Structural Mapping and Geomorphology of Ireland's Southwest Continental Shelf Using High Resolution Sonar

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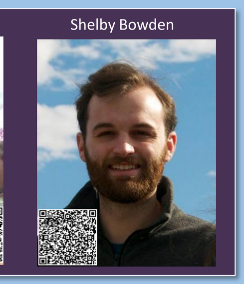


LOCATION OF STUDY SITE

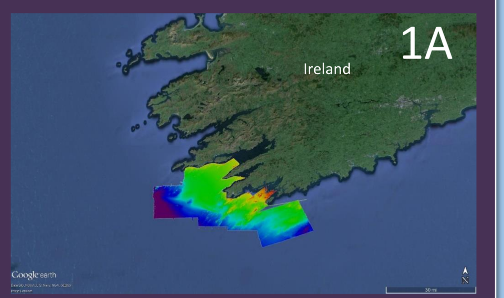


FIGURE 1A: Google Earth image showing study site off the coast of southwest Ireland

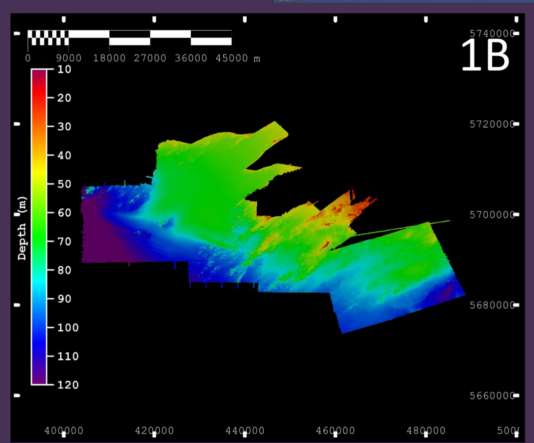


FIGURE 1B: CUBE BASE Surface image showing the study area at a 1 m resolution.

ABSTRACT

Bathymetric surveys were conducted on the continental shelf off the southwest coast of County Cork, Ireland by the Marine Institute of Ireland, the Geological Survey of Ireland, and the INFOMAR project. Data were collected from July 2006 through September 2014 using a Kongsberg EM2040 multibeam echosounder aboard the R/Vs *Celtic Voyager* and *Keary*, and a Kongsberg EM1002 on the R/V *Celtic Explorer*. Sonar data were post-processed with CARIS HIPS and SIPS 9.0 to create 2D and 3D bathymetric and backscatter intensity surfaces. The offshore study site is part of the 286 Ma western Variscan orogenic front and has several massive outcrops. These outcrops were structurally mapped and relatively aged, and exhibit significant deformation and fracturing. Google Earth, ArcGIS, and previous terrestrial studies were used to further analyze how geomorphology is controlled by seafloor composition and structural features. Rock type and age were interpreted by comparing fracture analysis and backscatter classification of the joints and folds to similar onshore outcrops, to determine an age of 416-299 Ma for the shelf's outcropping strata and associated structural features. The oldest features observed are 1st order anticlines and synclines containing Upper Devonian and Lower Carboniferous beds. Within the Devonian layers are NE-SW plunging 2nd and 3rd order folds. Jointing is observed in all layers and is superimposed on folding, with some joints appearing to be pre-Variscan. Rotation of the regional folds is the youngest structural feature, as both the 2nd and 3rd order folds and rock fractures are warped. Our study shows that high resolution sonar is an effective tool for offshore structural mapping and provides an important resource for understanding the geomorphology and geologic history of submerged outcrops on continental shelf systems.

BACKGROUND

County Cork is a geologically complex area that has experienced varying tectonic regimes since the Devonian. Following the Ordovician Caledonian Orogeny, north-south extension in the Middle and Late Devonian (387 mya) formed the Bantry and Kinsale Sub-Basins (Fig. 2a) (MacCarthy, 2007). Subsidence of the region and continued extension is displayed in a fining upward marine transgression in the stratigraphic sequence (Fig. 2b) (Higgs, 2000). In the Late Carboniferous, the Munster Basin experienced extensive N-S compression during the Variscan Orogeny which formed regional anticlines and synclines, faults, and a complex system of rock fractures (Fig. 2c) (Naylor, 1978). Erosion from post-Variscan weathering and two glaciation events has exposed joint sets and deposited quaternary sediments in topographically low areas.

