The evolution of shallow crustal structures in early rift-transform interaction: a case study in the northern Gulf of California.

Georgios-Pavlos Farangitakis[1], Jeroen van Hunen[1], Lara M. Kalnins[2], Patricia Persaud[3], Kenneth J.W. McCaffrey[1]
1 Department of Earth Sciences, Durham University, Science Site, Durham, DH1 3LE, UK georgios-pavlos.farangitakis@durham.ac.uk, jeroen.van-hunen@durham.ac.uk, k.j.w.mccaffrey@durham.ac.uk 2 School of GeoSciences, University of Edinburgh, The King's Buildings, Edinburgh, EH9 3FE, UK lara.kalnins@ed.ac.uk
3 Louisiana State University, Department of Geology and Geophysics, E235 Howe-Russell-Kniffen, Baton Rouge, LA 70803, United Statesppersaud@lsu.edu

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1. Introduction

The Gulf of California is a transtensional boundary between the Pacific and N. American plates with nearly all of the plate motion accommodated by a series of en-echelon dextral transform faults and rift segments. Here, we delineate the tectonic configuration in the northern Gulf of California which can provide insight into the early history of mature now-inactive transform margins. Plate motion is distributed in a pull-apart structure located between the Cerro Prieto Fault (CPF) in the NE and the Ballenas Transform Fault Zone (BTFZ) in the SW (**Figure 1**). The northern Gulf transforms strike at a 7-9º more northern angle to the general transform strike in the southern Gulf (Lonsdale 1989). A plate rearrangement occurred at 2Ma with rifting migrating from the Tiburon basin to its current location in the N. Gulf. (Seiler *et al.* 2009). Previous structural interpretations include: (**Figure 1**):

- Lonsdale (1989) and Axen (1995): continuous succession of NW transforms and NE rifts similar to southern segments but inconsistent with bathymetry (**Figure 1A**) .
- Fenby and Gastil (1991) and Reed *et al.* (2005): N-S trending rift segment in the northern part of the N. Gulf where the Consag and Wagner basins are located but don't meet plate motion vector constraints (**Figure 1B**).
- Nagy and Stock (2000): N to NNW striking faults inherited from earlier extension accommodating plate boundary deformation with dextral-oblique slip (**Figure 1C**).
- Finally, along with previous structural interpretations (Persaud *et al.* 2003, Martin-Barajas *et al.* 2013), we propose an updated version of the model proposed by Nagy and Stock (2000) with the northernmost N. Gulf extension being accommodated by a series of dextral oblique faults which define the Wagner and Consag basins (**Figure 1D**).

