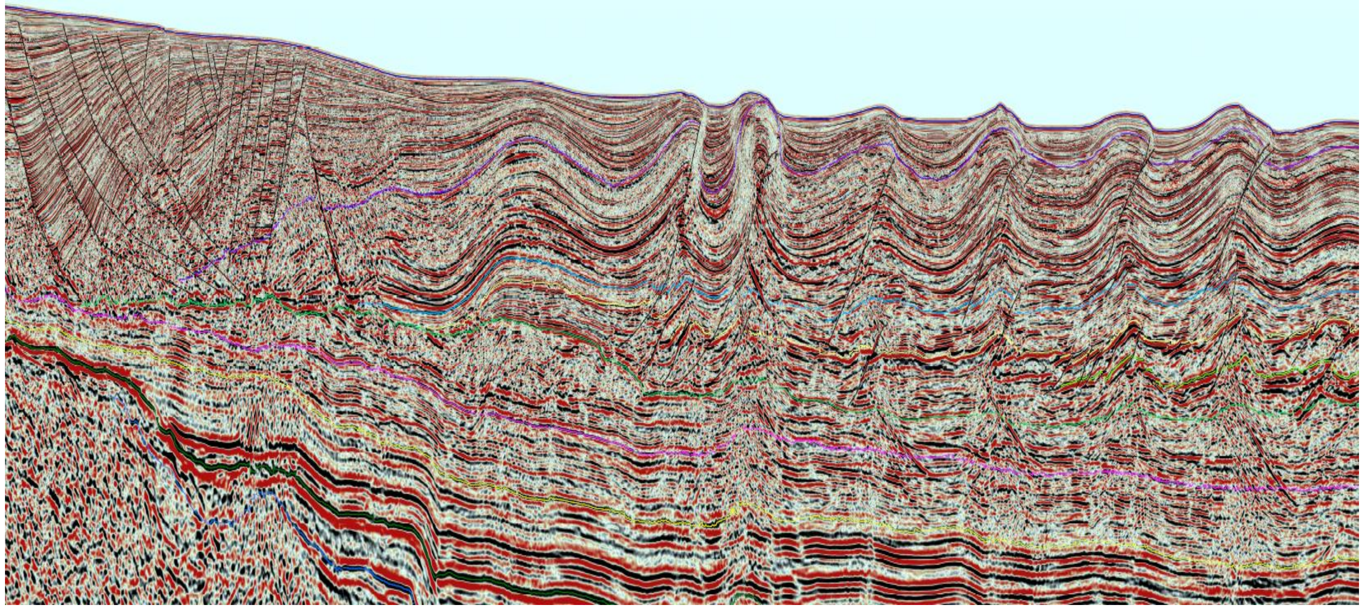
MGOM Multibeam – Structure at Seabed



Note: high resolution image subject to confidentiality

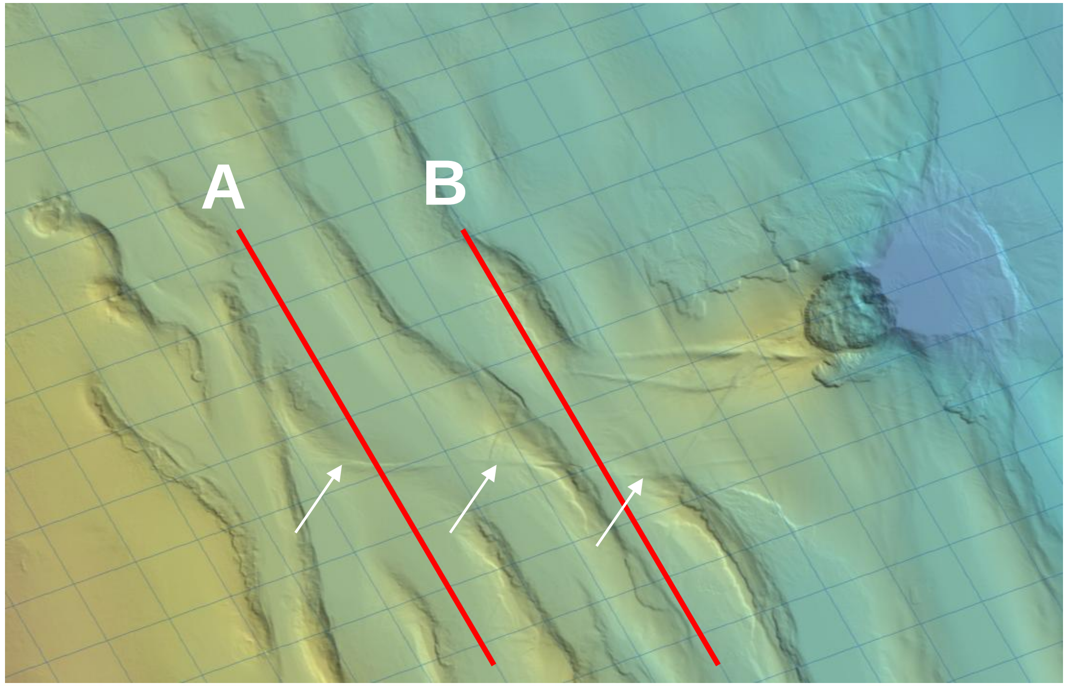
- Recent canyon\erosional features at the Campeche escarpment (1)
- Broader but shorter NE-SW trending anticlines in the Perdido Fold Belt (2)
- Curvilinear ridges\mounds of the main Campeche salt province (3)
- Isolated salt diapirs of the northern Salina del Istmo (4)
- Long sinuous anticlines of Mexican Ridges (5)