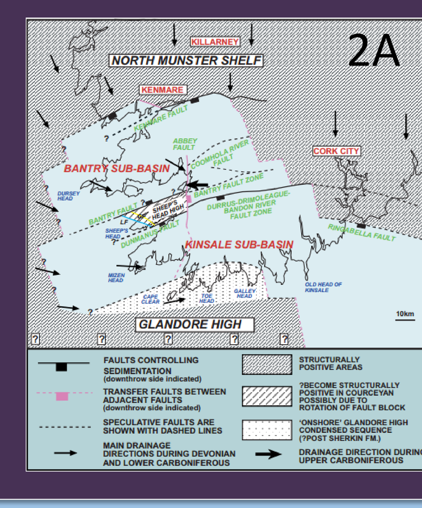


FIGURE 2A (left): Illustrates the Bantry and Kinsale Sub-Basin formation in the region including sedimentation controlling faults and drainage directions (MacCarthy, 2007).

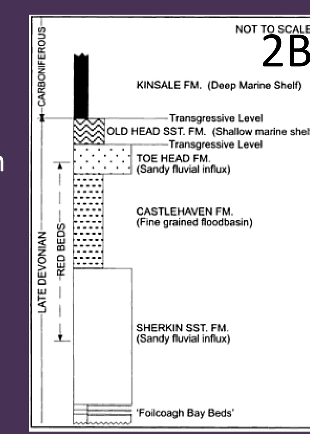


FIGURE 2B (left): Stratigraphic column illustrating fining upward marine sediment transgression (Higgs, 2000).

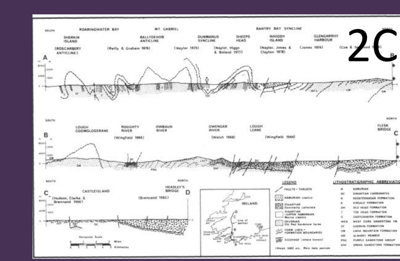
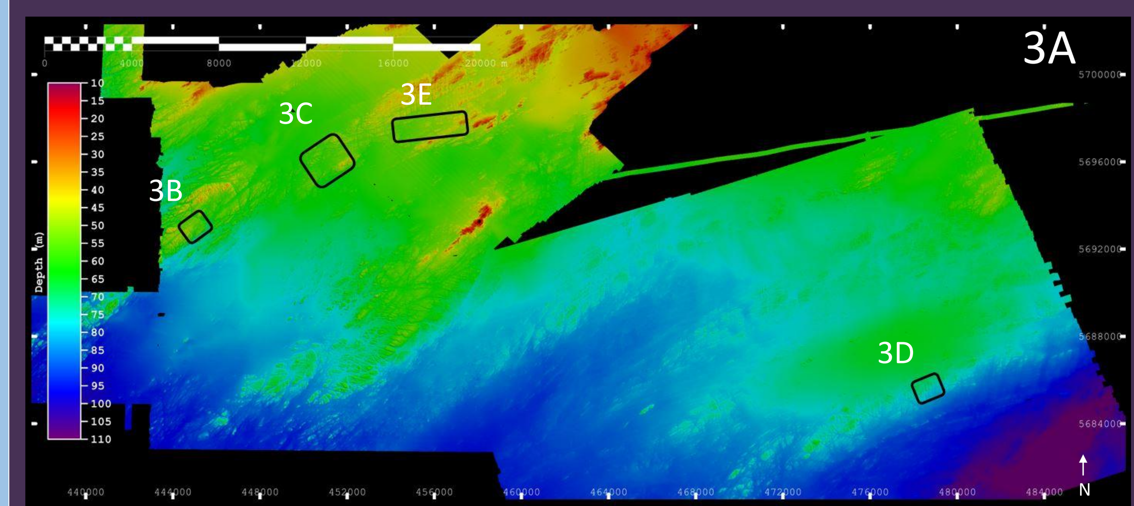


FIGURE 2C (above): Model showing folding and faulting patterns caused by the Variscan orogenic front (Naylor, 1978).

STRUCTURAL FEATURES

FIGURE 3A (below): Image of BASE surface area indicating structural feature location sites.



