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RESEARCH FOR GRAND CHALLENGES

GEOMAR

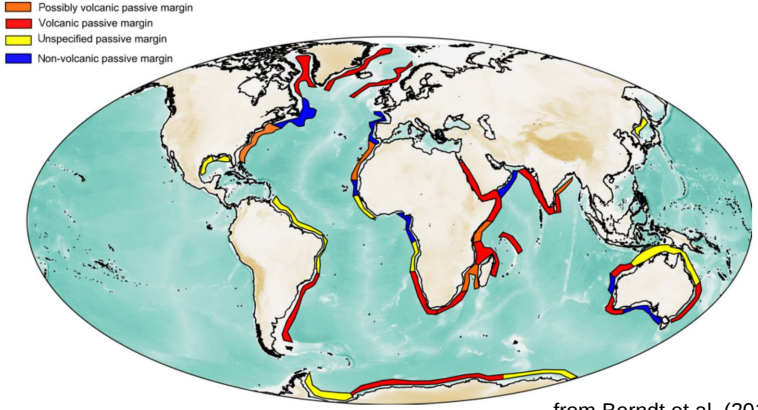
Integrated Geophysical Analysis of Passive Continental Margins

Insights into the Crustal Structure of the Namibian Margin from Magnetotelluric, Gravity, and Seismic Data

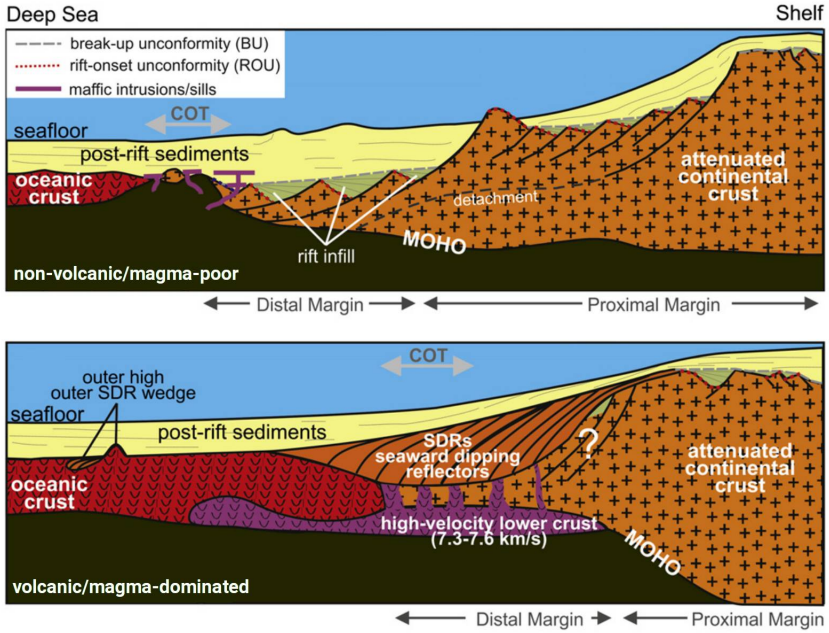
Gesa Franz
Supervisors: Marion Jegen, Max Moorkamp, Christian Berndt, Wolfgang Rabbel

Passive Continental Margins

- The tectonically inactive transition from continental to oceanic crust
- Differentiation between two end-member types volcanic & non-volcanic

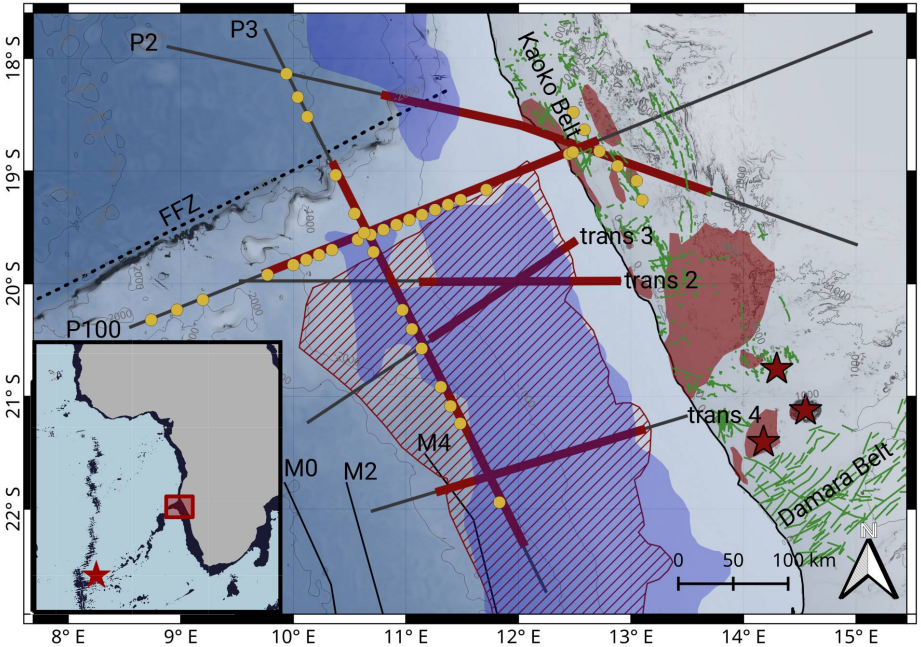


from Berndt et al. (2019)



Franke (2013)

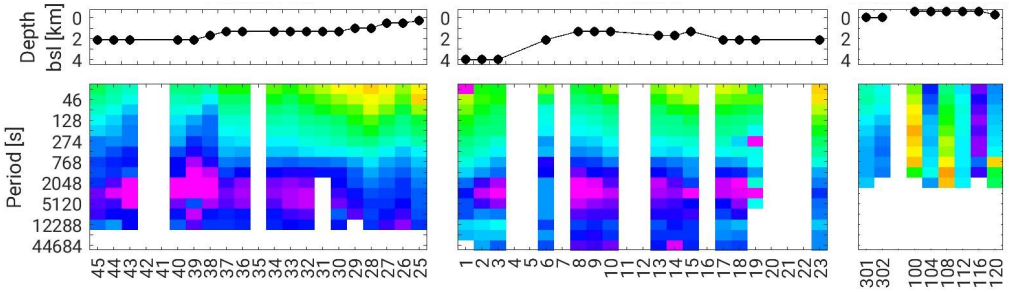
Namibian Passive Continental Margin

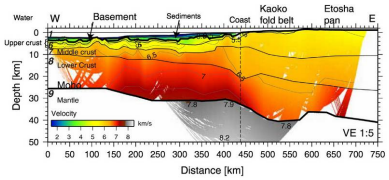


- SAMPLE project: South Atlantic Margin Processes and Links with Onshore Evolution

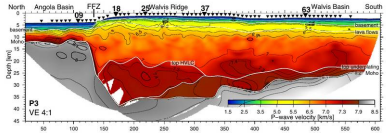
- MT stations
- high velocity magmatic underplating Fromm et al. (2015); Fromm, Jokat, Ryberg, et al. (2017) (profiles P100 and P2), Planert et al. (2017) (profile P3), and Gladczenko et al. (1998) (profiles trans 2 trans 4)
- seaward dipping reflectors (SDR) (Koopmann et al., 2016)
- Florianopolis fracture zone (FFZ)
- sediment cover thicker than 3 km, taken from Maystrenko et al. (2013)
- continental flood basalts, red stars mark the Brandberg, Messum, and Doros intrusive complexes (Owen-Smith et al., 2017; Teklay et al., 2020)
- magmatic dikes of the Kaoko and Damara belts (Salomon et al., 2017; Trumbull et al., 2004, respectively)
- Magnetic lineations M0 (125 Ma), M2 (127.5 Ma), M4 (130 Ma) are taken from Moulin et al. (2010)

Motivation & Objectives

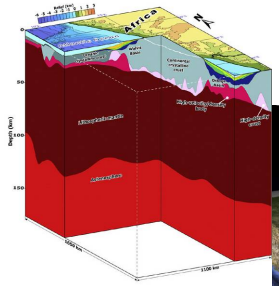




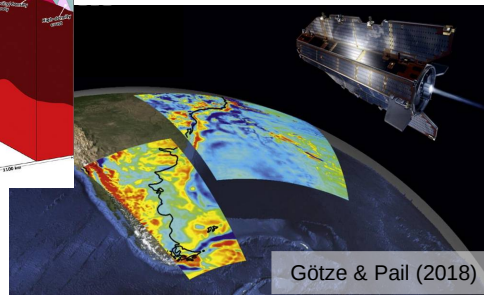
Fromm et al. (2017)



Planert et al. (2017)



Maystrenko et al. (2013)



Götze & Pail (2018)

- Improve electrical resistivity model from Namibian passive margin by integrated analysis and joint inversion
- Compare the effect of different types of constraints
- Derive parameter relationships from integrated analysis
- Link results to magmatic processes, margin formation history, geodynamic processes

Outline

First Part: Comparison of JI Results

- Improve electrical resistivity model from Namibian passive margin by integrated analysis and joint inversion
- Compare the effect of different types of constraints

Second Part: Unbiased Parameter Analysis

- Derive parameter relationships from integrated analysis
- Link results to magmatic processes, margin formation history, geodynamic processes

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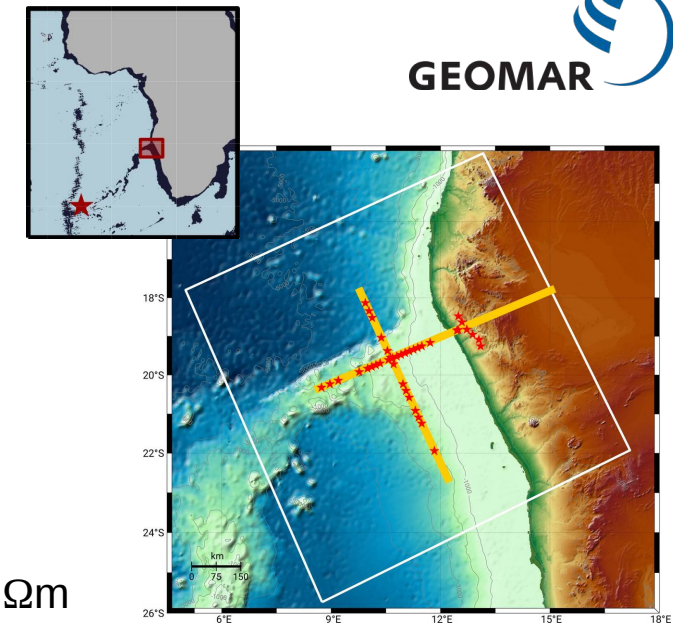
Part I: Comparison of Joint Inversion Results