Mexican Ridges

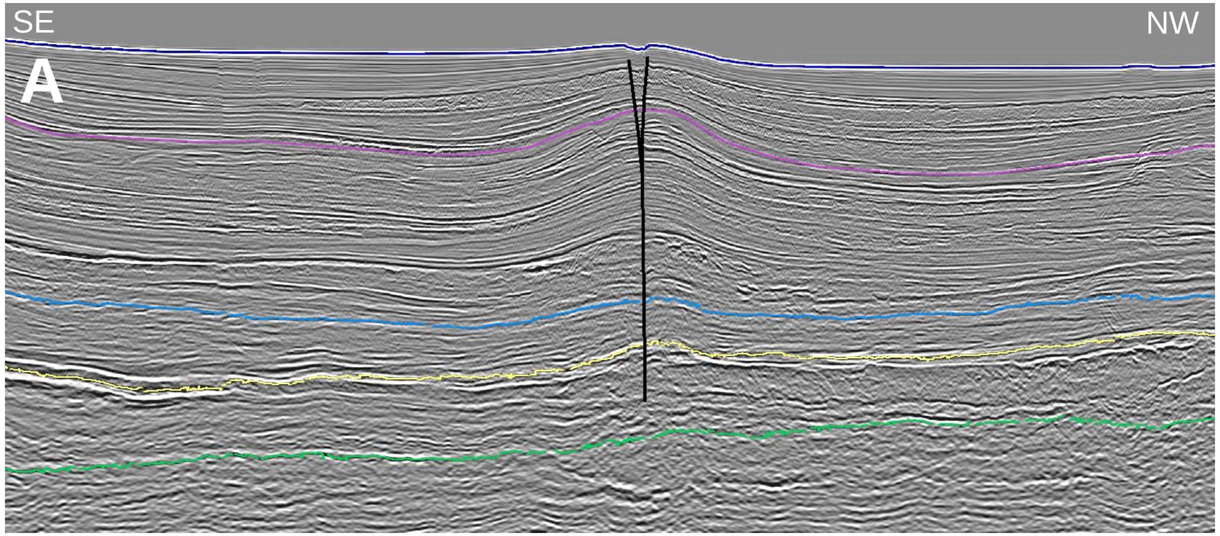


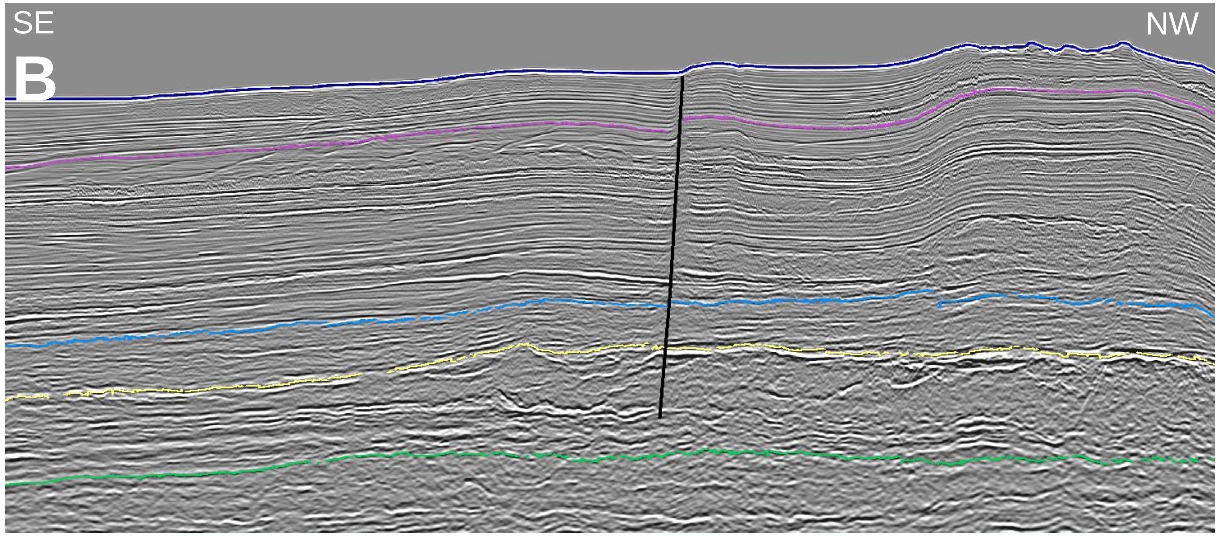
- The Mexican Ridges are characterised by a series of coast-parallel anticlines
- Extension at the continental shelf has resulted in gravitationally driven fault propagated high amplitude, low half-wavelength folds
- Structurally complex area, difficult to correlate across 2D seismic lines

- Multibeam used to qualitatively support seismic interpretation
- Correlation of faults across lines
- Understanding 3D nature of structural features



Multibeam – Qualitative Analysis Seismic Interpretation





- 2 seismic lines perpendicular to the E-W trending lineament cross-cutting the folds
- The seismic lines show a high-angle strike-slip fault, with apparent vertical offset an effect of lateral displacement of dipping strata
- For example, steeper-dipping Miocene strata exhibit a more pronounced apparent vertical offset than shallower Upper Oligocene strata

- Multibeam makes it easier to identify subtle strike-slip faults and correlate across 2D seismic lines

Traditional Uses of High Resolution Bathymetry Datasets

- Seabed structure data (DEMs) etc. has traditionally been focused on infrastructure
  - Planning and monitoring – Damage assessment and inspections
  - Infrastructure – Umbilicals, riser connections, pipelines
  - Site and cable route surveys - Automated planning process (*Least Cost Paths)*
  - Seabed seeps - Pockmark identification and extraction (Possible hydrocarbon migration)

- Identified an opportunity
  - Regular GIS requests include adding structure at the onset of interpretation
    - Convert from raster into a loadable vector format
    - Manually Digitise - Time and costs associated

  - Apply relatively simple GIS workflow to automate the process of feature extraction with the principle aim to provide a first pass polygon fault set
  - Evaluate how this dataset be more widely utilised within our interpretation process?
  - Can we gain more insights from this dataset which may prove useful during project initiation stages?
  - Utilise the DEM and associated derived (secondary) datasets

Feature Identification and Classification

- Two components associated with the identification and extraction of seabed features
  - Feature morphology, shape and extent
  - Fold axial trace (ridge axis)

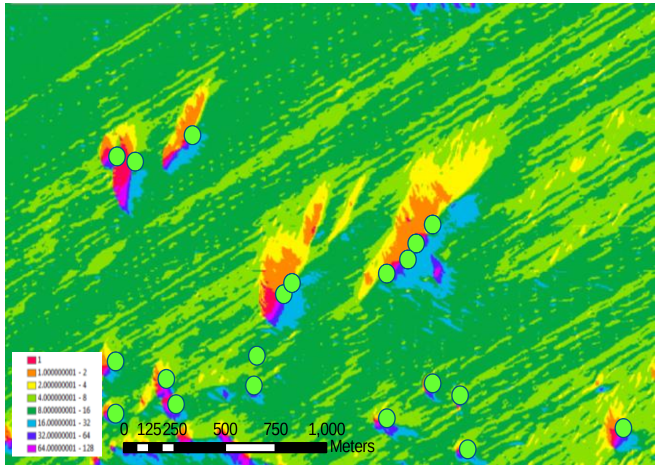
- Extracting the ridge axis provides the ability to convert the raster dataset into a vector feature class and therefore more easily integrated into geoscience software
- Determining feature morphology provides the ability to classify\categorise the identified structures
- All GIS processes and workflows were undertaken using the ESRI application suite and spatial analyst\3D extensions
- Integrated into a single Python process
  - Repeatable
  - Relatively quick processing time
  - Make adjustments to the workflow to trial and experiment (iterative)

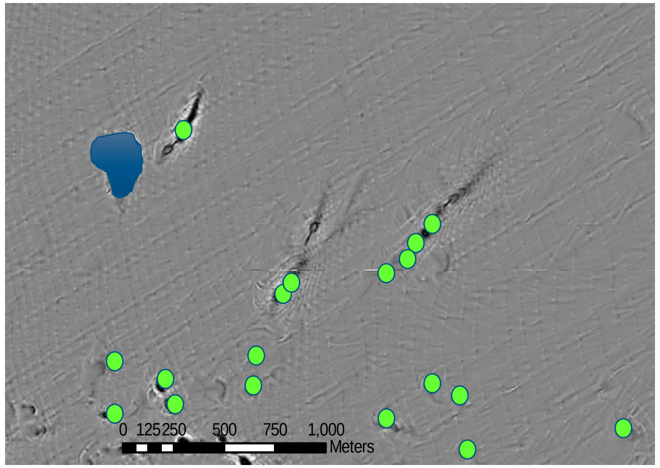
Feature Identification and Classification

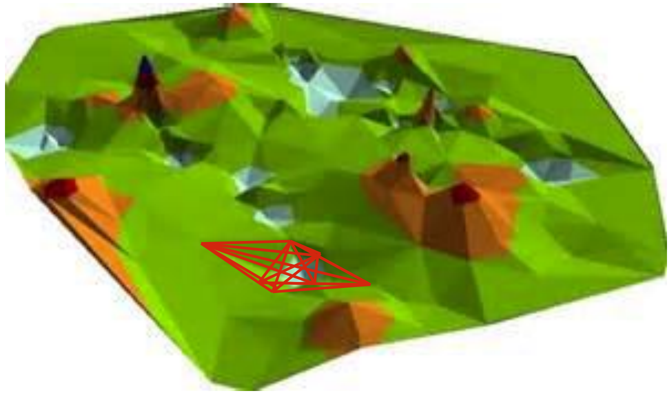
- TGS has experience in developing proprietary workflows related to Seabed Risk Mapping with emphasis on external (e.g. infrastructure) and environmental factors

- Involves advanced GIS techniques to analysis a high resolution DEM
  - DEM derived attributes: Flow Direction + Profile Curvature + Slope Angle
  - Allows identification and extraction of Pockmarks
    - Adapted from Andrews, Brothers and Barnhardt (2010)

- Derived attributes are highly dependent upon high resolution data (Gigante!) (15m)