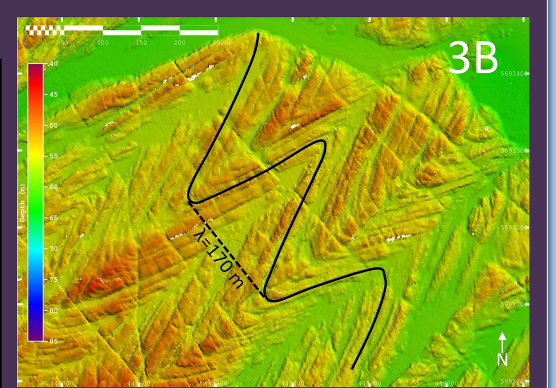


FIGURE 3B (above): Second order folding as indicated by wavelength (λ) measurement.

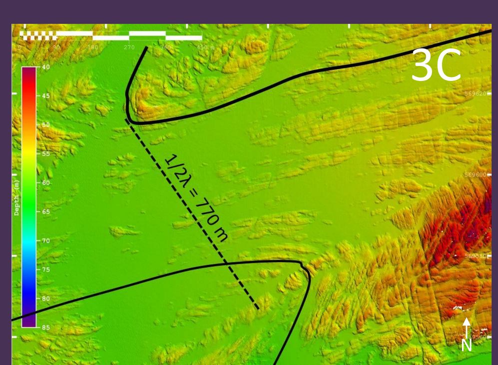


FIGURE 3C (above): Third order folding as indicated by half-wavelength (1/2 λ) measurement.

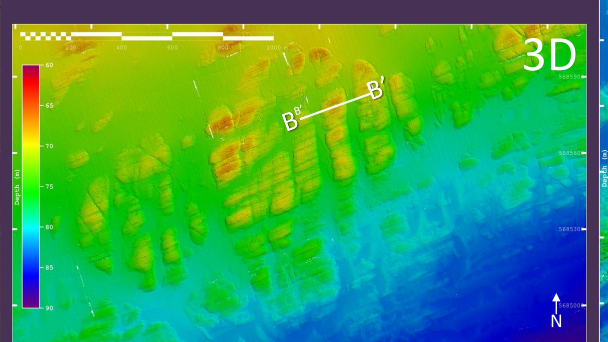
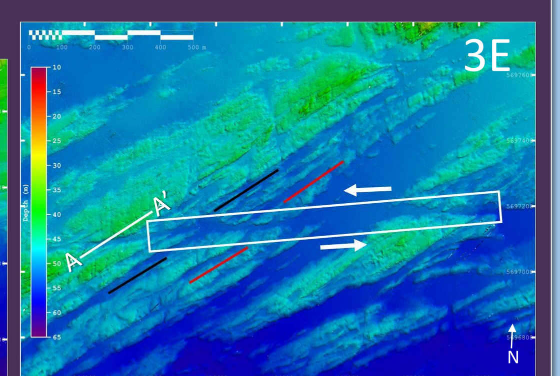
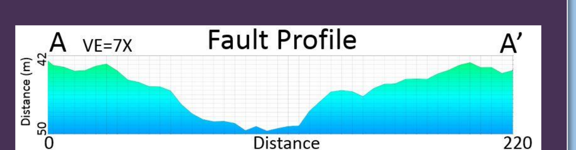


FIGURE 3D (above): Joint sets and Joint Profile (shown below) B-B'.





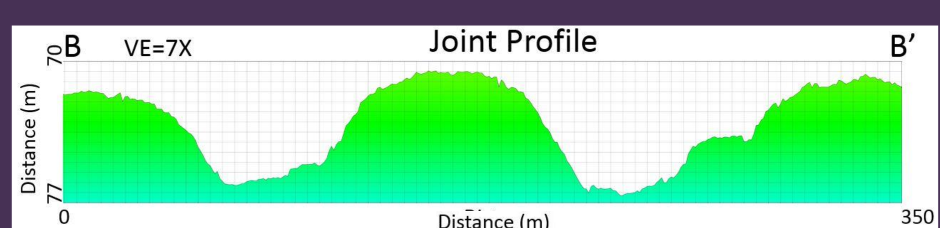


FIGURE 3E (above): Strata displacement observed in bathymetry. Colored lines on image illustrate offset along left lateral strike-slip fault (white box). Fault Profile A-A' is shown, orthogonal to the fault.