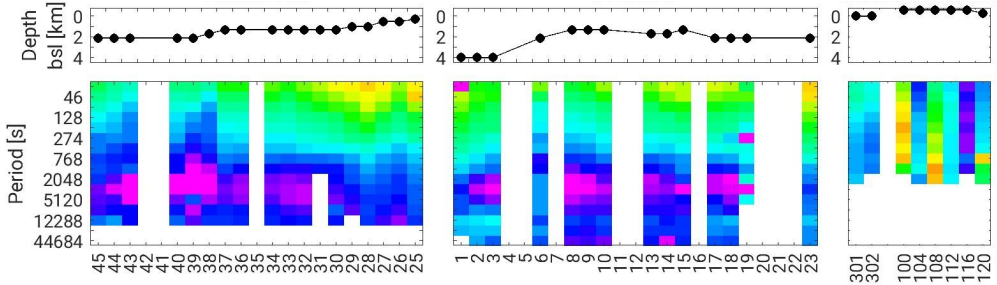
Franz, G., Moorkamp, M., Jegen, M., Berndt, C., & Rabbel, W. (2021). Comparison of Different Coupling Methods for Joint Inversion of Geophysical Data: A Case Study for the Namibian Continental Margin. Journal of Geophysical Research: Solid Earth, 126 (12), 1–28. doi:10.1029/2021jb022092

Magnetotelluric Data & Inversion

- 32 marine & 8 onshore stations

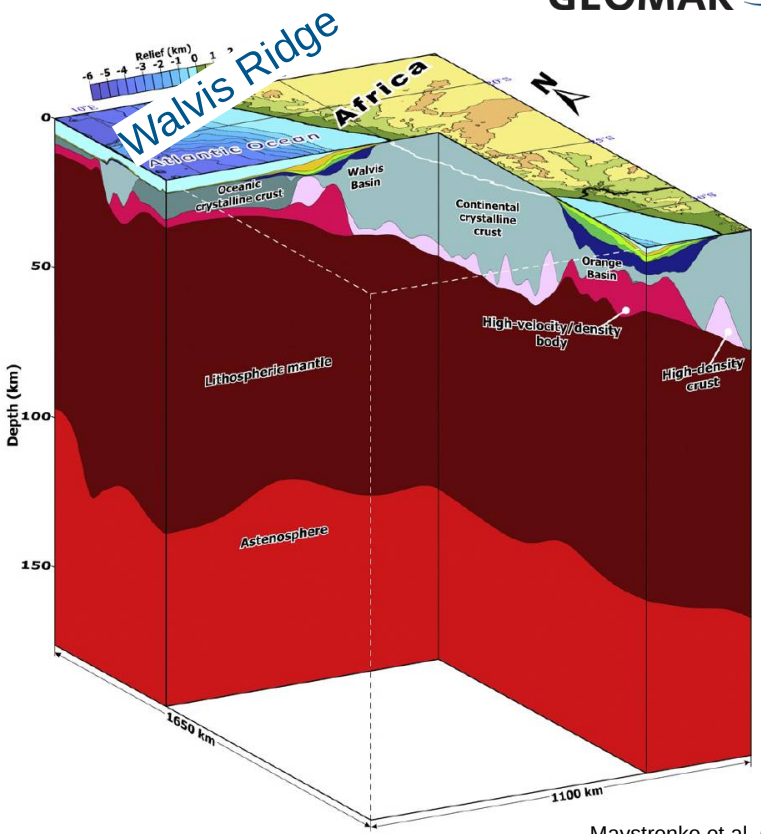


- 3D inversion on 10 km horizontal, and 300 m - 50 km vertical grid (96 × 96 × 34 cells)
- 16 periods ~30 – $5 \cdot 10^4$ s
- Starting Model includes bathymetry, sediment layer, 50 Ωm half-space



Density Constraint Model

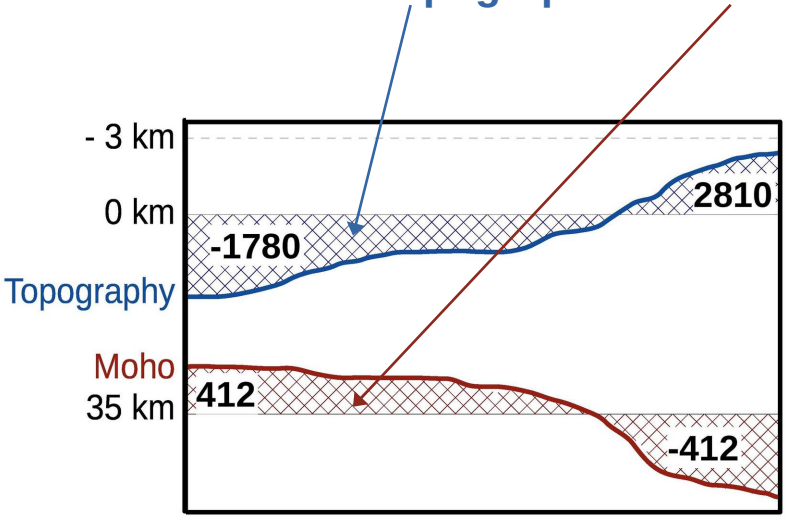
- Large scale 3D geological model
- Gravity forward modeling with 2D seismic constraints
- 10 layers & blocks of distinct density

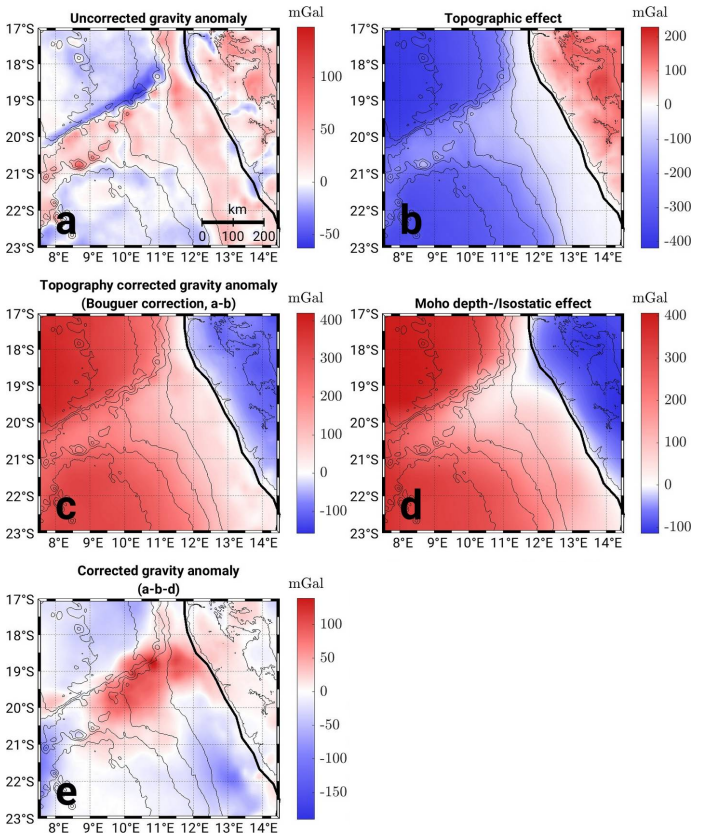


Maystrenko et al. (2013)

Gravity Data & Inversion

- EIGEN-6C4 gravity anomaly at 3000 m
- Correction of **topographic** & **isostatic effect**