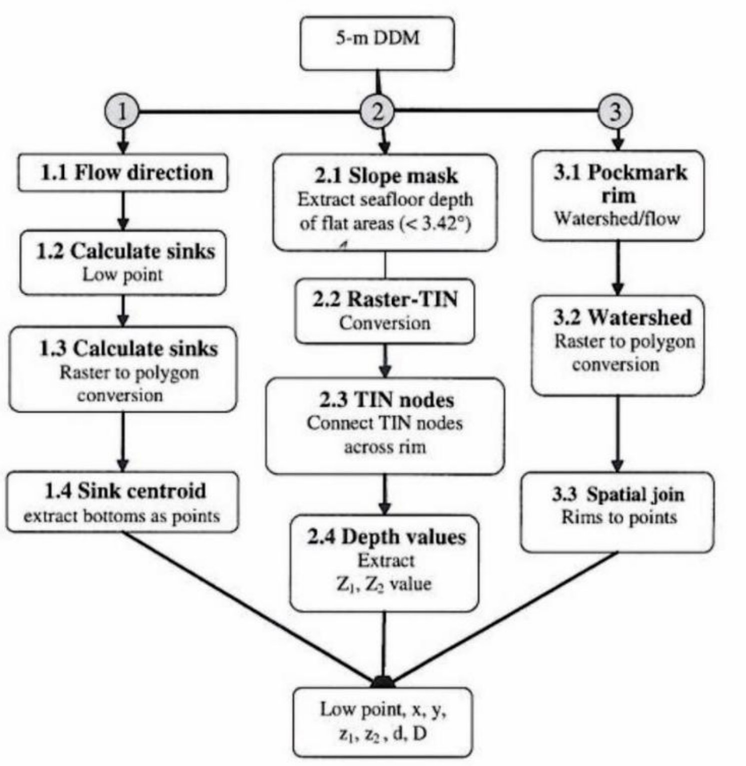






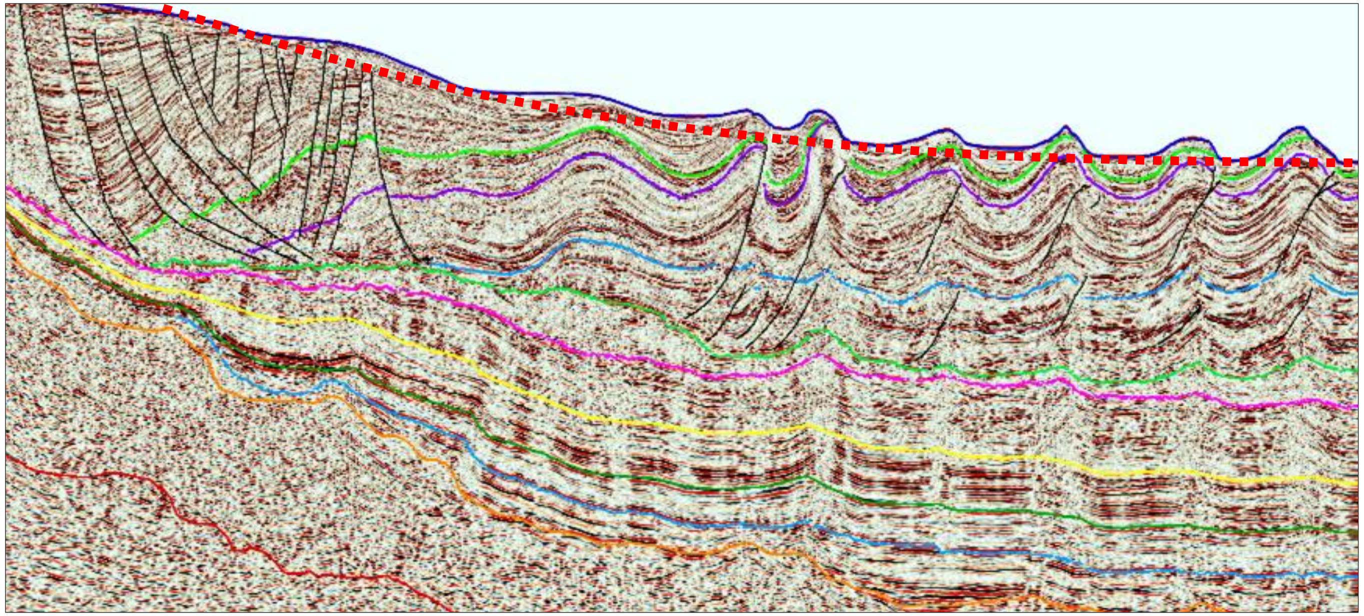
Feature Identification and Classification

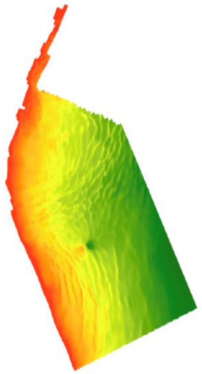
- Initial concept to utilise the existing workflows by inverting the DEM
  - Converting seabed structure (ridges and folds) into seabed depressions
- Proved successful in feature identification, but due to the model workflow it made ridge detection problematic
- Andrews *et al.* (2010) concluded that this process did not identify long, elongated pockmark features particularly well.
  - A finding that was supported in a TGS study



Andrews *et al*. (2010)

Feature Identification: Shape and Extent





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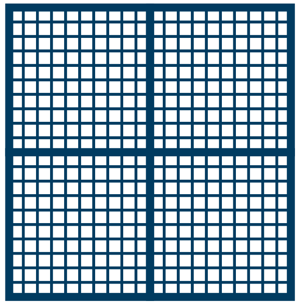

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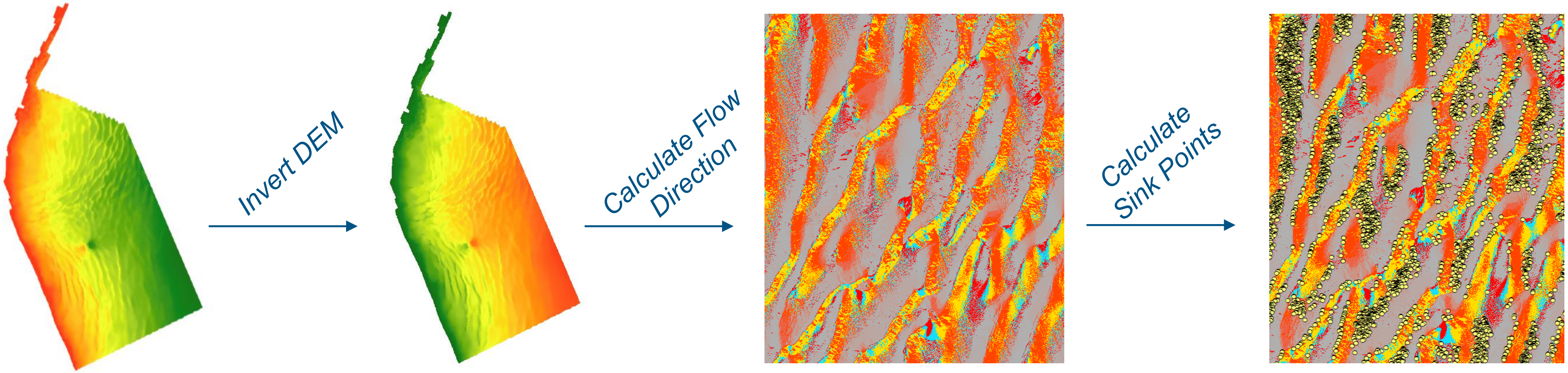
Ridge Shape & Extent

Feature Identification: Ridge Axis

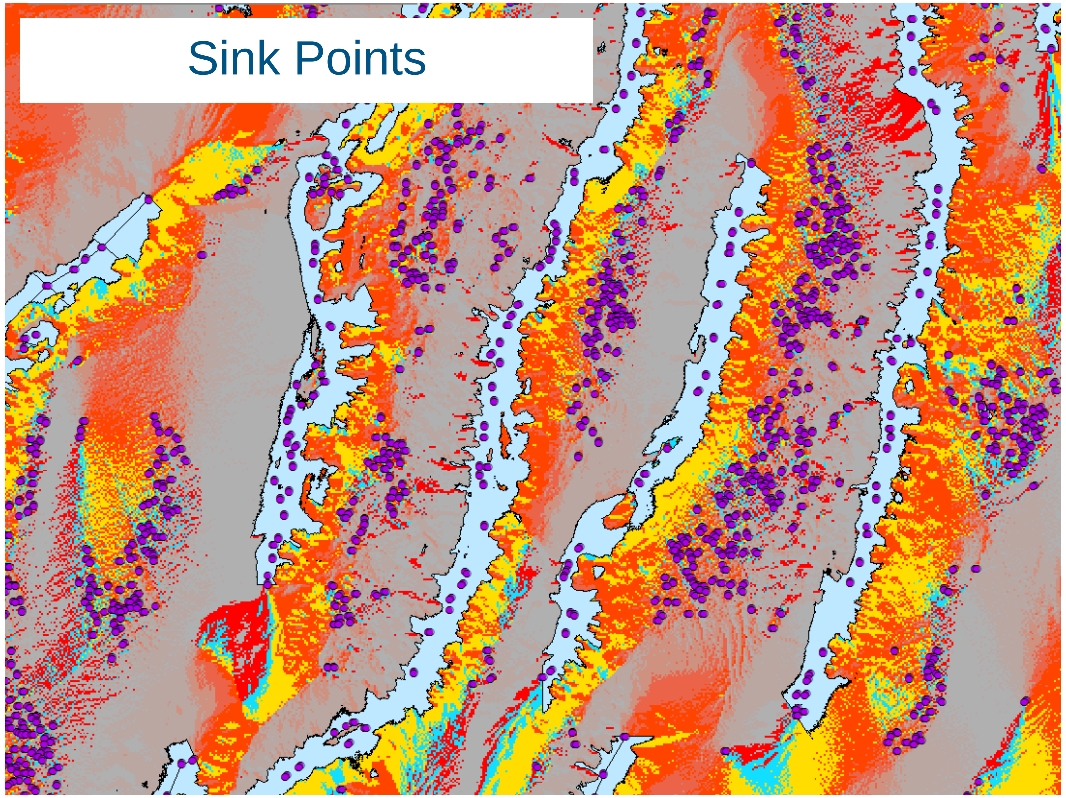
- Numerous hydrological algorithms exist and therefore the DEM was inverted to make use of these
- Flow direction typically used to identify fluvial channels and is required to determine the local sink points