JOINT RELATIVE AGING

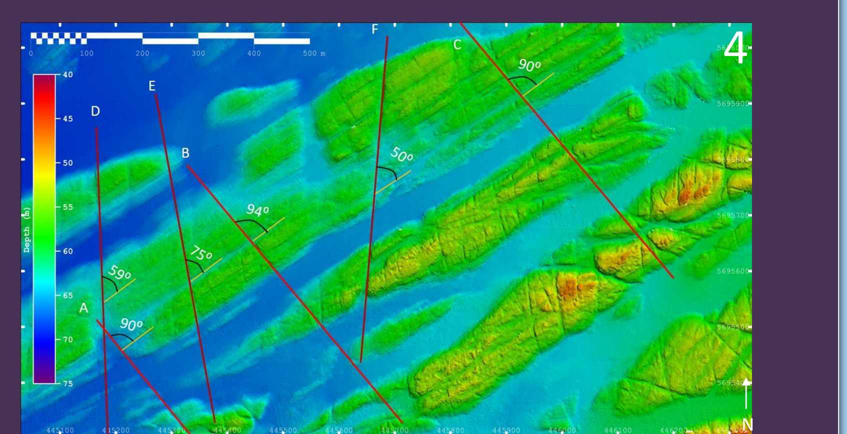
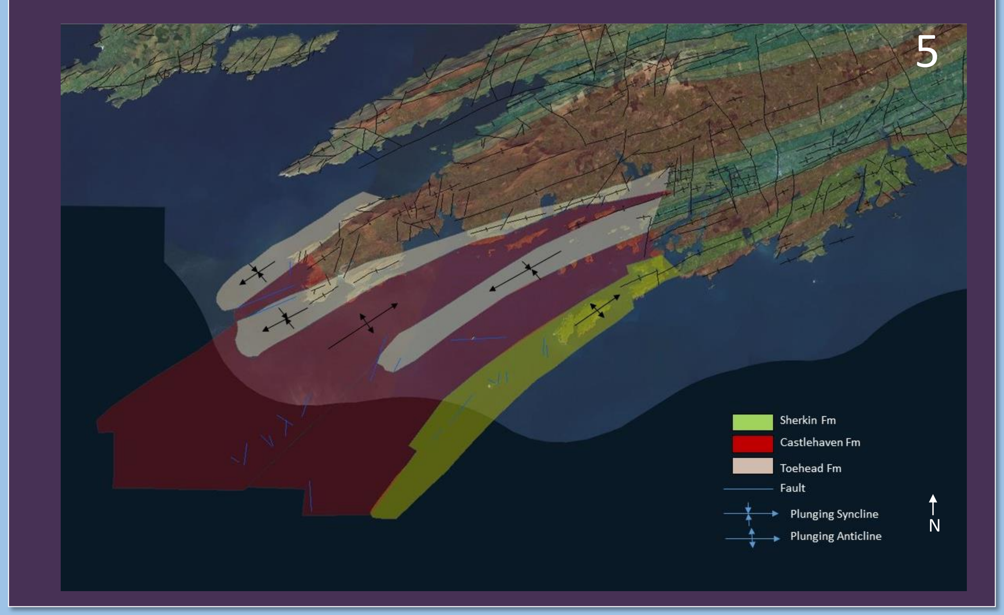


FIGURE 4: Angles between joint and bedding show relative joint ages. Joints consistently perpendicular to bedding formed before bedding folded, while joints with a varying angle to bedding formed after bedding folding.

OFFSHORE GEOLOGIC MAP

FIGURE 5: Map created in ArcGIS showing the onshore geologic map (Geologic Survey of Ireland's 1:100k Geologic Bedrock Map) and this study's proposed offshore extension of formations, fold axes, and faults.