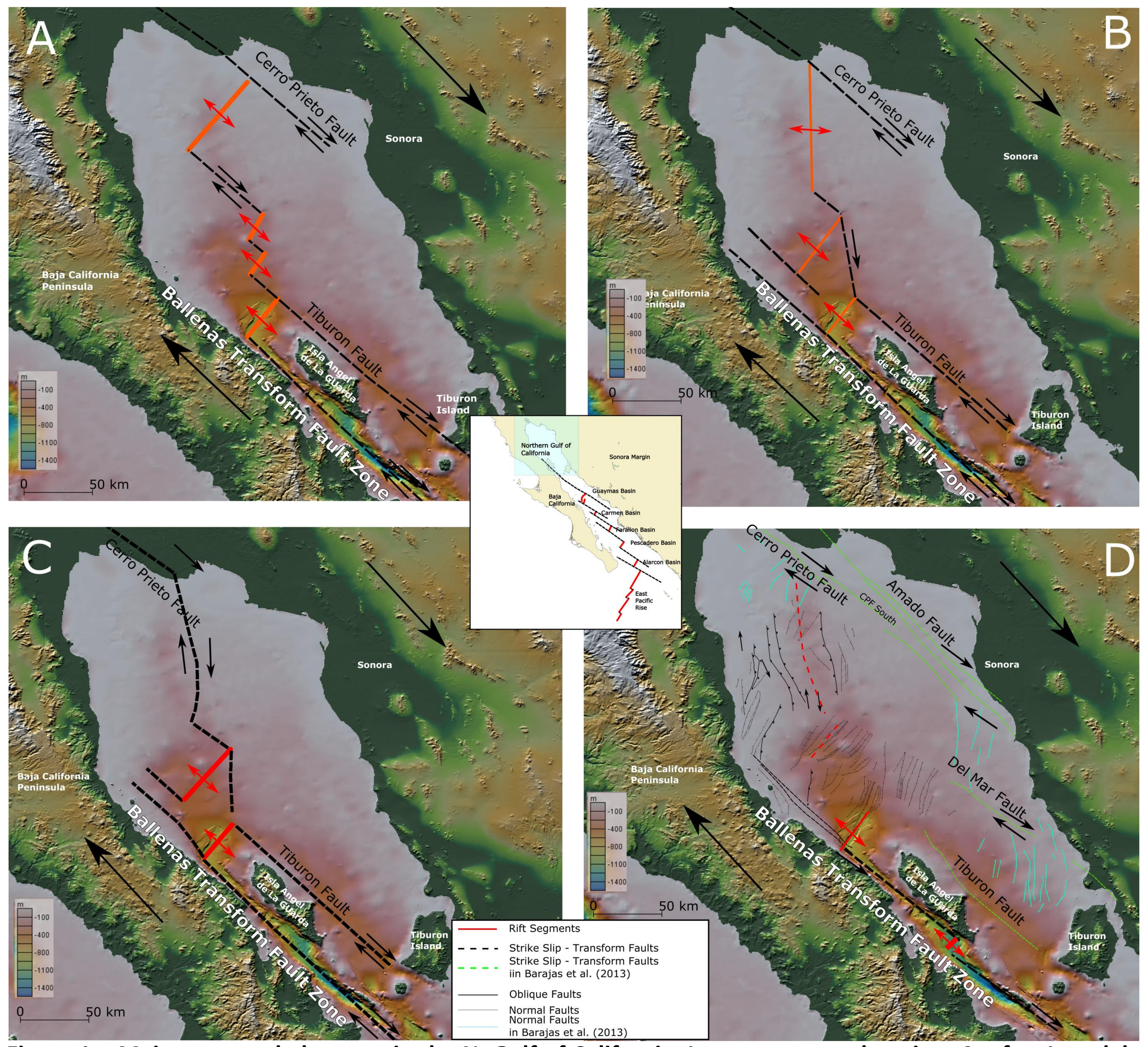

Figure 1 – Main structural elements in the N. Gulf of California. Inset map: area location. A: after Lonsdale (1989) and Axen (1995); B: after Fenby and Gastil (1991) and Reed *et al.* (2005) ; C: after Nagy and Stock (2000); D: This work (red and black faults) combined with Martin-Barajas *et al.* 2013 (faults in blue and green). Bathymetry from GMRT Grid Version 3.3.

2. Methodology

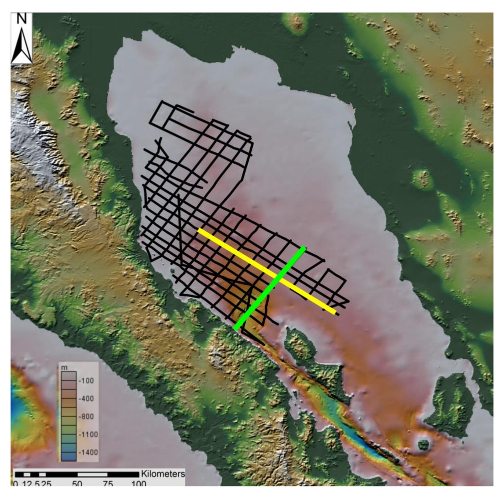

Figure 2 – UL9905 high res MCS survey location. Green line: line 64 in Figure 4. Yellow line: line 25 in Figure 4. Bathymetry from GMRT Grid Version 3.3.