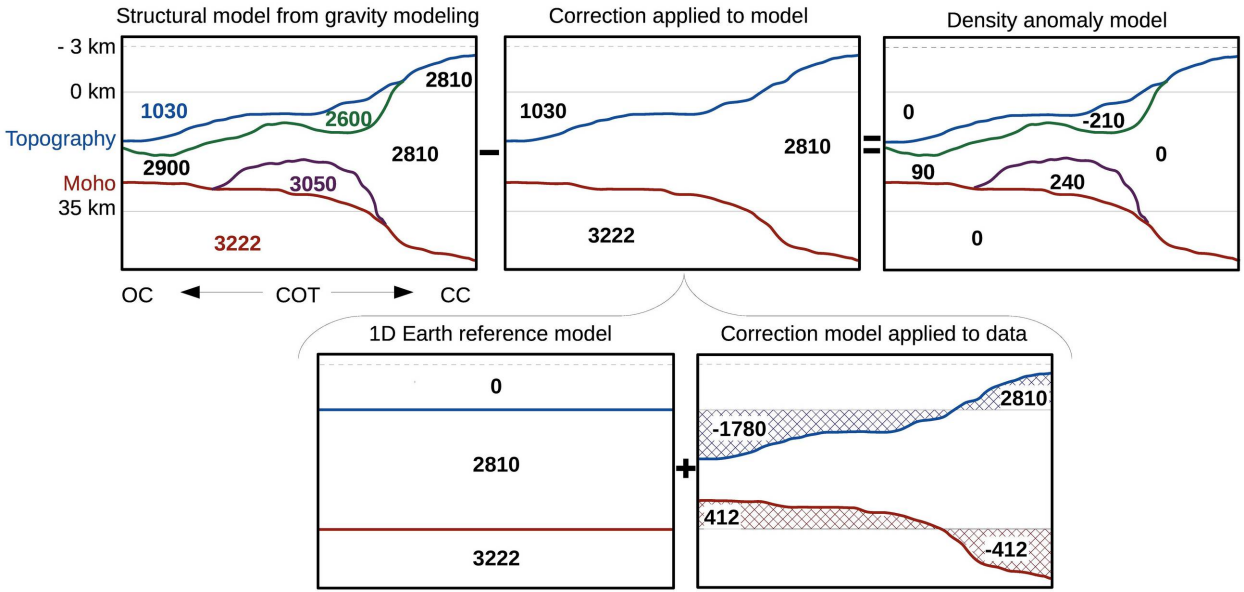


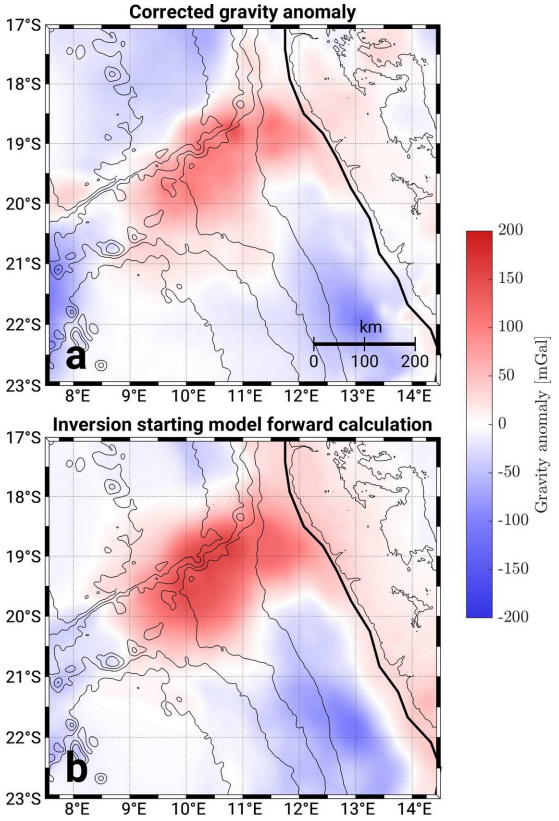


Satellite gravity data available from International Centre for Global Earth Models (ICGEM)

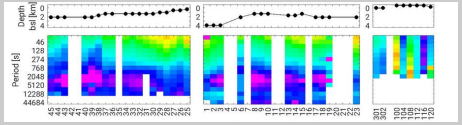
Gravity Data & Inversion

- Starting model creation





(Joint) Inversions

	Data	Cross-Model	Objective Function
MT-only			$\phi = w_{MT}\,\phi_{d_{MT}} + \lambda_{MT}\,\phi_{Reg_{MT}}$

All inversions performed with jif3D (Moorkamp et al., 2011) using cross-gradient coupling (Gallardo & Meju, 2003)

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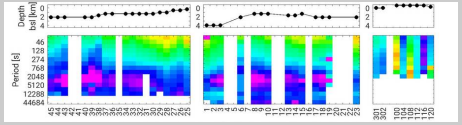
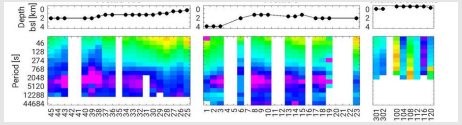
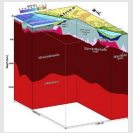
(Joint) Inversions

	Data	Cross-Model	Objective Function
MT-only			$\phi = w_{MT}\,\phi_{d_{MT}} + \lambda_{MT}\,\phi_{Reg_{MT}}$
JI1 (MT data inversion constrained with fixed model)			$\phi = w_{MT}\,\phi_{d_{MT}} + \lambda_{MT}\,\phi_{Reg_{MT}} + \kappa\,\phi_{Cross_{MT-dens}}$

All inversions performed with jif3D (Moorkamp et al., 2011) using cross-gradient coupling (Gallardo & Meju, 2003)

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(Join

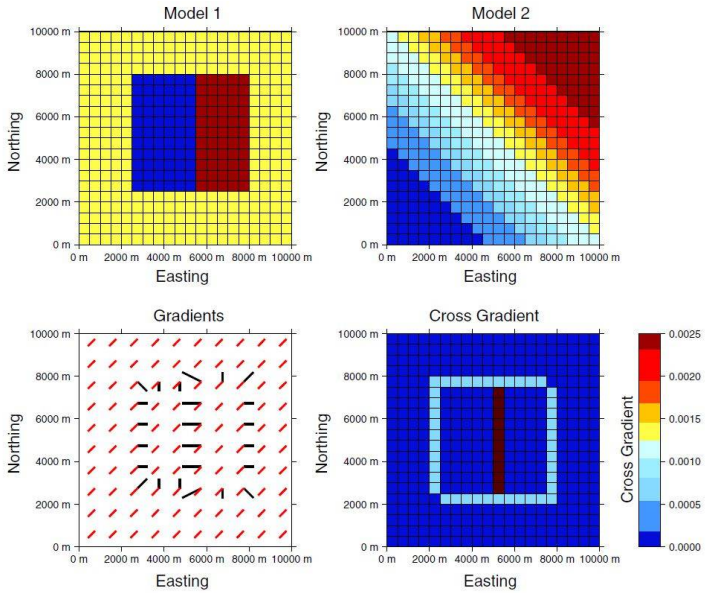
	unction
MT-only	eg_{MT}
JI1 (MT dat with fixed n	$g_{MT} + \kappa \phi_{Cross_{MT-dens}}$

Cross-Gradient coupling

$$\Phi_{Cross}(m) = (\nabla m_1 \times \nabla m_2)^T C_M^{-1} (\nabla m_1 \times \nabla m_2)$$

$$\nabla m_1 \times \nabla m_2 = \begin{pmatrix} \frac{\delta m_1}{\delta x} \\ \frac{\delta m_1}{\delta y} \\ \frac{\delta m_1}{\delta z} \end{pmatrix} \times \begin{pmatrix} \frac{\delta m_2}{\delta x} \\ \frac{\delta m_2}{\delta y} \\ \frac{\delta m_2}{\delta z} \end{pmatrix}$$

Gallardo & Meju (2003)



Moorkamp (2017)

All inversions performed with jif3D (Moorkamp et al., 2011) using cross-gradient coupling (Gallardo & Meju, 2003)

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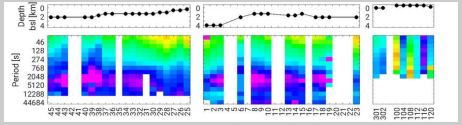
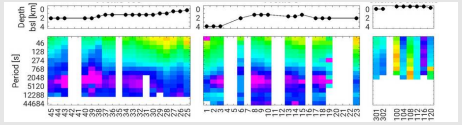
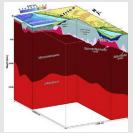
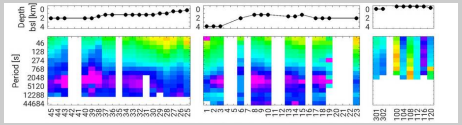
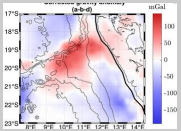
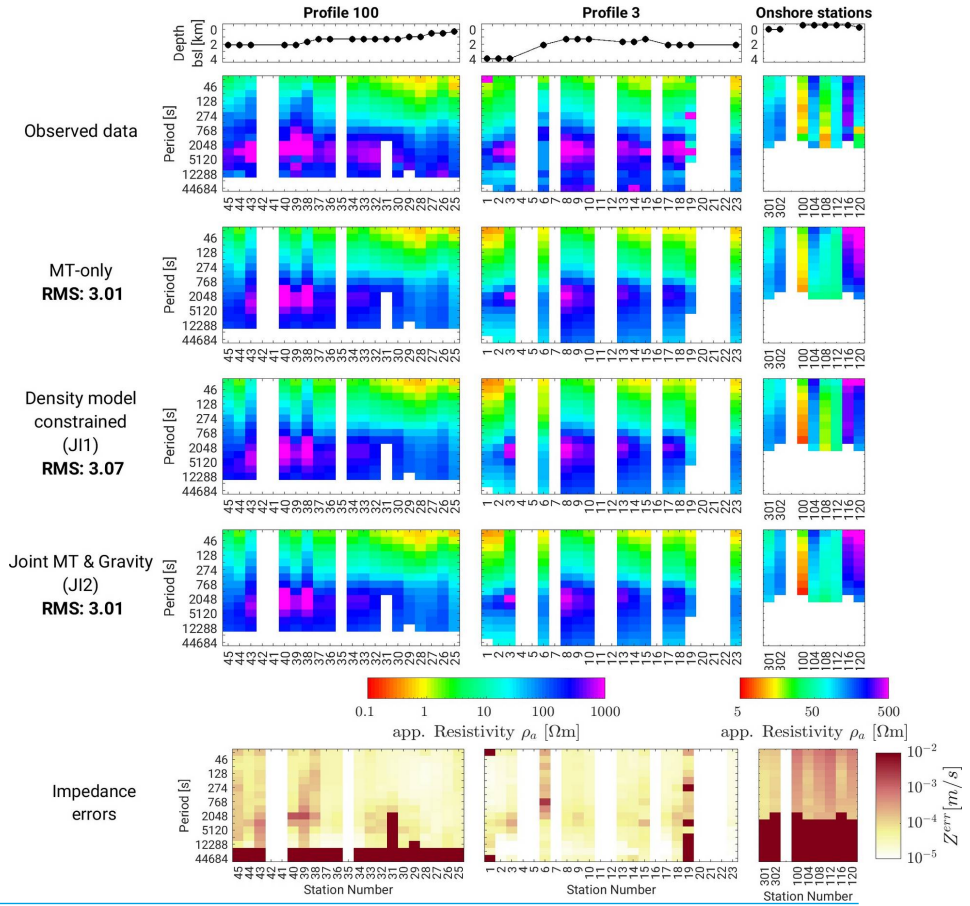
(Joint) Inversions