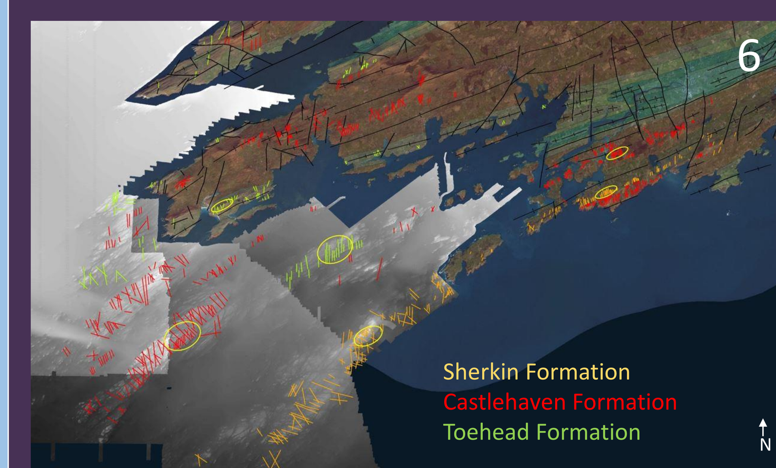


METHODS

- Bathymetric surveys were conducted by the Marine Institute of Ireland, the Geological Survey of Ireland, and the INFOMAR project from July 2006 - September 2014.
- A Kongsberg EM2040 multibeam echosounder aboard the R/Vs *Celtic Voyager* and *Keary*, and a Kongsberg EM1002 on the R/V *Celtic Explorer* were used to collect bathymetry and backscatter data.
- The raw sonar soundings were processed to create 2D and 3D bathymetric and backscatter classification surfaces using CARIS HIPS and SIPS 9.0 software.
- Onshore and offshore joint, fault, and fold data were collected using ArcGIS 10.3 using the ESRI World Imagery Basemap and the Geologic Survey of Ireland 1:100k Geologic Basement shapefile.
- Joint data were plotted in rose diagrams using Stereonet 9 software.
- A proposed offshore geologic map showing first order folds, faults, and basement rock type was created in ArcGis 10.3 based on merged data from the study.

DATA COLLECTION

FIGURE 6 (below): ArcGIS image showing onshore and offshore joint lineaments along which measurements were taken. Lineament color indicates the different formations studied: orange= Sherkin, red=Castlehaven, and green=Toehead Formations.



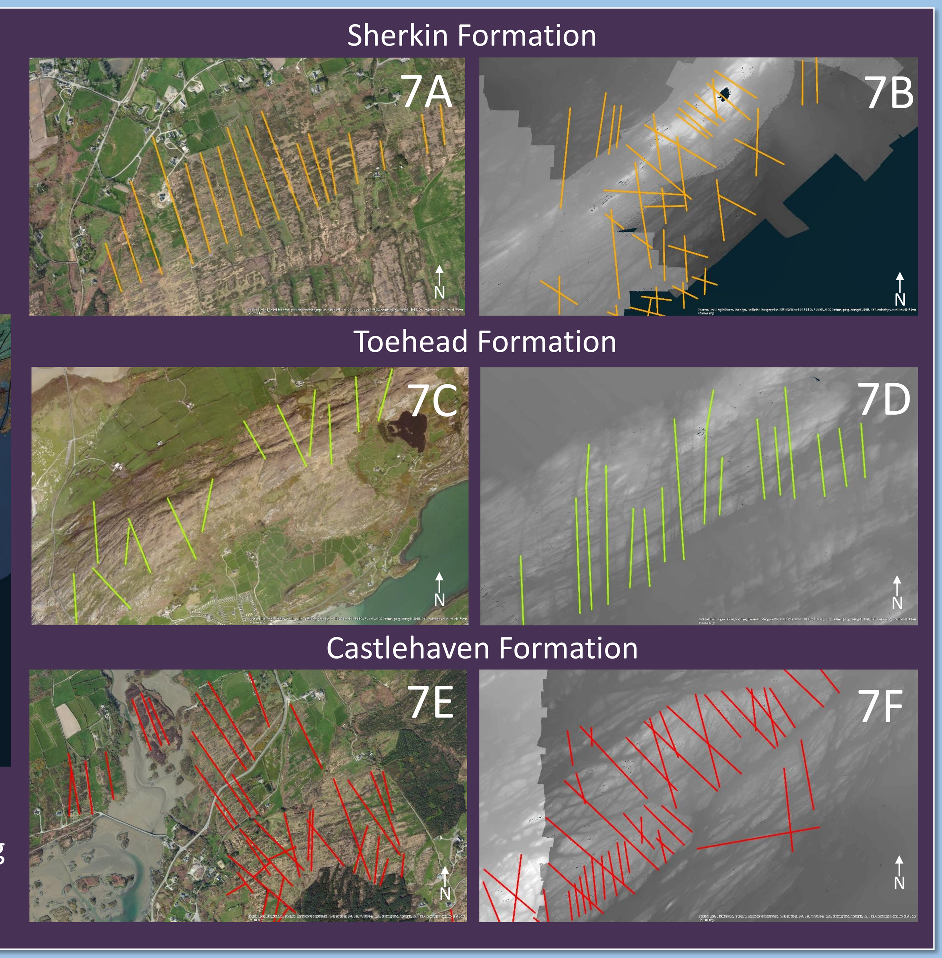
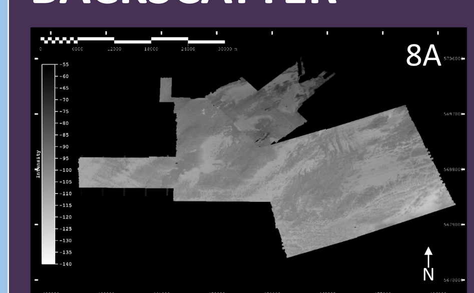


FIGURE 7, A-F (right): Lineaments for each formation showing how onshore and offshore length and heading measurements were taken.