- First 3D analysis of the seismic stratigraphy of the UL9905 high res reflection seismic dataset acquired by LDEO, Caltech, and CICESE. The data were acquired with a 48 channel, 600 m streamer, at a sampling interval of 1 ms (shot spacing of 12.5 or 25 m) and were recorded for 2-3 s. (Stock *et al.* 2015, **Figure 2**).
- Seismic unconformities or characteristic reflectors are interpreted as seismic horizons and produce time thickness maps.
- Faults from each line are correlated in 3D fault panels.
- We analyse the marine gravity data of Sandwell *et al.* (2014, V 24.1) using the method of Phethean *et al.* (2016) to highlight lineaments of a certain strike based on band-pass filtering and directional derivatives. This enhances the portion of the gravity field associated with spreading centres or transforms.

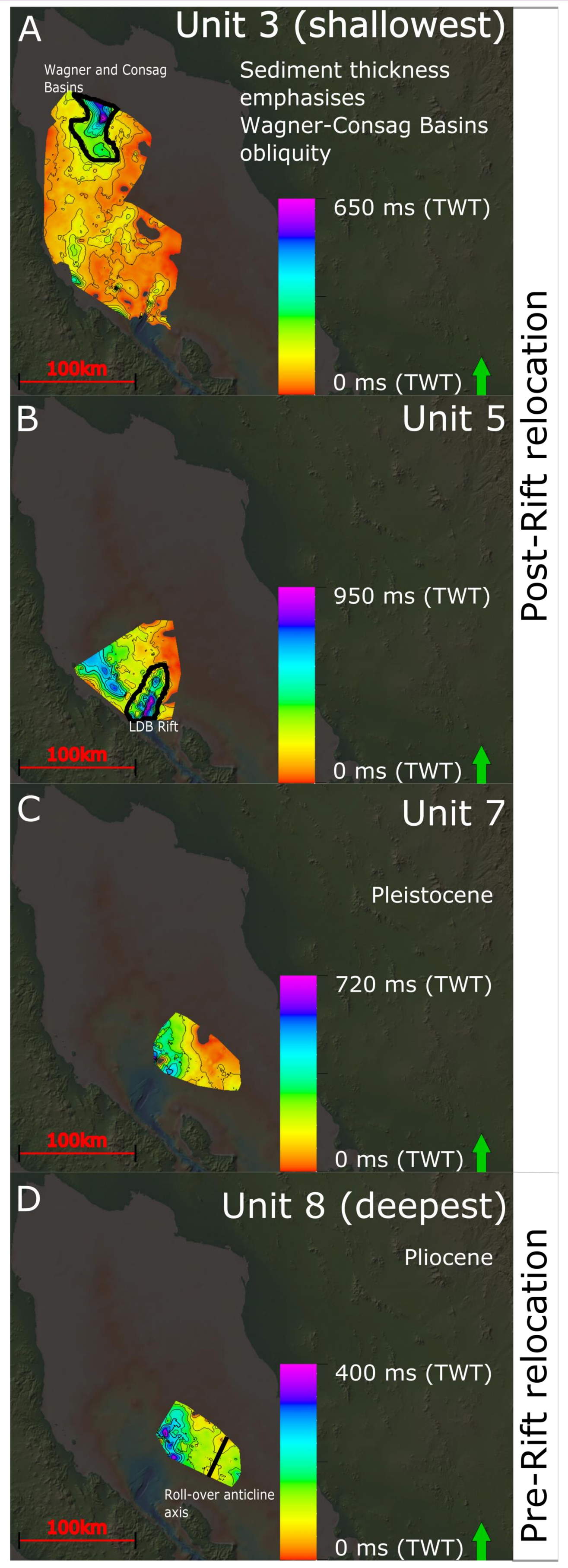

Figure 3 – Time thickness maps of the identified units (in TWT ms). Contours every 50 ms. Ages from Martin-Barajas *et al.* (2013). Bathymetry from GMRT Grid Version 3.3. Green arrow indicates North.