	Data	Cross-Model	Objective Function
MT-only			$\phi = w_{MT}\,\phi_{d_{MT}} + \lambda_{MT}\,\phi_{Reg_{MT}}$
JI1 (MT data inversion constrained with fixed model)			$\phi = w_{MT}\,\phi_{d_{MT}} + \lambda_{MT}\,\phi_{Reg_{MT}} + \kappa\,\phi_{Cross_{MT-dens}}$
JI2 (joint data inversion of MT and satellite gravity data)			$\phi = w_{MT}\,\phi_{d_{MT}} + w_{grav}\,\phi_{d_{grav}} + \lambda_{MT}\,\phi_{Reg_{MT}} + \lambda_{grav}\,\phi_{Reg_{grav}} + \kappa\,\phi_{Cross_{MT-grav}}$

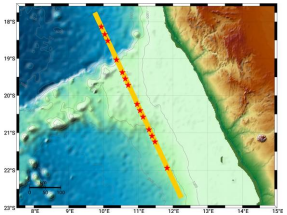
All inversions performed with jif3D (Moorkamp et al., 2011) using cross-gradient coupling (Gallardo & Meju, 2003)

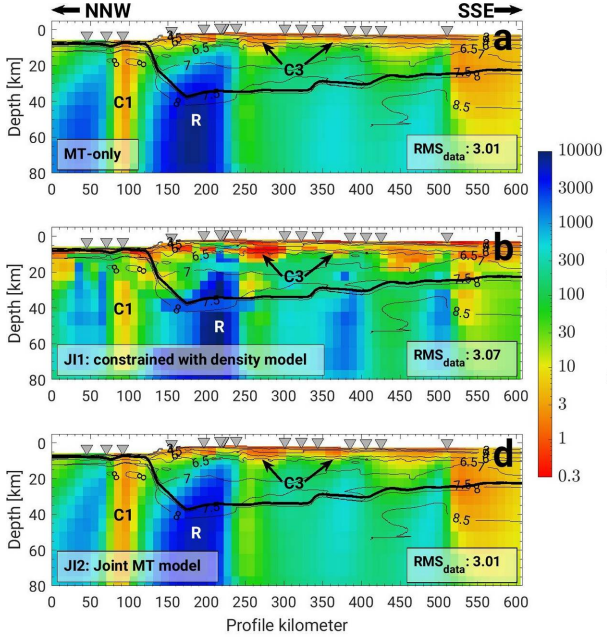
Comparison of data fit

- Data fits for MT-only, JI1, and JI2 are all very similar
- Onshore stations' fits are generally poorer

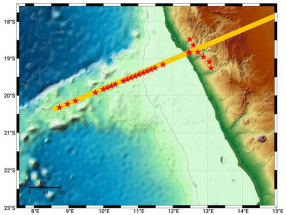


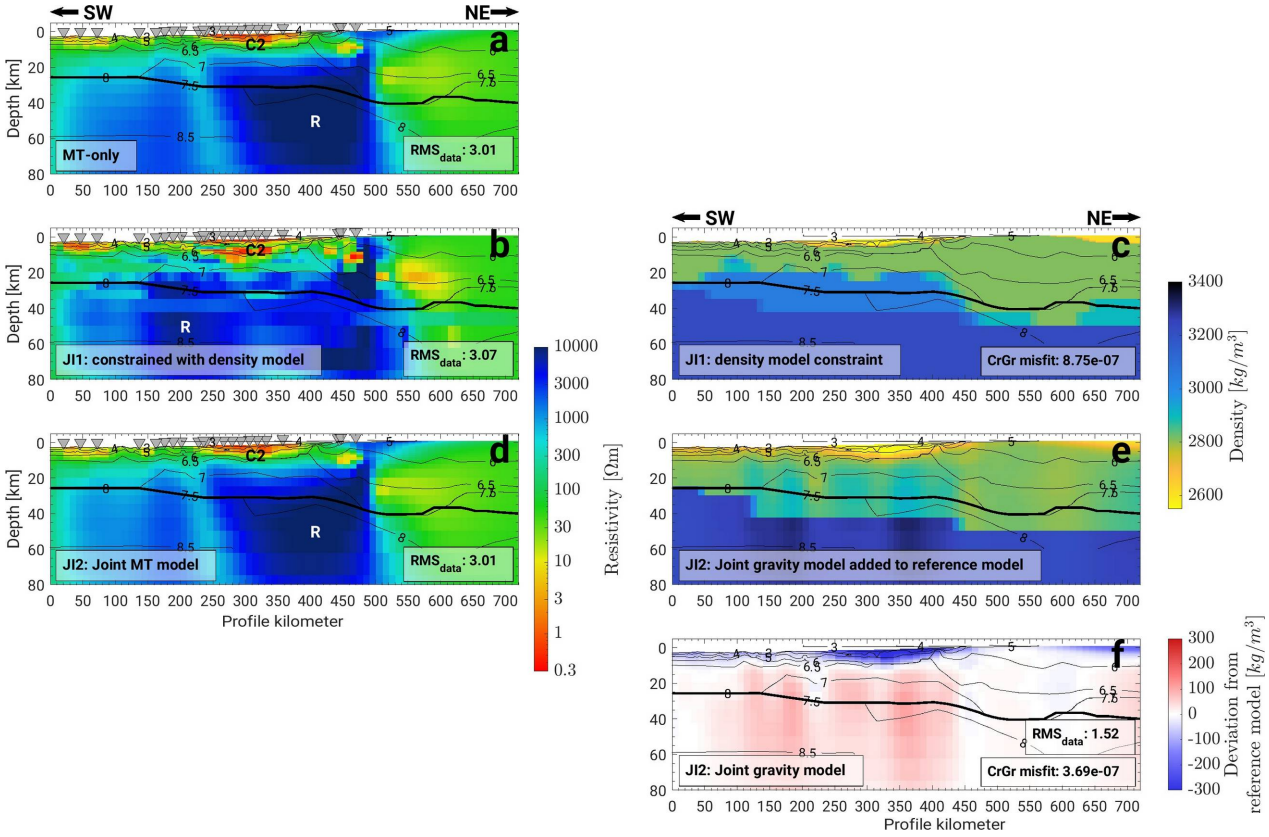
Model Comparison profile P3





Model Comparison profile P100





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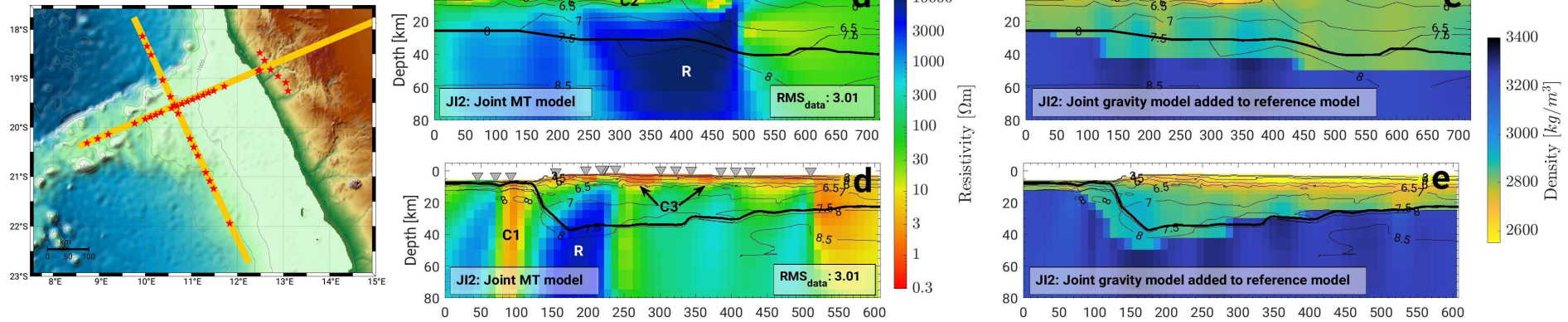
Part II: Unbiased Parameter Analysis

Franz, G., Jegen, M., Moorkamp, M., Berndt, C., & Rabbel, W. (2022). Formation and geophysical character of transitional crust at the passive continental margin around Walvis Ridge, Namibia. EGUsphere [preprint] . doi:10.5194/egusphere-2022-708 **(in Review)**

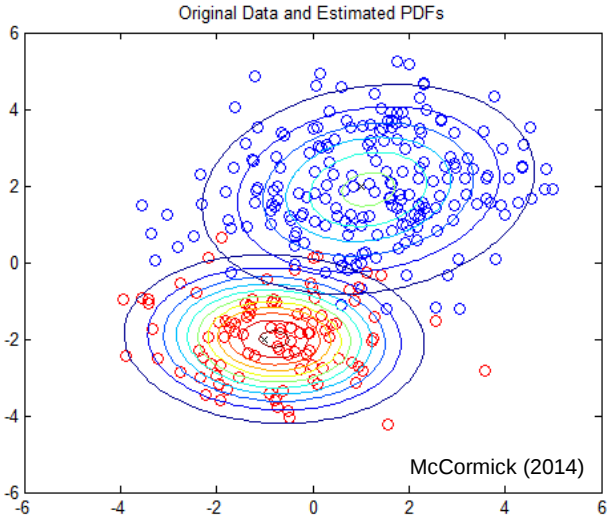
Input Models

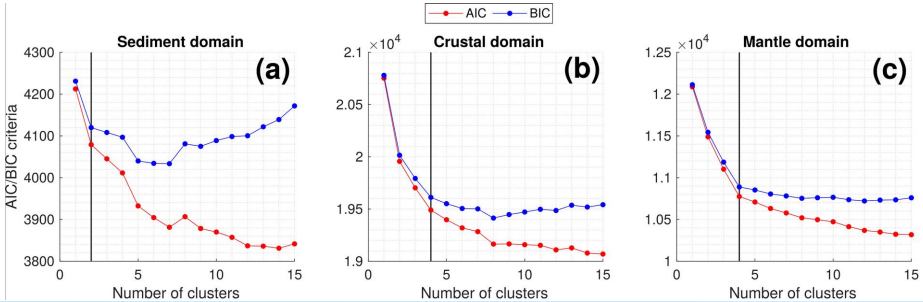
- Model cells with maximum horizontal distance of **10 km** to MT stations
- Absolute density values are density anomaly inversion output plus reference model