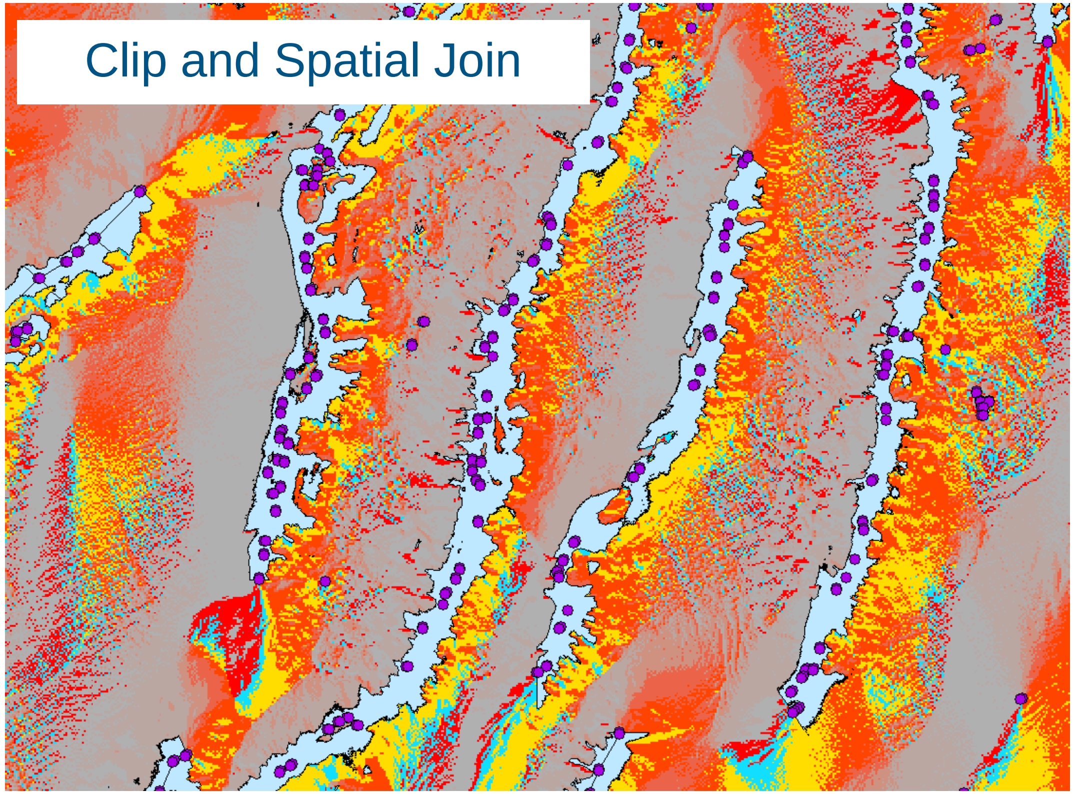


Flow Direction: *The d*irection of flow from each cell to its steepest downslope neighbour
Sink: *An area of internal drainage*

Feature Identification: Ridge Axis

- Numerous hydrological algorithms exist and therefore the DEM was inverted to make use of these
- Flow direction typically used to identify fluvial channels and is required to determine the local sink points → Inferred Ridge Axis





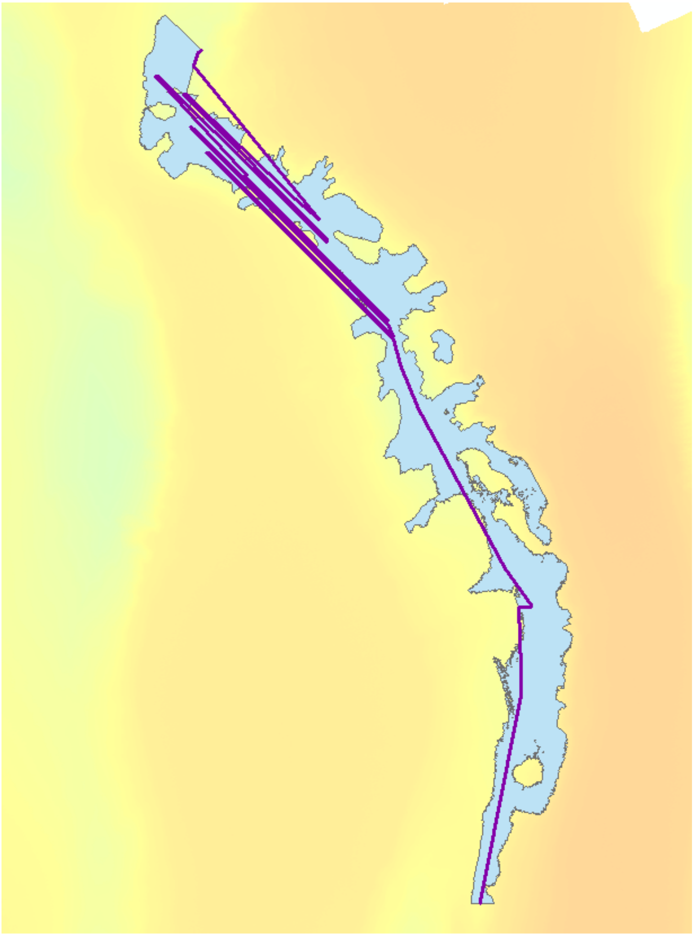
Feature Identification: Dot to Dot!

The problem: In which order to join the points?

- Based on a vector-to-distance matrix (Euclidean distance)
- A matrix is calculated and an iterative process is applied to determine the ridge line

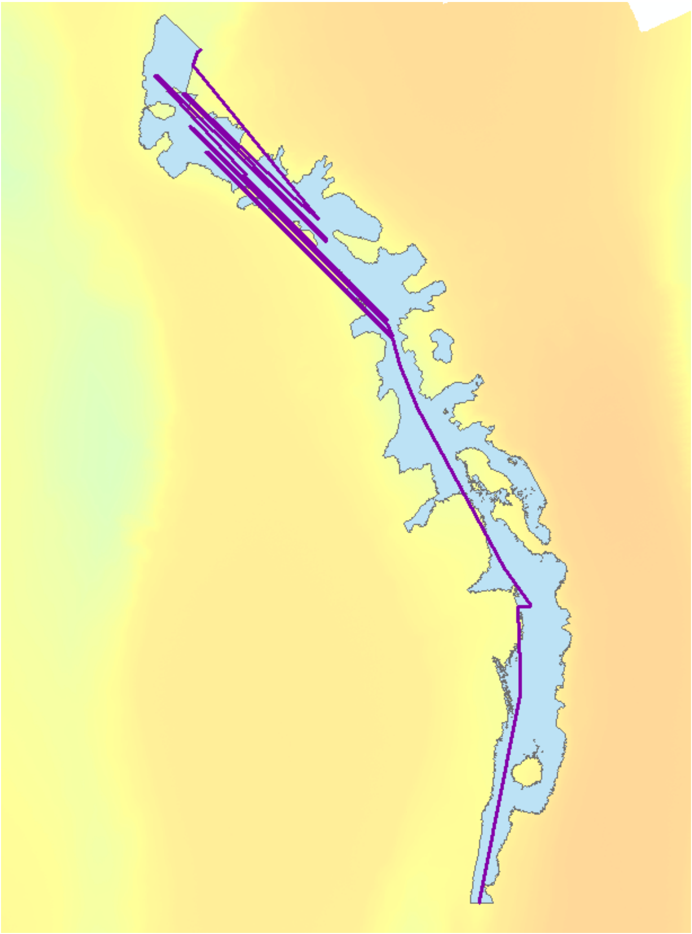
```
def dist(self, coord1, coord2):
    '''
    Eucleadean distance
    '''
    if (coord1[0] == -1 and coord1[1] == -1) or (coord2[0] == -1 and coord2[1] == -1):
        return 0
    if self.useAngle:
        angle_dist = round( math.sqrt(  math.pow(math.fabs(math.cos(math.radians(self.angle))) * (coord1[0] - coord2[0]), 2) +  math.pow(math.fabs(math.sin(math.radians(self.angle))) * (coord1[1] - coord2[1]), 2)  ), 4)
        dist = round( math.sqrt(  math.pow( (coord1[0] - coord2[0]), 2) +  math.pow( (coord1[1] - coord2[1]), 2)  ), 4)

        return (angle_dist * self.angle_weighting) + (dist * (1 - self.angle_weighting))
    else:
        return round( math.sqrt(  math.pow( (coord1[0] - coord2[0]), 2) +  math.pow( (coord1[1] - coord2[1]), 2)  ), 4)
```