3. Results & Interpretation: Seismic Data

We correlate six different stratigraphic units through the seismic dataset. These new time thickness maps allow us to view the deformation in 3D and examine the interaction between tectonics and sedimentation in detail. Unit 8, the deepest, corresponds to the top Pliocene (as interpreted from Martin-Barajas *et al.* 2013) and shows no thickness change related to the current extensional regime. However, it shows signs of thickening to the SE, which corresponds to the older abandoned Tiburon spreading centre (**Figure 3D**). This indicates that the units above are the ones which have been affected from the rift relocation. Unit 7 (**Figure 3C**) marks the onset of subsidence in the Delfin Basins due to the rift relocation. Units 8-6 appear to be uplifted and eroded over a roll-over anticline formed over a broad extensional zone (**Figures 3C-D,4,5**) (interpreted as the Angel de la Guarda detachment in Martin-Barajas *et al.* 2013).

Units 6 and 5 display the greatest thickness changes within the extensional basins and indicate active and rapid sedimentation during rifting (**Figure 3B**). Finally, the shallowest unit (Unit 3) appears to highlight the oblique morphology in the Wagner and Consag basins through the sigmoidal nature of its thickest part in the north indicating the presence of the dextral oblique basin boundary faults on its margins (**Figure 3A**).

Through the 3D fault correlation process we (**Figure 5**):

- Identify a horsetail structure in the northernmost part of the BTFZ as evidenced by the numerous small SW-NE trending extensional faults in that area.
- Highlight the oblique boundary faults that define the Wagner and Consag Basins and distribute the extension in the northernmost part of the N. Gulf (previously identified by Martin-Barajas *et al.* 2013).
- Highlight the two rift segments in the Upper and Lower Delfin Basins (previously identified by Persaud *et al.* 2003).
- Identify the potential location of a strike slip fault that connects the Upper and Lower Delfin Basin rift segments, not seen in the data but justifiable by the diffraction in the termination of faults in the Upper Delfin Basin.
- Identify a wide ESE dipping extensional fault zone (in the same location as the Angel de la Guarda detachment in Martin-Barajas *et al.* 2013) with an overlying roll-over antiform.