BACKSCATTER



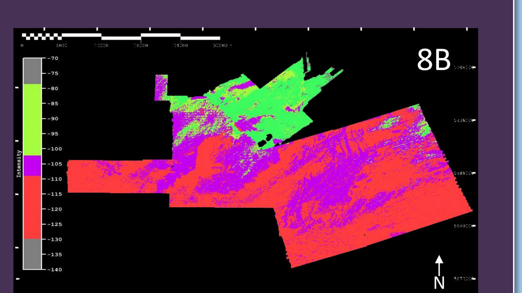
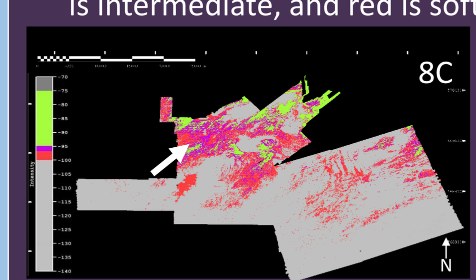
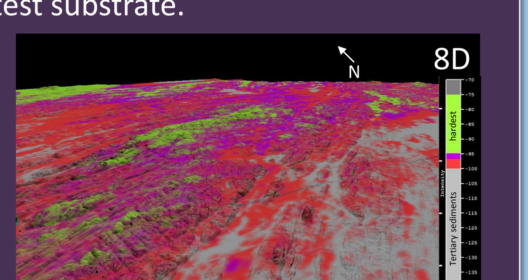


FIGURE 8, A-D:

a) Backscatter intensity across entire BASE surface (backscatter was not collected during the 2006 cruise).
b) Relative substrate hardness classification. Green is hardest, purple is intermediate, and red is softest substrate.





c) Relative hardness of substrate across study area with Quaternary sediments excluded (gray). Arrow indicates image 8D view direction.
d) Northeast facing oblique 3D classified backscatter drape image (VE=2x) showing harder substrate (colors) in the anticline.

RESULTS

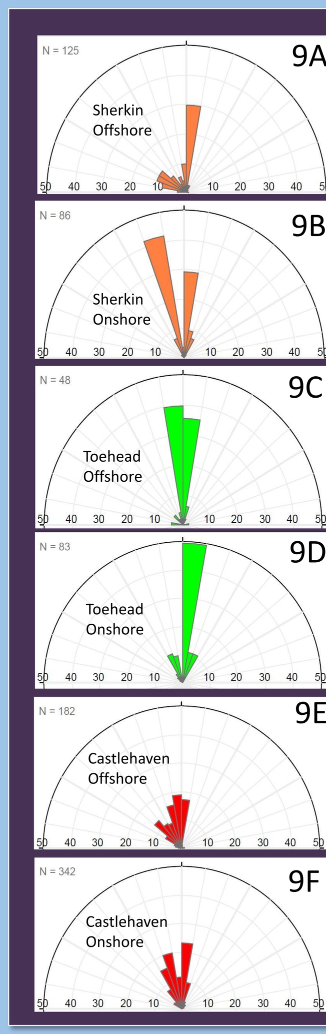
- First, second, and third order folds and faults are measureable on the bathymetric surfaces (Fig. 3 A-E).
- Angle between different joint sets and bedding ranged from ~90° to ~40-80° (Fig. 4).
- Offshore joints were visible in the bathymetry and were significantly longer than onshore joints (Figs. 6, 7 A-F, & 9 J-L)
- Shallower outcrops with the highest intensity backscatter return displayed visible structural features, while deeper surrounding areas with a lower return had a homogenous surface (Fig. 8 A-D).
- Relationships were found between onshore and offshore basement rock type, joint heading, and preservation level (Figs. 5 & 9 A-L).