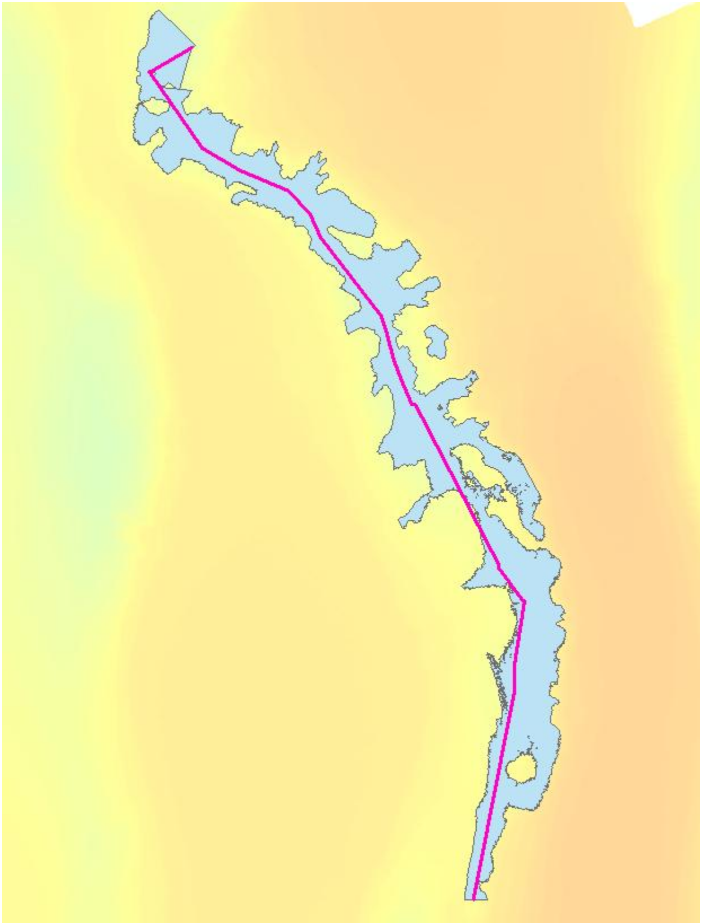
- Distance of the points and their distribution is the key controlling factor
- Ability to add weightings to line orientation etc.



ArcMap

Feature Identification: Ridge Axis





- This result may be used as a fault map\layer through a fully-automated process
- Identified further improvements to the method and parameterisation, but yet to be implemented

Fault Linkage and Orientation

- Numerous thrust faults with similar and opposing dip, link and transfer displacement within the structure as it changes vergence along strike
- The transitions from one fault to another along strike are in the form of antithetic thrust fault linkages
- Identified as a potential area for a classification procedure

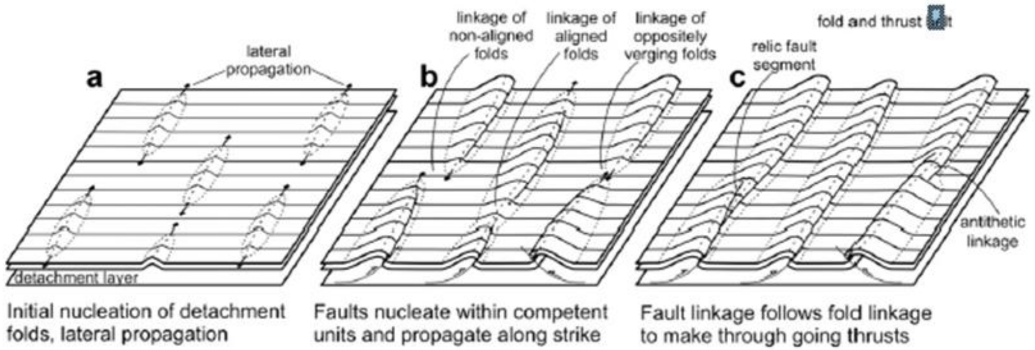


Fig. 1. An example of a model for the structural evolution of a fold and thrust belt, based partly upon and expanded from the modelling results of Liu and Dixon (1991). (a) Numerous low-amplitude detachment folds initiate and grow by lateral propagation. (b) Faults nucleate within competent units and propagate along strike within the folds. Forethrusts form in the forelimbs, backthrusts in the backlimbs. Each fold may nucleate a number of faults along its length. (c) Fault linkage follows fold linkage creating through-going thrust surfaces.

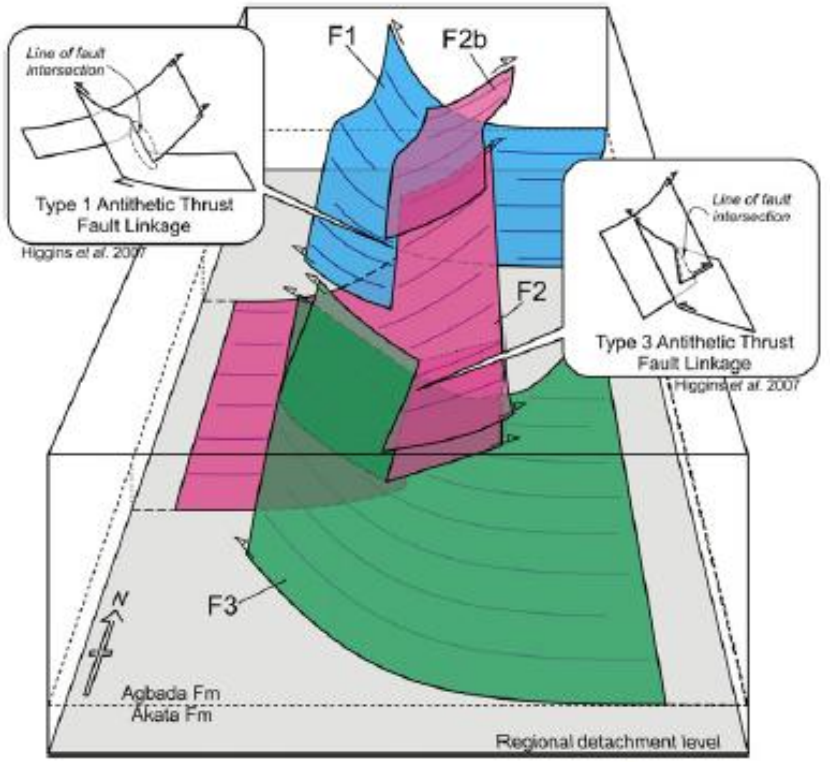
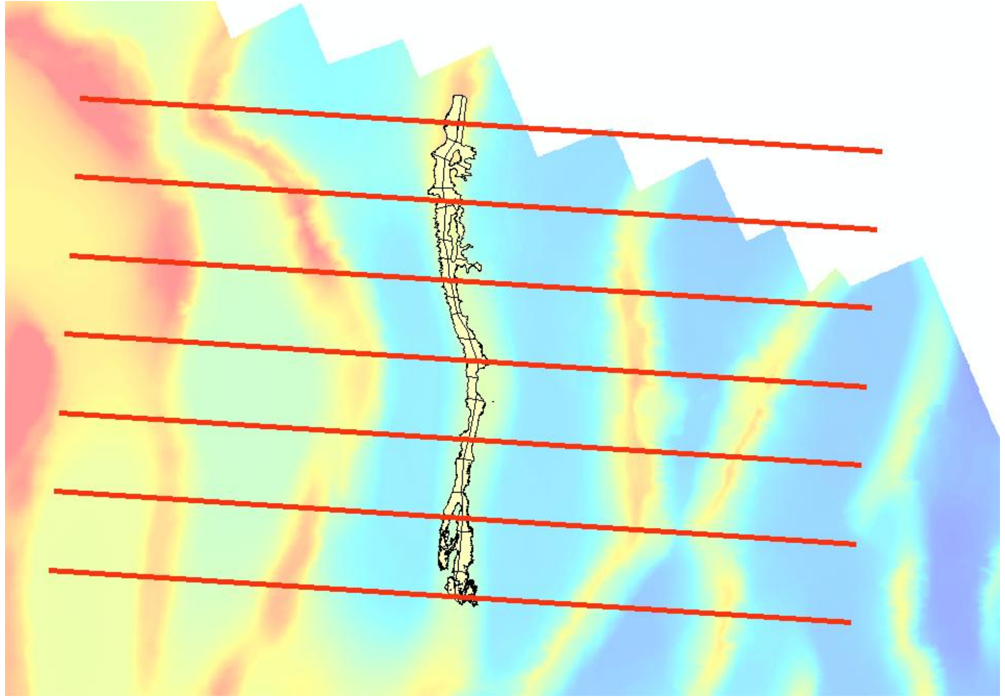