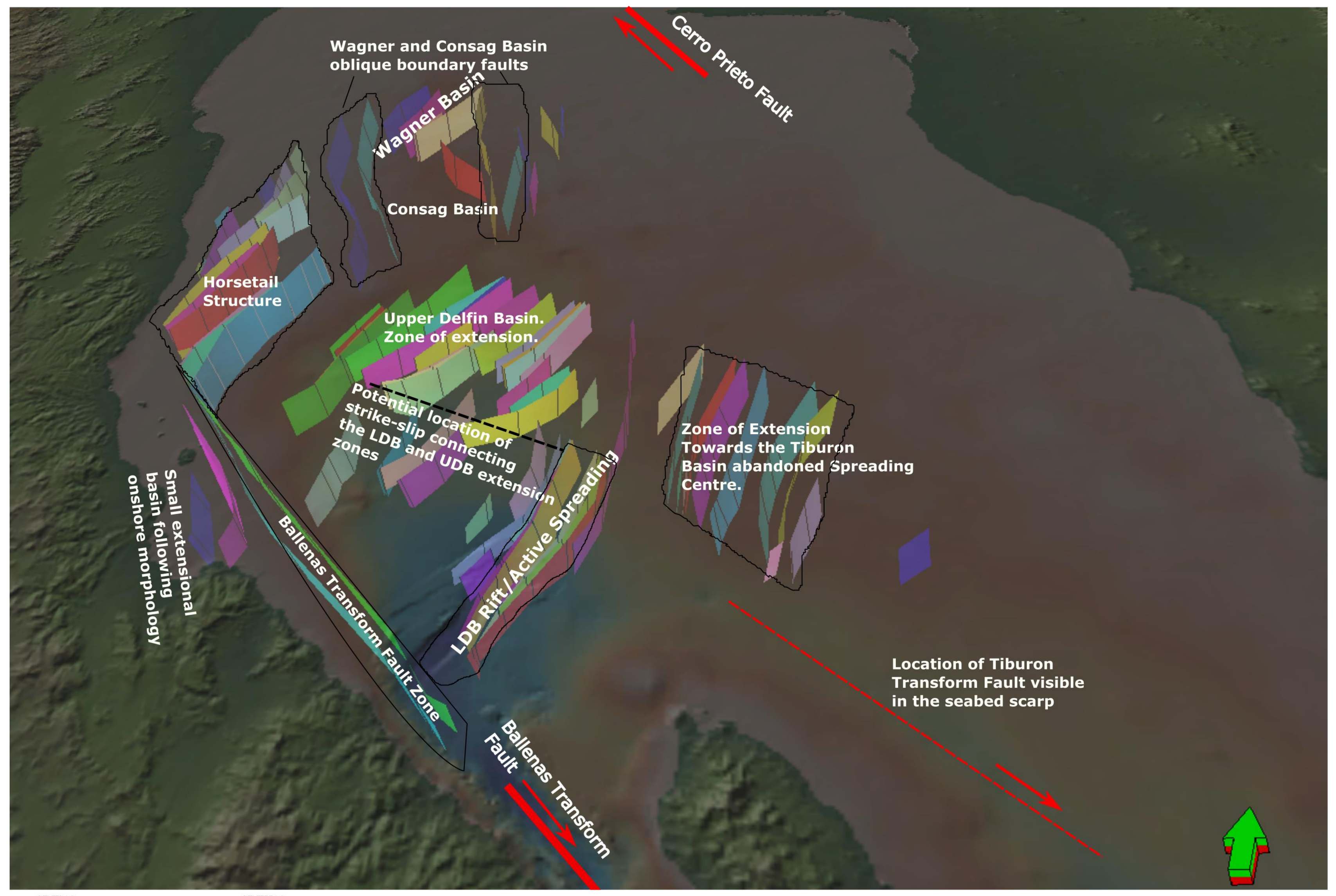

Figure 5 – 3D representation of the structural configuration of the N. Gulf with the interpretations from the UL9905 dataset. Location of CPF and BTF is inferred from Persaud et al. (2003), bathymetry from GMRT Grid Version 3.3