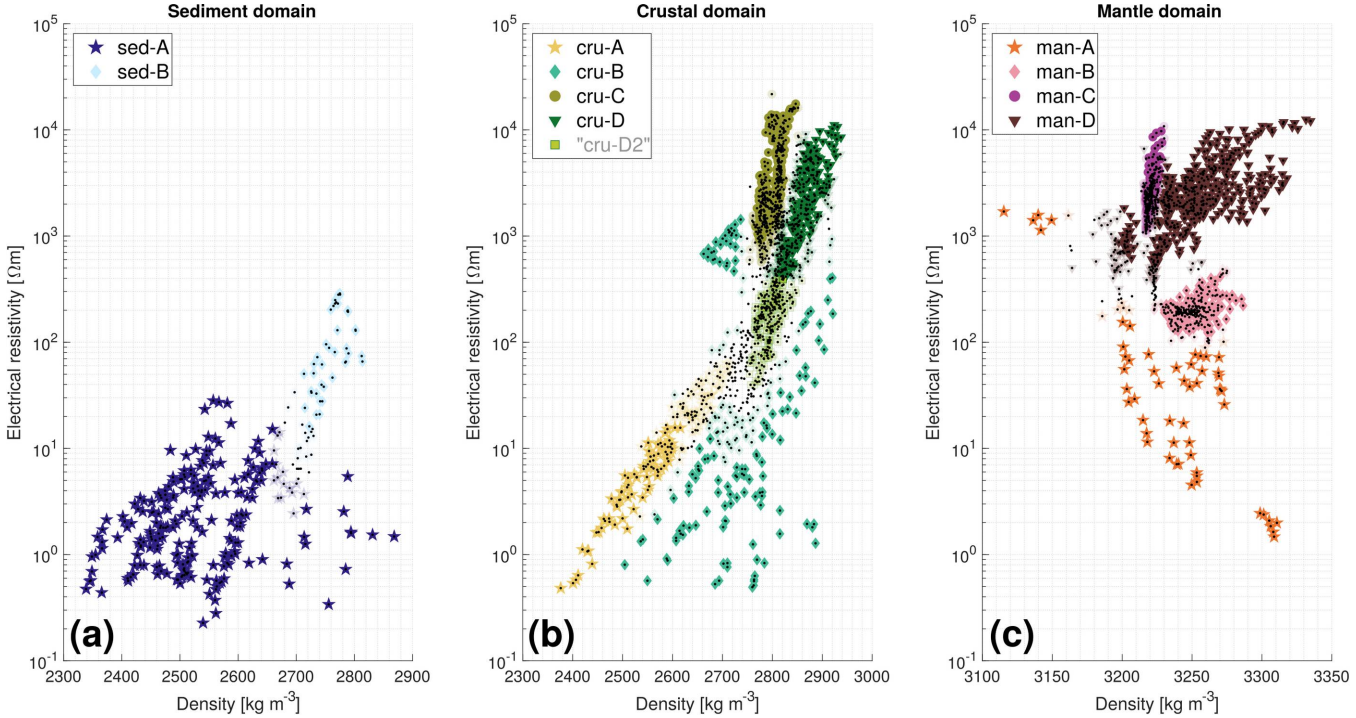
Gaussian Mixture Model Clustering

- Clusters are generated from Gaussian distributions
- Typically ellipsoidal shape
- Clusters can overlap
- Every data point is assigned to the cluster with the highest probability (measure for certainty)
- Needs number of clusters as input (theoretical information criteria AIC, BIC)



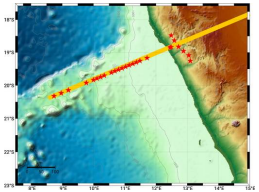


Identified Clusters and Distribution within Model

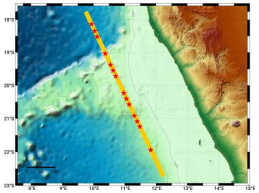


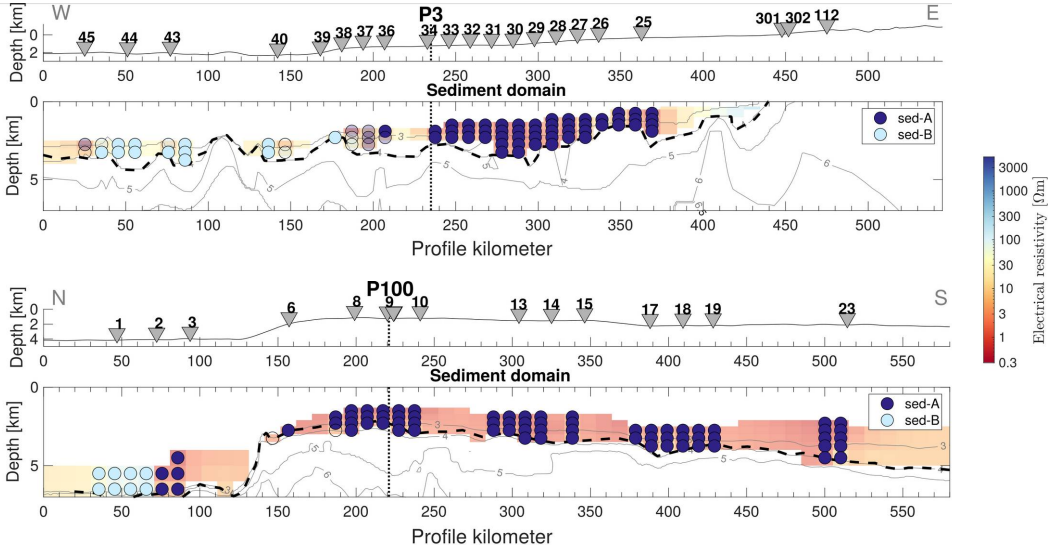
Identified Clusters and Distribution within Model

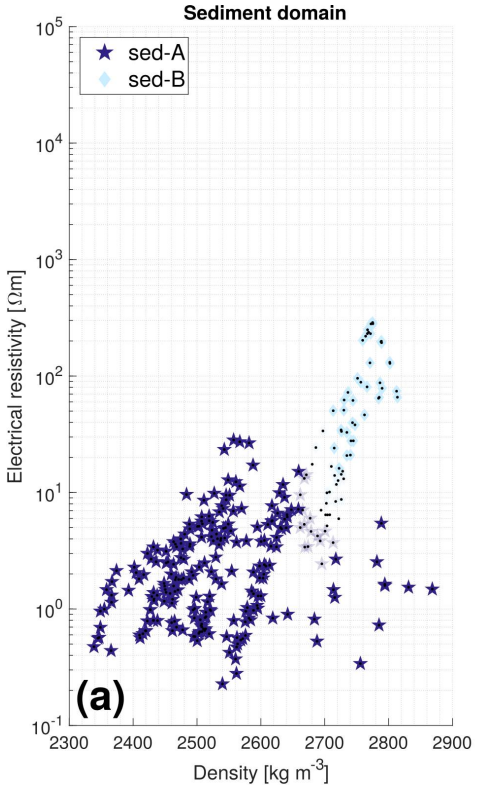
Profile P100



Profile P3

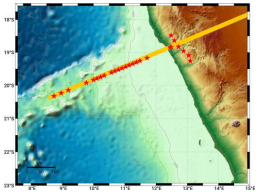




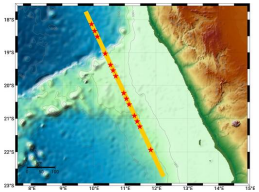


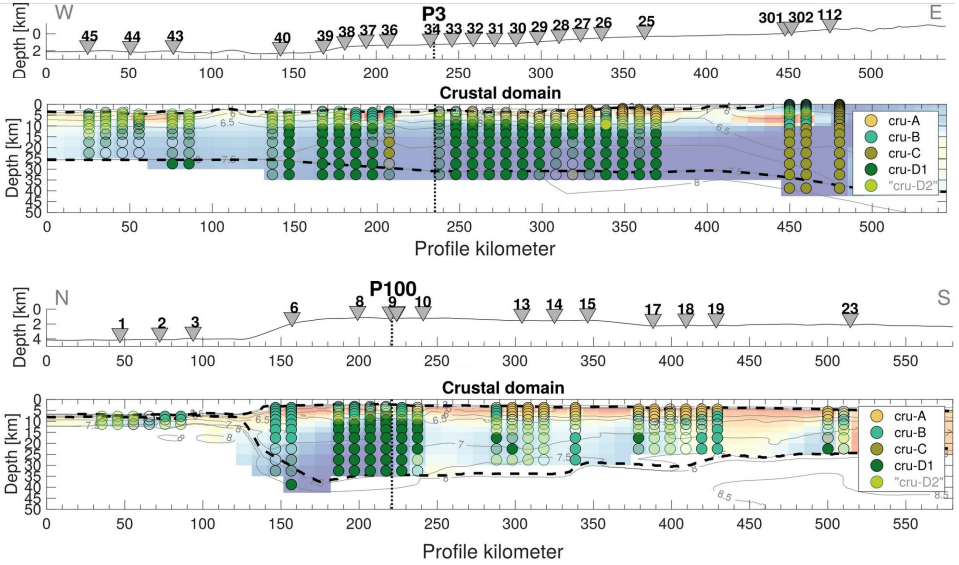
Identified Clusters and Distribution within Model