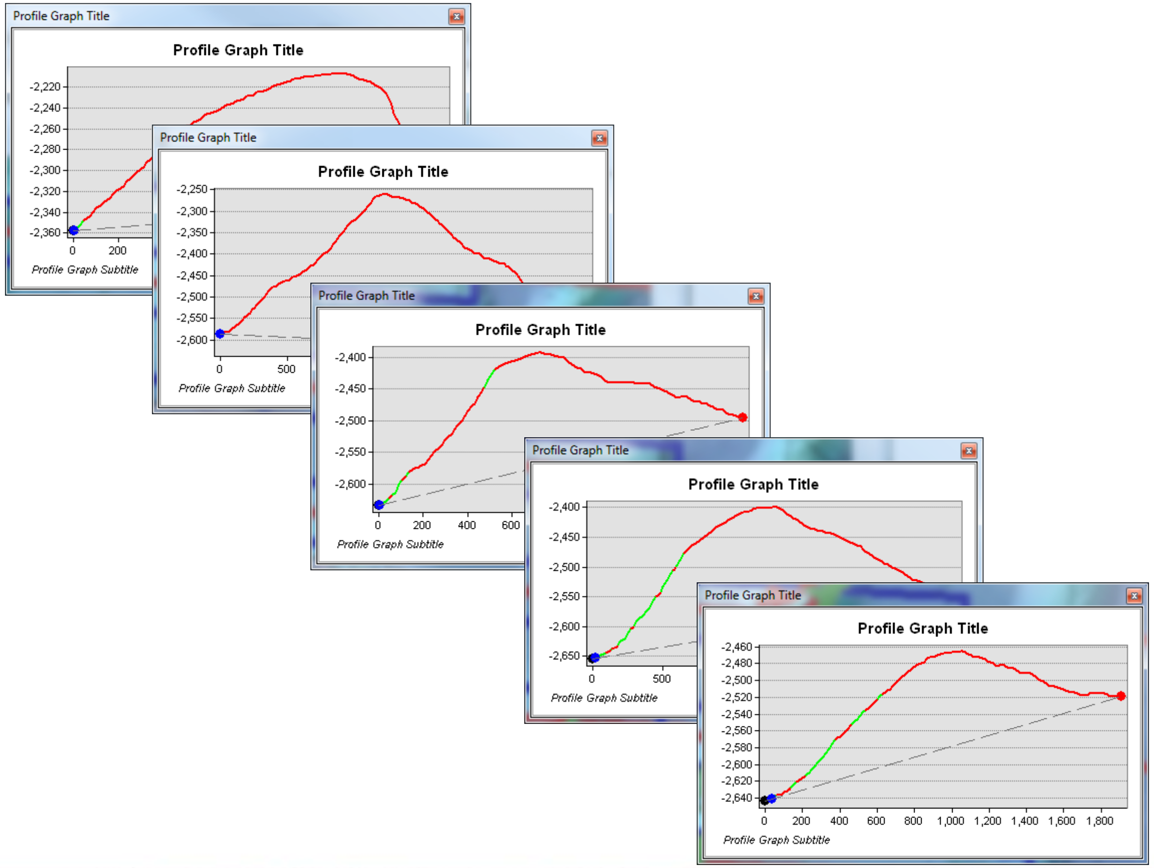
Fig. 8. Three-dimensional conceptual diagram of antithetic fault geometries and linkages. Faults F1 (blue) and F3 (green) detach at the Agbada–Akata Fm boundary. Fault F2 (pink) detaches at a regional level within the Akata Fm (grey surface).

Higgins *et al*. (2009)

Feature Classification

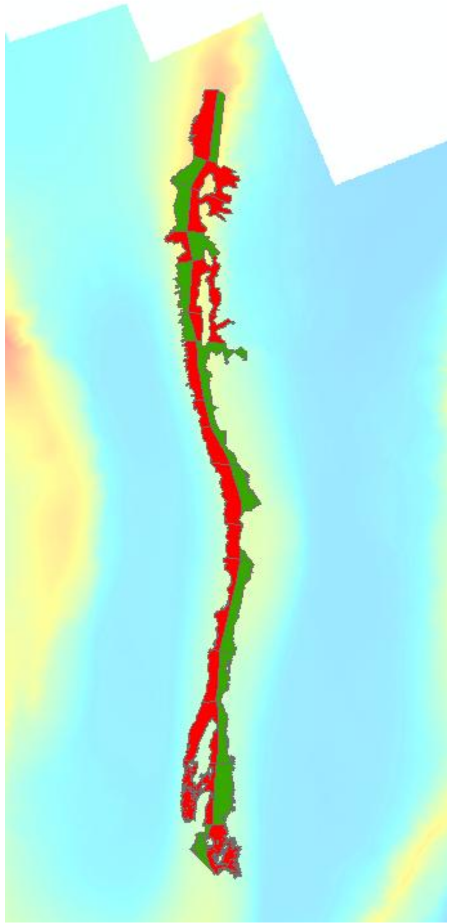
- Assumption that surface morphology can be used as a proxy for subsurface structure
- Several lines used to ground-truth the classification process
- Attributes extracted include mean and median elevation, slope, plan and profile curvatures.



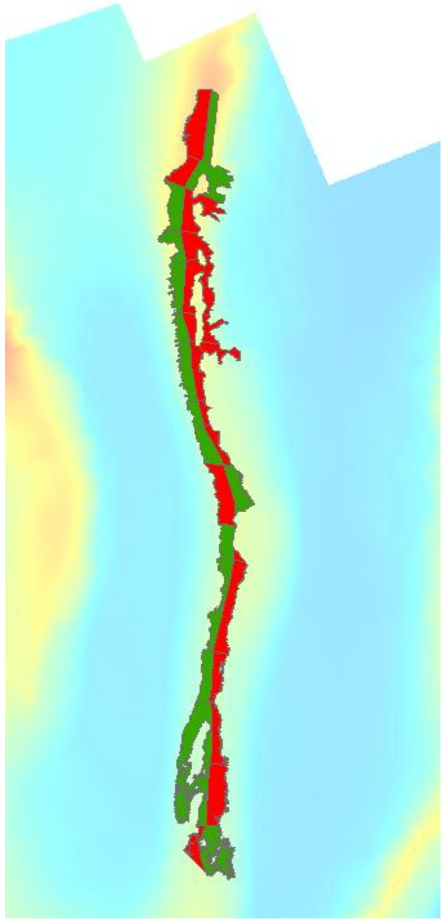


Feature Classification

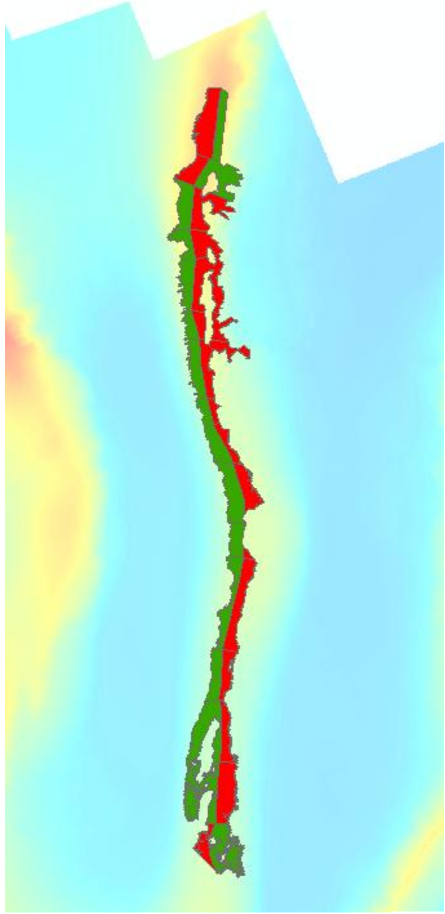
- Attempt to determine whether any discernible relationship exists between feature morphology, and how this may be related to fault linkages