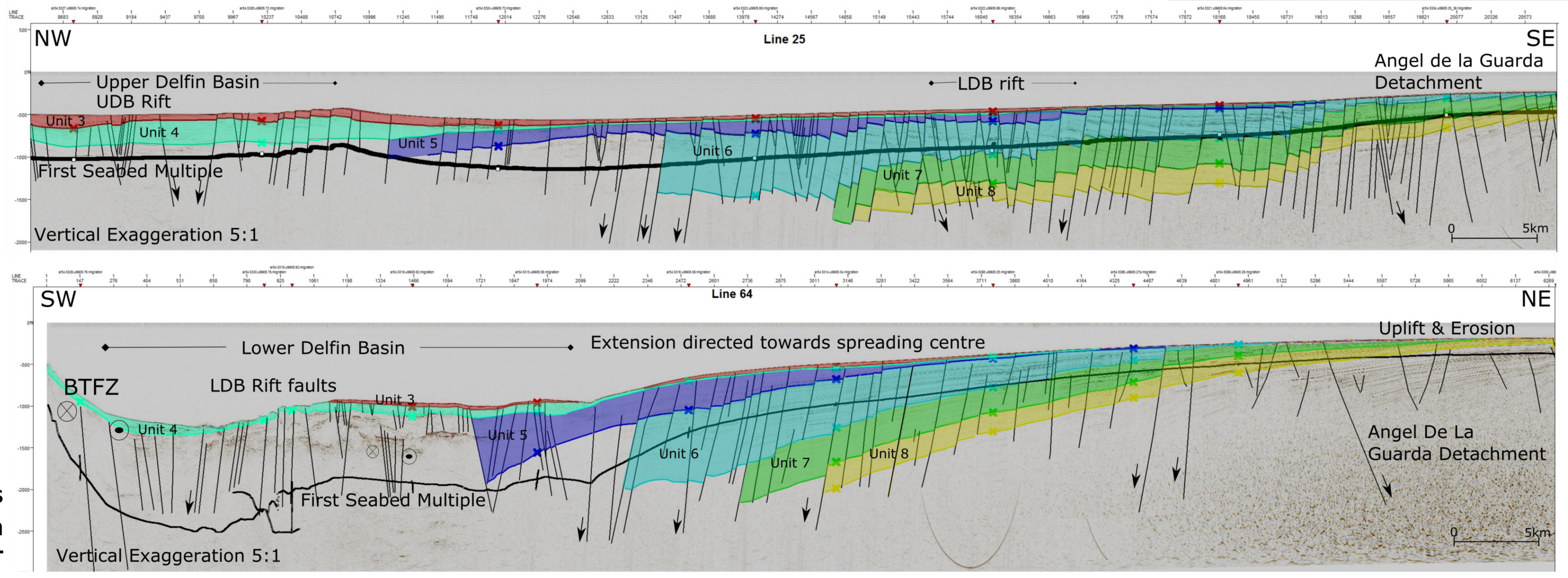

Figure 4 – Interpretation of lines 25 & 64 (Z axis in ms TWT). Vertical exaggeration ratio is 5:1. Location of seismic lines shown in Figure 2.