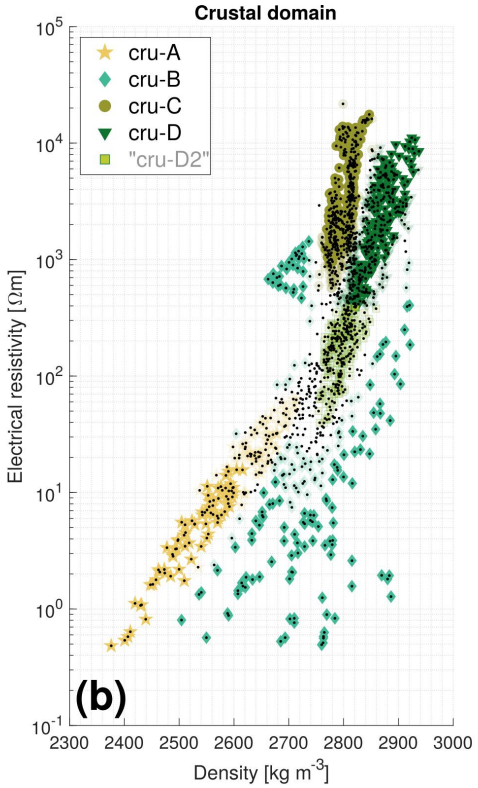
Profile P100



Profile P3

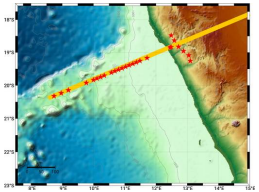


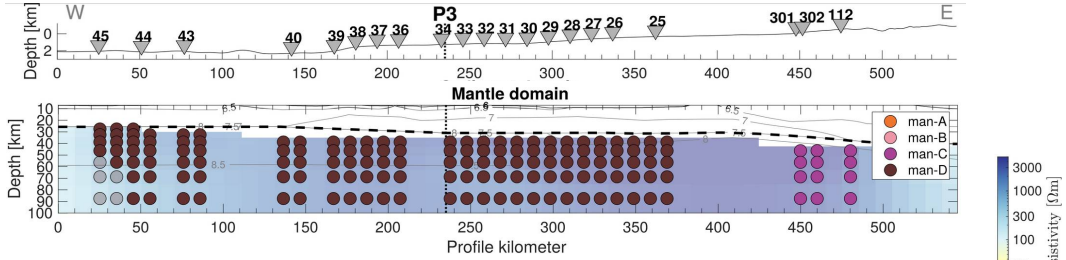




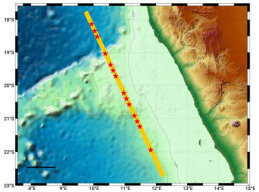
Identified Clusters and Distribution within Model

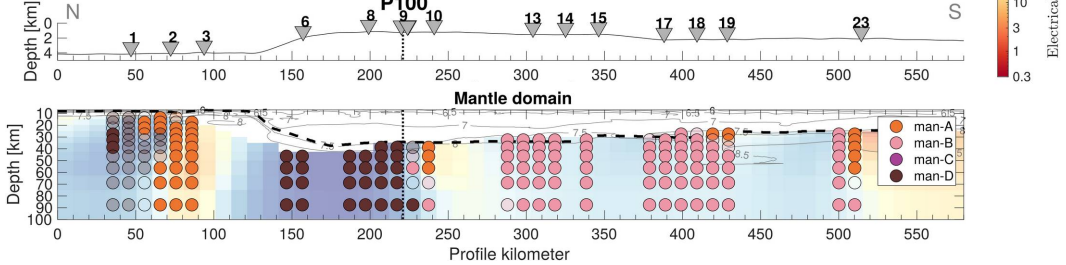
Profile P100

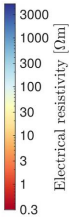


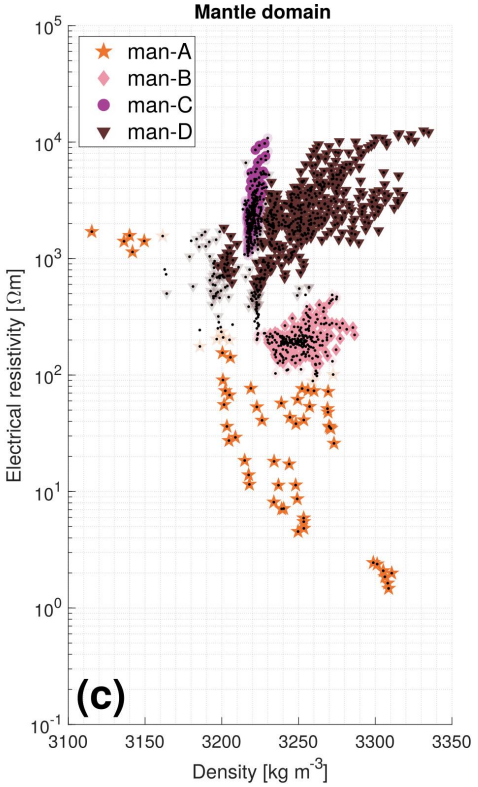


Profile P3



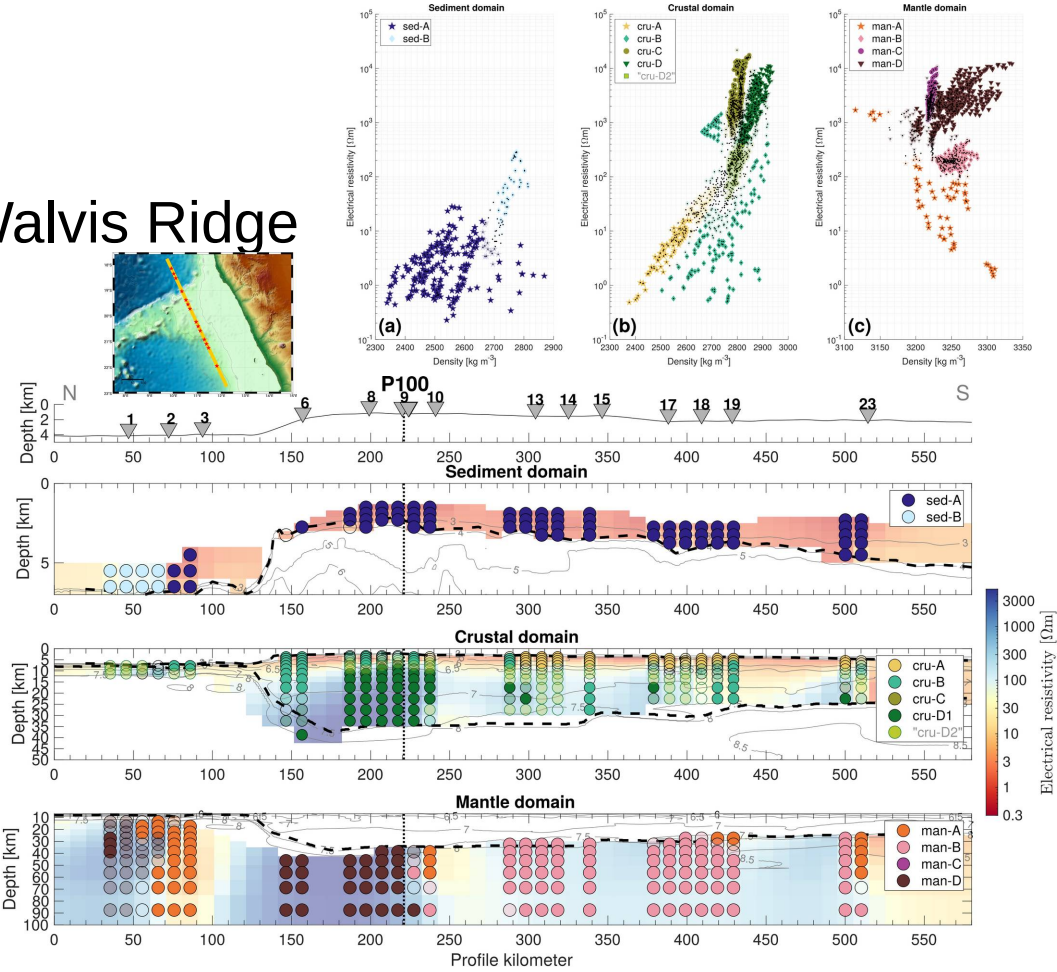






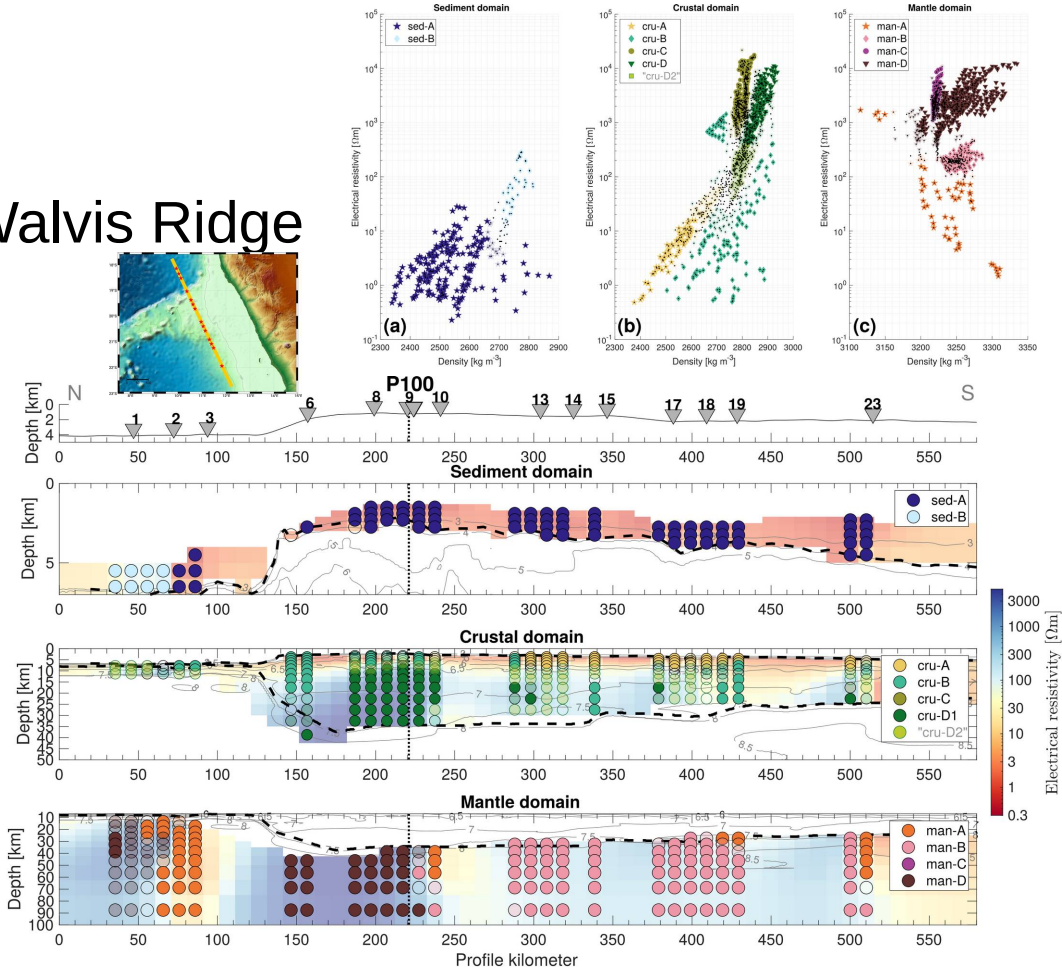
Transitional Crust South of Walvis Ridge