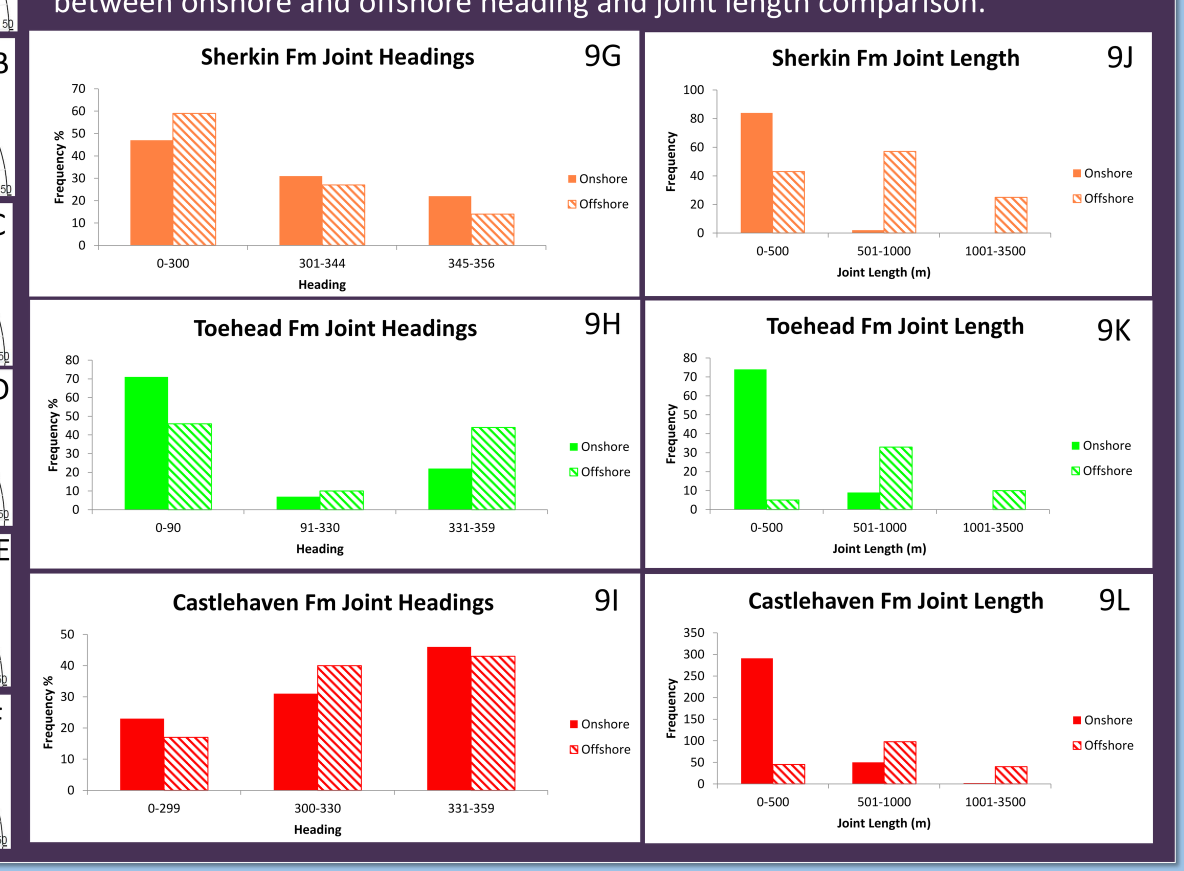
DISCUSSION

Geologic maps are a useful tool for understanding a region's climatic and geologic past; however, offshore structural analysis has previously been nearly impossible due to bedrock inaccessibility. Study results indicate that bathymetric surveys using high resolution sonar provide sufficient data for offshore structural analysis through rock type identification and feature correlation. Where quaternary sediment has not been deposited, offshore rock fractures were better preserved than onshore equivalents, making them easier to identify (Fig. 9 J-L). Patterns between joint heading, bedrock preservation extent, and folds onshore can be correlated with offshore features to identify rock type and fold propagation consistent with the region's geologic past (Bresser and Walter, 1999; Fig. 5, 9 A-I). Relative age of structural features can also be determined in bathymetry using the Law of Cross-Cutting Relationships (Fig. 4). Coring and further research from future surveys would ground truth and increase the accuracy of bathymetric structural analysis.

JOINT DATA

FIGURE 9. A-F: Rose diagrams (left) showing dominant onshore and offshore joint orientation. **G-I:** Frequency distribution graphs (below) showing correlation between onshore and offshore heading and joint length comparison.





ACKNOWLEDGEMENTS

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