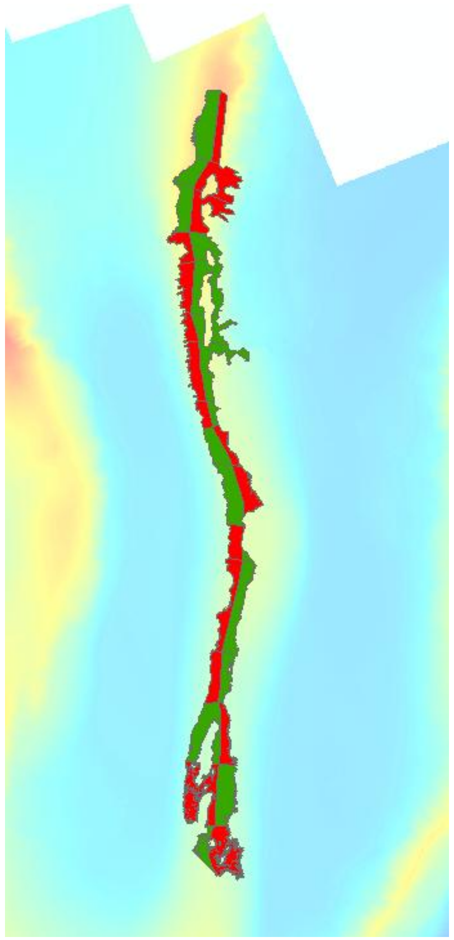
Median Elevation



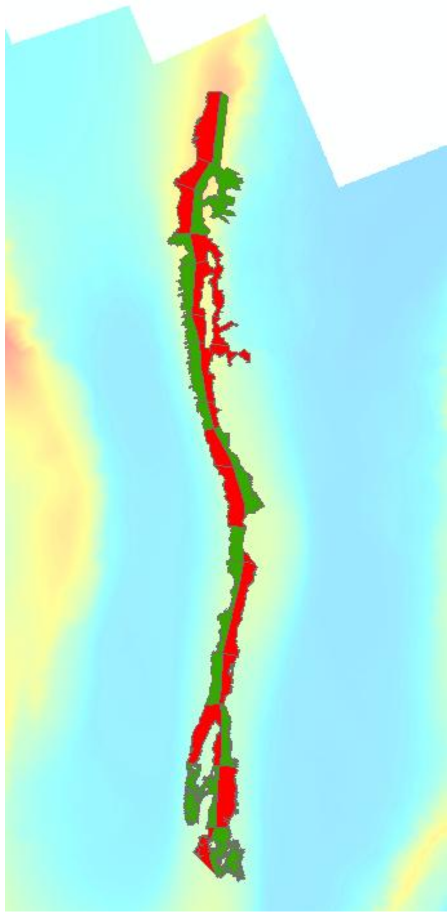
Median Slope



Mean Slope



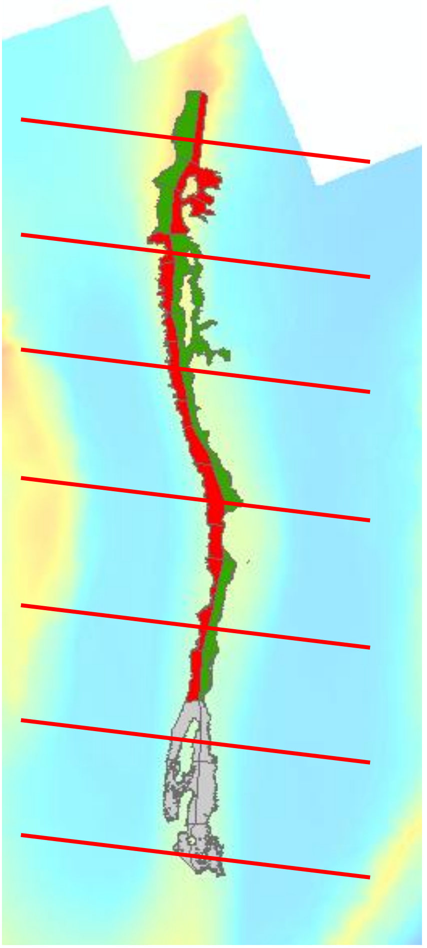
Mean Plan Curvature

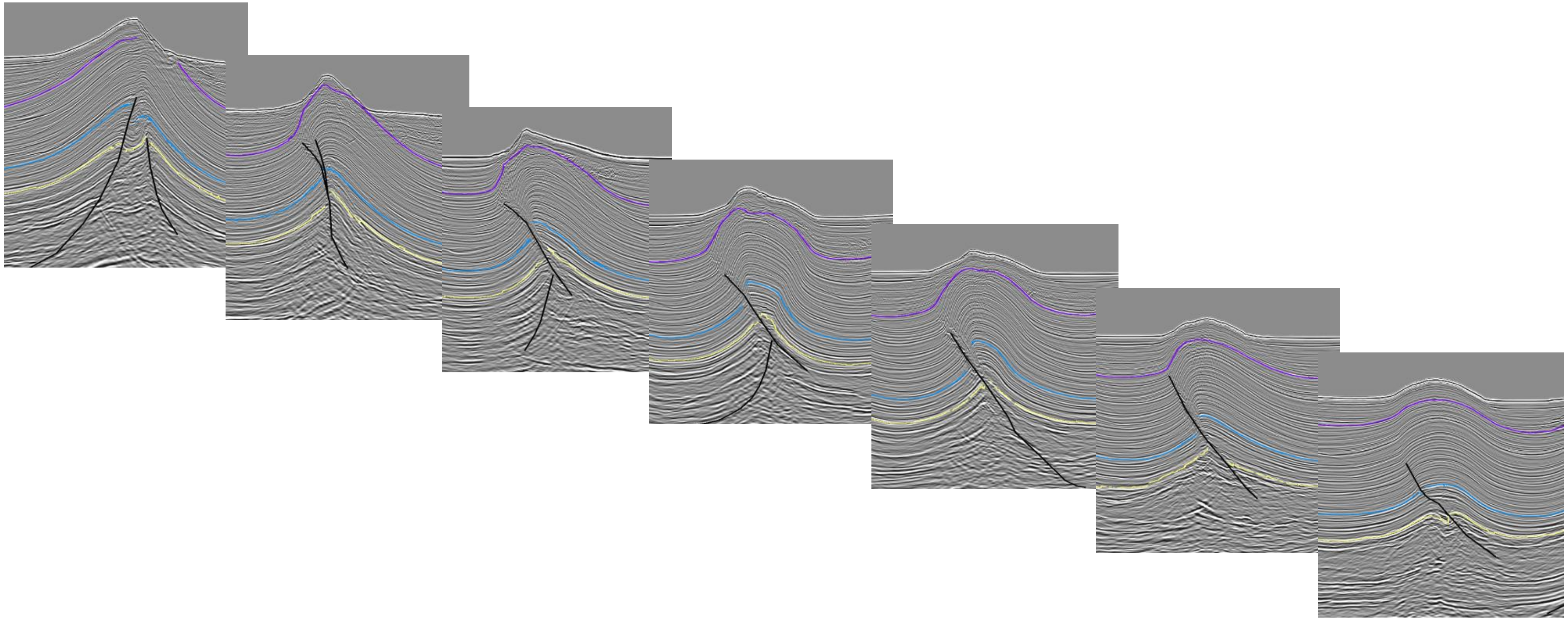


Mean Profile Curvature

Feature Classification

Function – (ABS(MeanProfileA – MeanProfileB)) * (MedianSlopeA – MedianSlopeB))