- Sediments: sed-A
  - ➔ thick, coarse, clastic, terrigenous



Transitional Crust South of Walvis Ridge

- Sediments: sed-A
  - ➔ thick, coarse, clastic, terrigenous
- Upper crust: cru-A
  - ➔ alternating layers of massive basalt flows & weathered vesicular basalt flows or sediments



Discussion

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  - ➔ al
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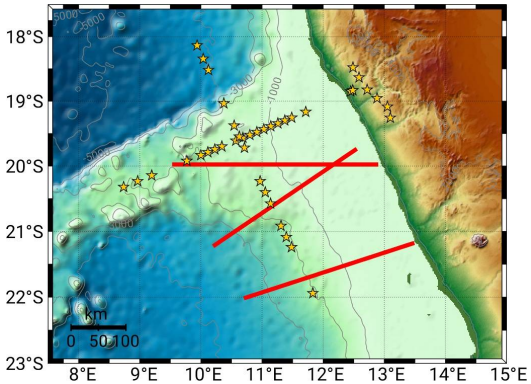
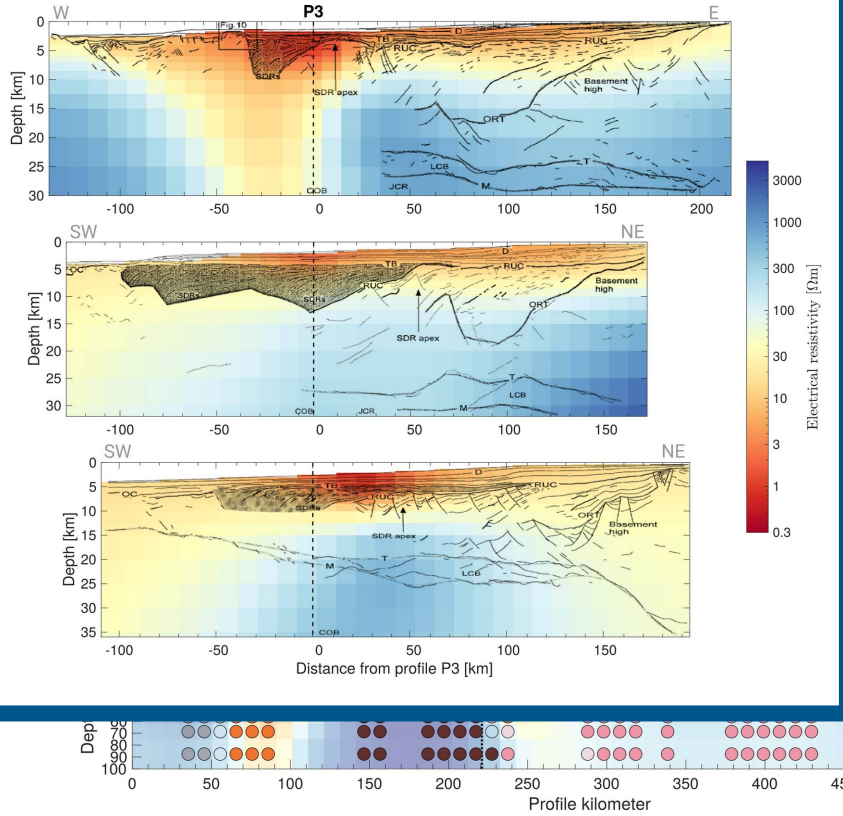
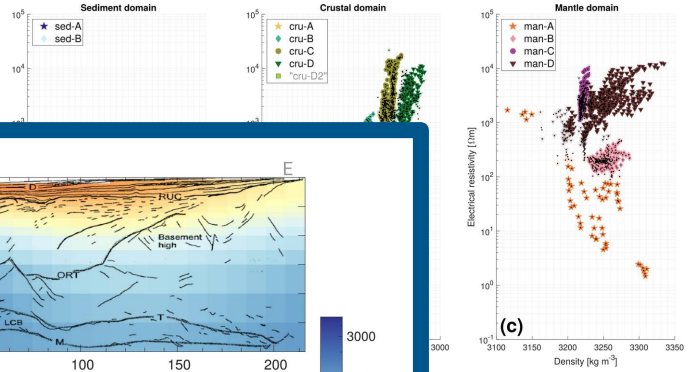
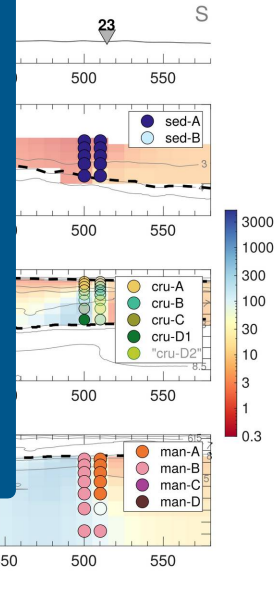
Seismic profiles by Gladczenko et al. (1998) image seaward dipping reflectors **(SDR)** → interlayered volcanic flows & sediments