4. Results & Interpretation: Gravity Data

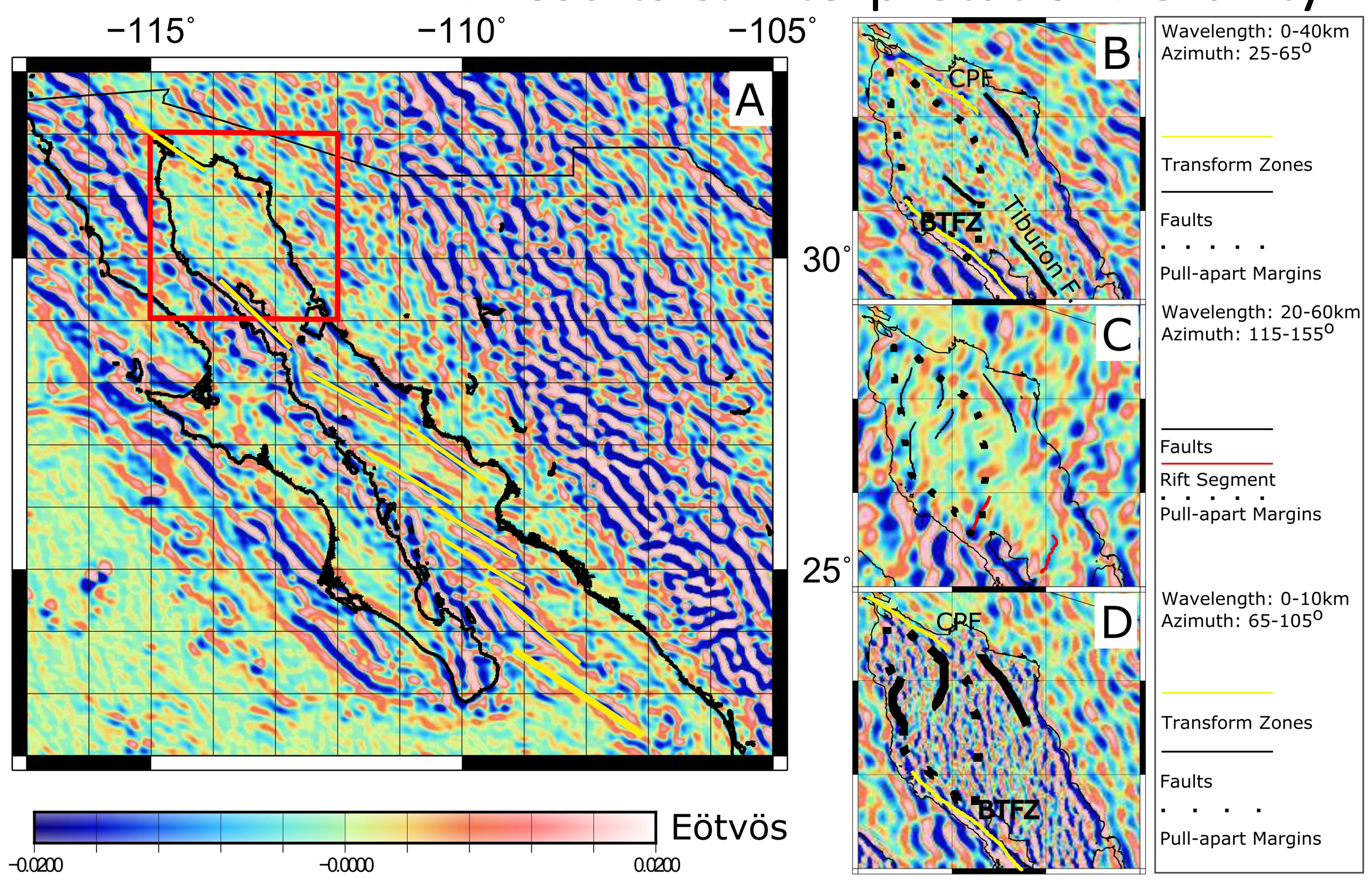

Figure 6 – A: Gulf of California directional gravity gradient map, red box indicates location of N. Gulf maps. Right: (B-D) highlighted features in the N. Gulf using various band-pass filters.

We use a 20-60 km band-pass filter for azimuths between 25-65º to highlight strong negative gravity gradient zones that correspond to the Gulf transforms (**Figure 6A**). There is a clear difference in the nature of the gravity gradient between the southern and northern parts of the Gulf, with the southern transforms having very high negative values surrounded by high positive values. For the N. Gulf we impose a variety of different band-pass filters and directional derivatives to highlight different features (**Figure 6 B-D**). Thus, we identify the following:

- Comparatively strong linear anomalies along the CPF, BTFZ and TF (**Figures 6 A,B,D**). A pattern of relatively strong alternating positive and negative dots can be seen in these locations in **Figure 6C**.
- Many of the stronger blue lineaments in **Figures 6C-D** correspond with mapped faulted segments.
- In **Figure 6B** there is a strong linear anomaly that may correspond to the inferred strike slip fault from the seismic analysis connecting the LDB and UDB.

5. Conclusions

- In the Wagner and Consag basins, extension is distributed obliquely through the basin-oblique dextral boundary faults. This is evidenced from the gravity gradient analysis, the time thickness maps and also supported from previous work (Persaud *et al.* 2003).
- The 7-9º angle between the strike of the northern gulf transforms the general strike of transforms in the southern Gulf of California may be one of the reasons for the delayed rupture in the N. Gulf resulting in the pull-apart structure observed.
- Fault planes in the Upper Delfin Basin indicate a diffraction in their edges. This could indicate the presence of a strike slip fault connecting the two rift segments.
- From the time thickness maps it appears that subsidence in the N. Gulf is dominated by the current structural configuration from the Plio-Pleistocene boundary and onwards.

Questions to be addressed in the future:

- Can analogue experiments modelling rift migration between two large transform faults reproduce the structure of the N. Gulf??
- Are these structural patterns visible in other inactive mature transform margins (such as the Ghana-Cote d'Ivoire Margin, the Exmouth Plateau, the Falklands Plateau) in a fossilised form?
- Can the clear distinction between the gravity gradients of the N. and S. Gulf act as a way to determine the type, timing and localisation of rifting in other margins?

6. References

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