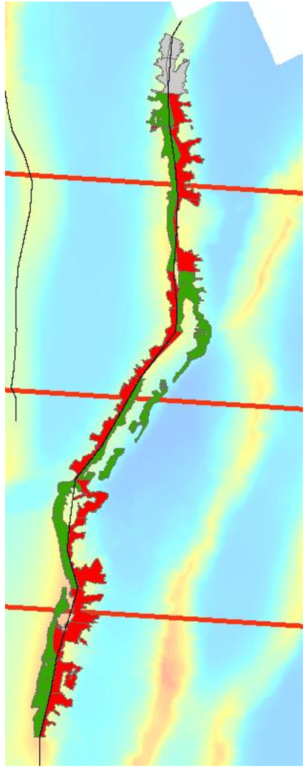


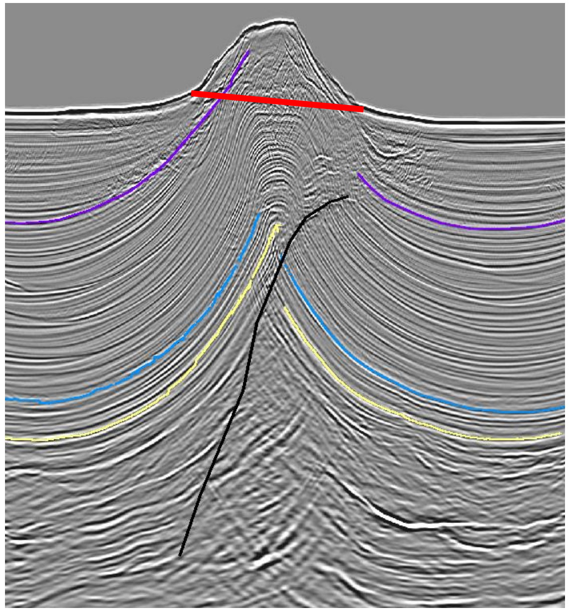
Feature Classification

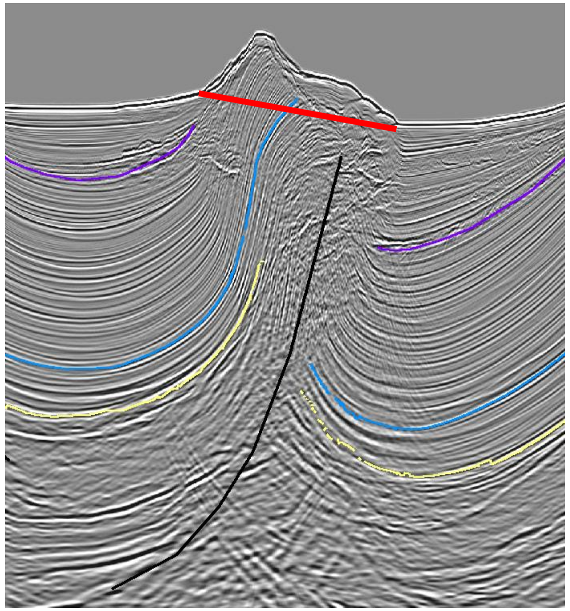
Is the surface morphology a good proxy for subsurface structure(s)?

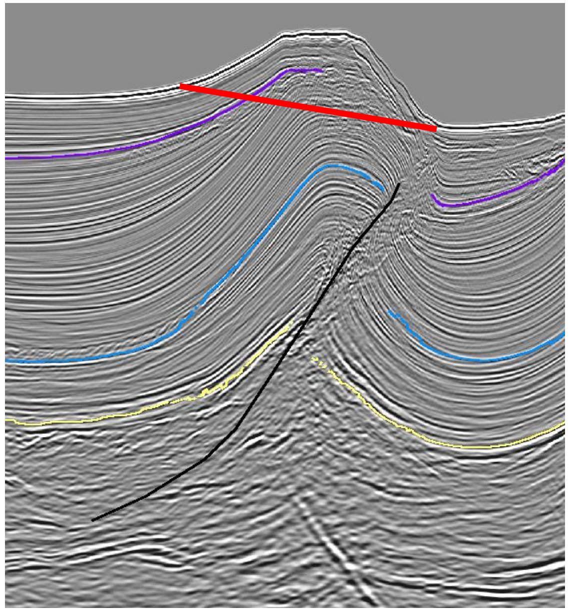
Has the original feature morphology changed (partially collapsed)?

Likely require addition of further attributes (mean bounding elevation at point of inflection) to predict in these cases and a better understanding of where to separate the different sections



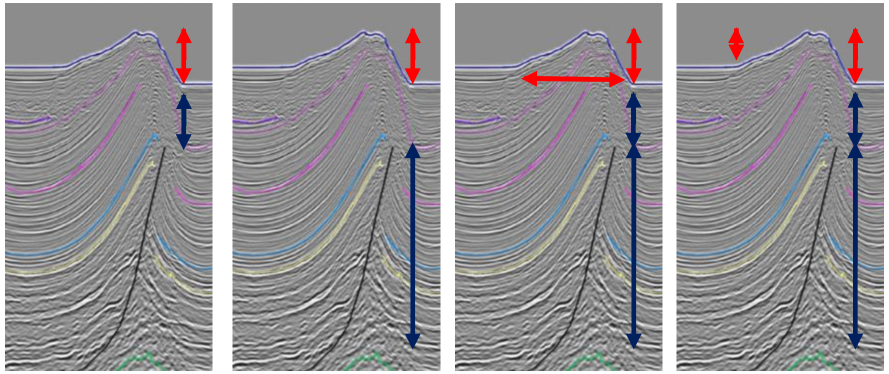


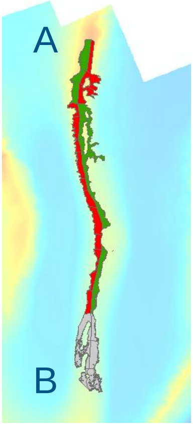


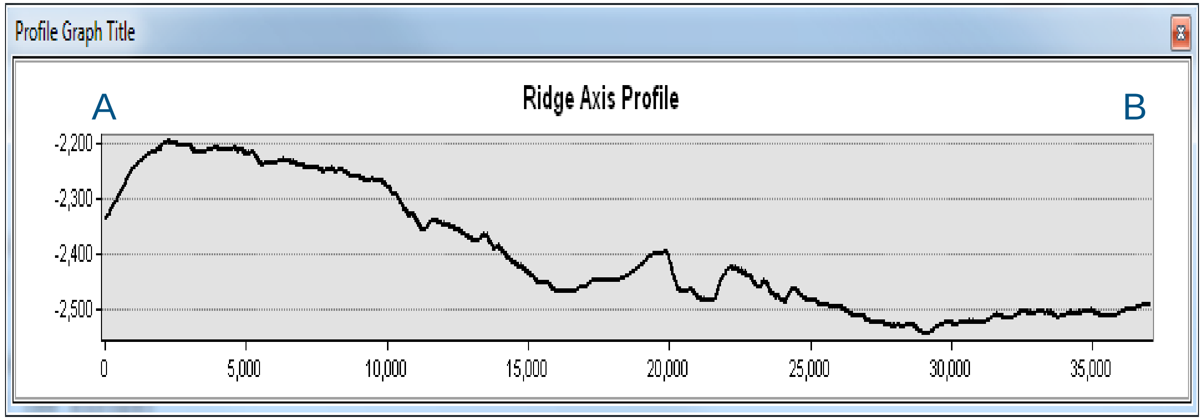


Feature Classification - Further Work

- Seabed morphology is a reasonable proxy for subsurface structures - with some limitations!
- It would be possible to further refine the Feature Classification BUT ultimately this becomes an esoteric exercise given the uniqueness of the data set
- Further studies may include:
  - Enhancing the initial classification process presented - additional independent variables
  - Adjust parameters in feature identification to determine individual features rather than a single fold (i.e. identify sub-structures and thereby improve the classification)
  - Investigate further the relationship between fault linkage and the profile of the fold ridge axis







Summary

- Multibeam data can provide high frequency, high resolution imaging of active tectonic and soft-sediment processes affecting seabed
- Demonstrated how multibeam data may be used to support a 2D structural seismic interpretation (qualitative and quantitative analysis)
- Demonstrated a relatively simple process for the automated extraction of feature morphology, shape and extent, and the conversion from Raster to Vector data formats
- Successfully customised a process to auto-generate the fold-ridge axis (as a proxy) to provide first-pass fault mapping
- Presented a novel approach to classifying feature morphology in an attempt to better understand and support structural interpretations i.e. fault linkages and fold development
- “Big Data” approach - repeatability and automation - methodology is an example of using GIS to efficiently evaluate large datasets and identify regional spatial geological trends
- The unprecedented extent and data quality of the Gigante seismic, multibeam and coring survey in the Mexican Gulf of Mexico will be an invaluable data resource for all future studies

Acknowledgements

- Jeremy Palmer (TGS) – For contributions made to the process of feature extraction and ridge-axis automation

Thank you

Kevin Goldsmith

713-860-2100

Kevin.goldsmith@tgs.com