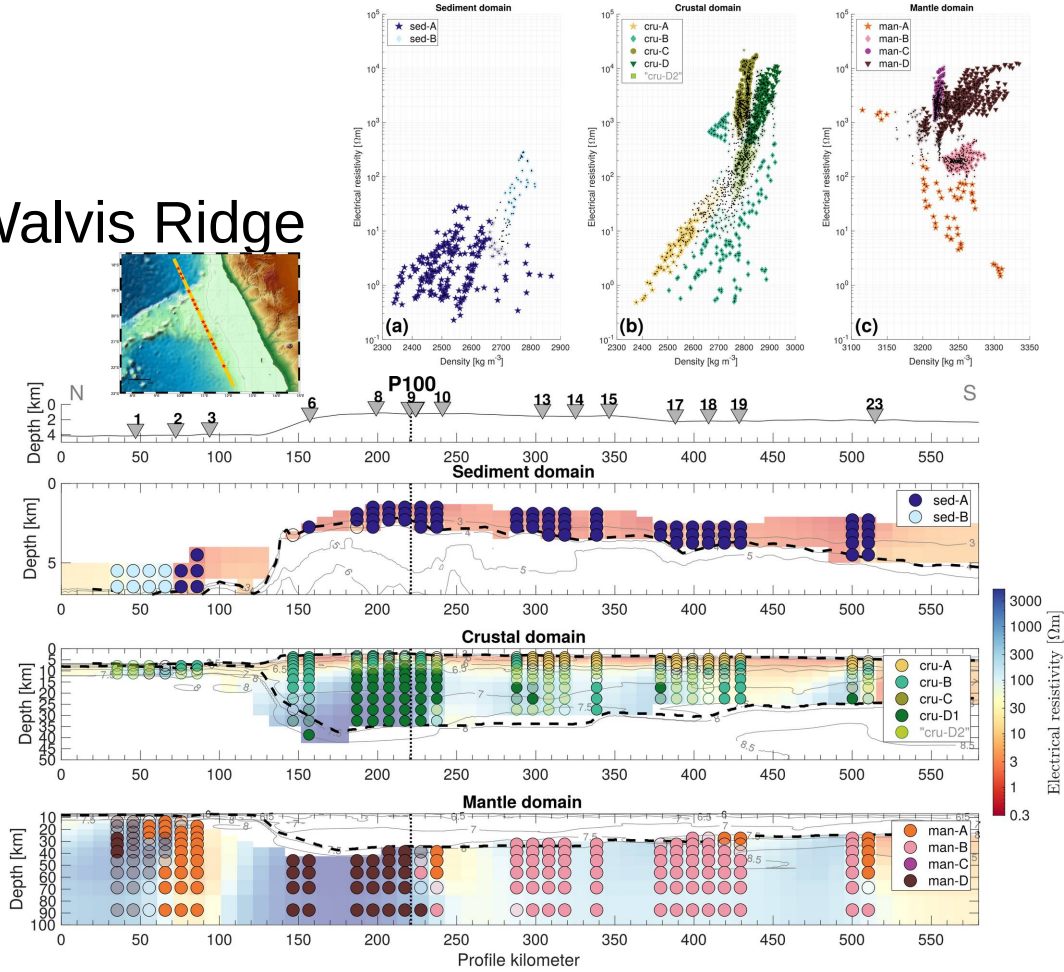






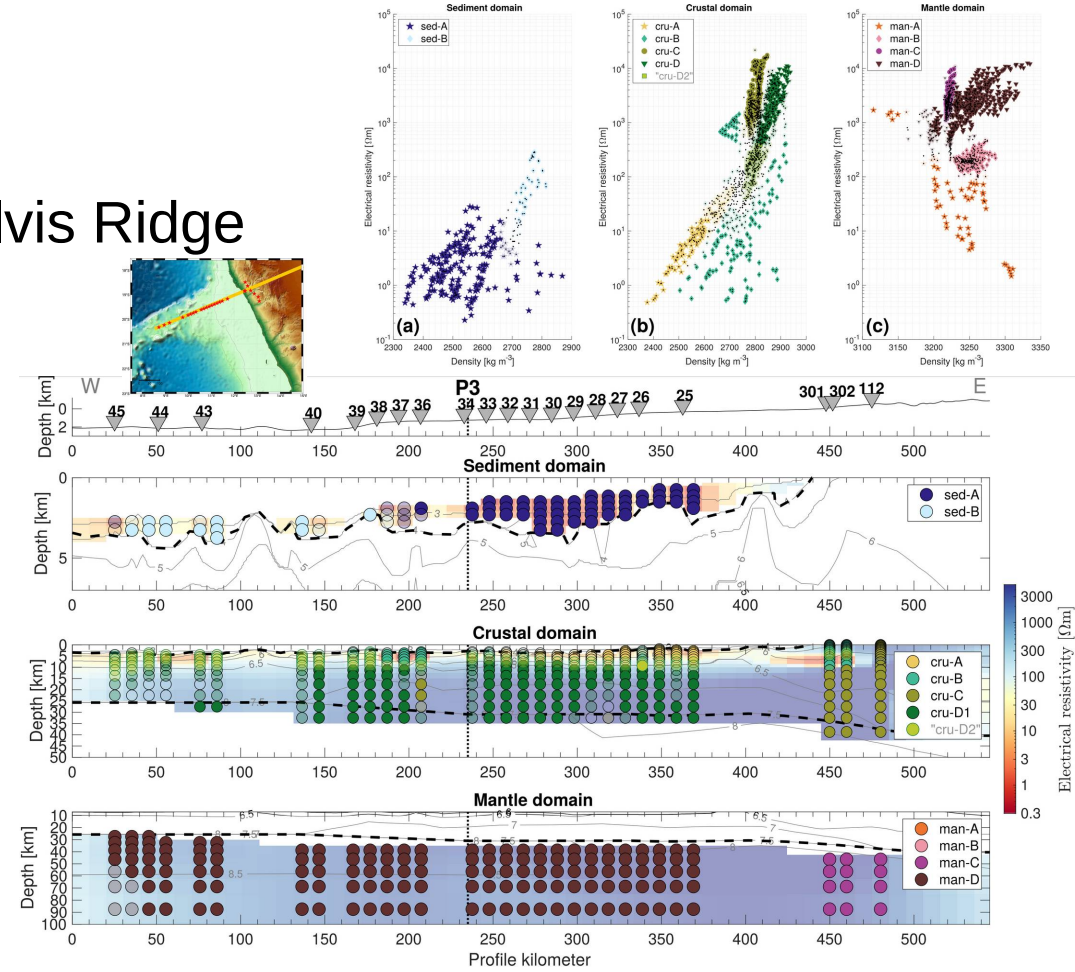
Transitional Crust South of Walvis Ridge

- Sediments: sed-A
  - ➔ thick, coarse, clastic, terrigenous
- Upper crust: cru-A
  - ➔ alternating layers of massive basalt flows & weathered vesicular basalt flows or sediments
- Crust: cru-B/cru-D2
  - ➔ intruded igneous crust
- Mantle: man-B
  - ➔ „normal“ upper mantle



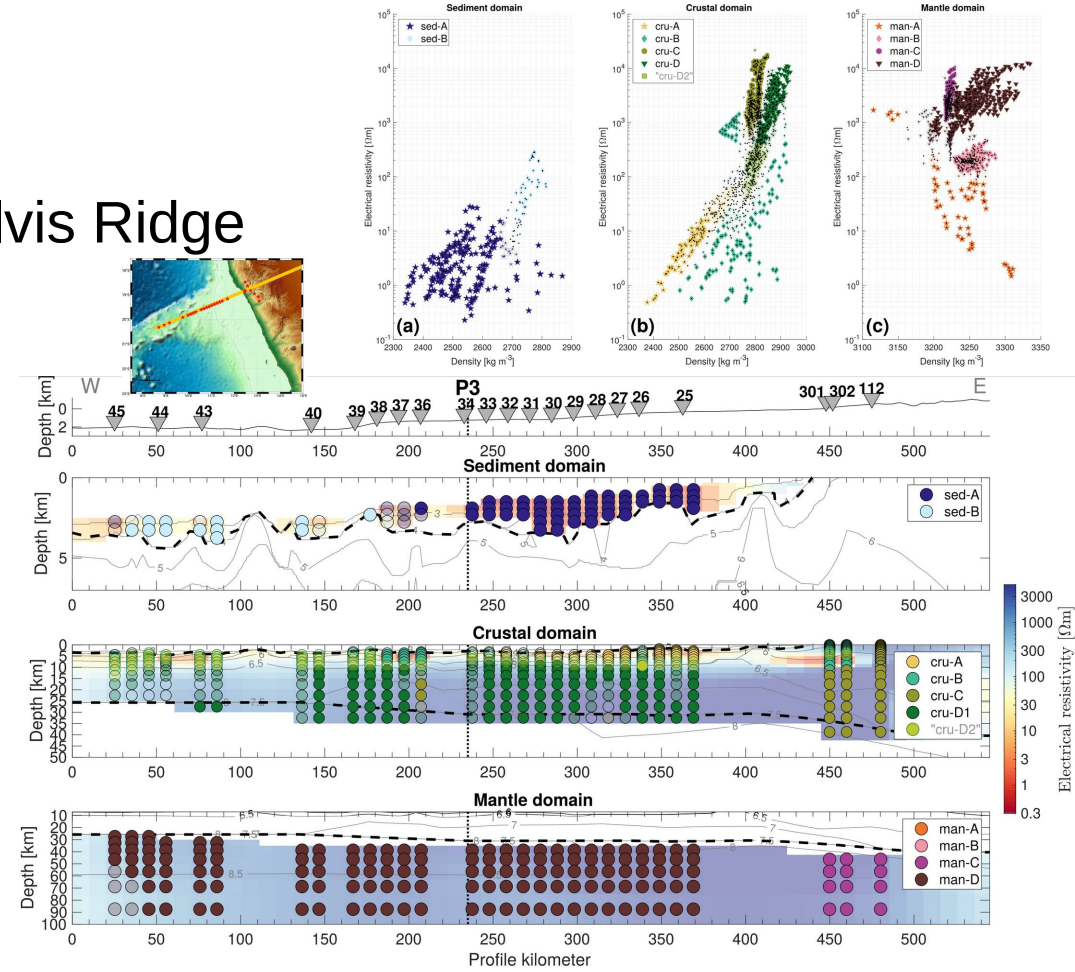
Transitional Crust Along Walvis Ridge

- Sediments: sed-A (near to coast)
  - ➔ thick, coarse, clastic, terrigenous
- Sediments: sed-B (far from coast)
  - ➔ fine, marine, biogenic (?)



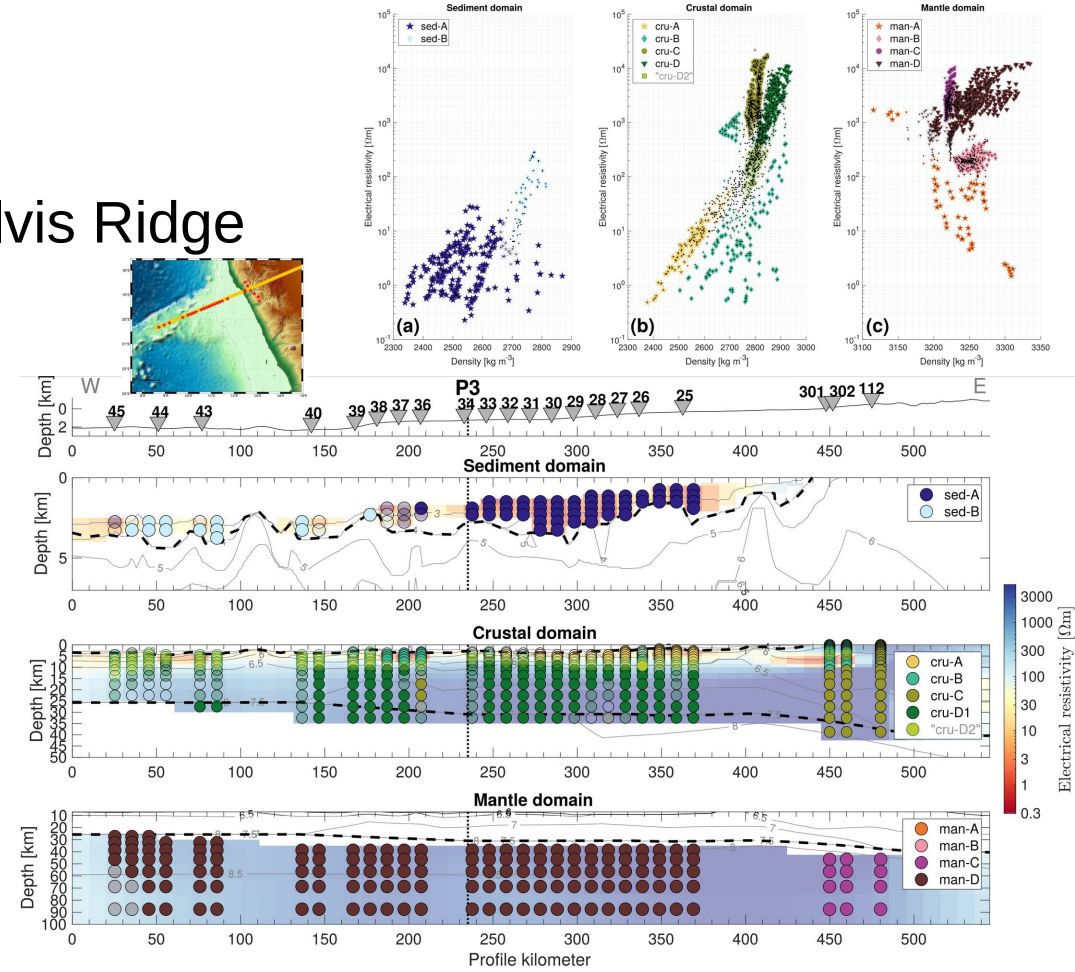
Transitional Crust Along Walvis Ridge

- Sediments: sed-A (near to coast)
  - ➔ thick, coarse, clastic, terrigenous
- Sediments: sed-B (far from coast)
  - ➔ fine, marine, biogenic (?)
- Upper crust: cru-A (near to coast)
- Crust: cru-D
  - ➔ massively underplated, intruded igneous crust



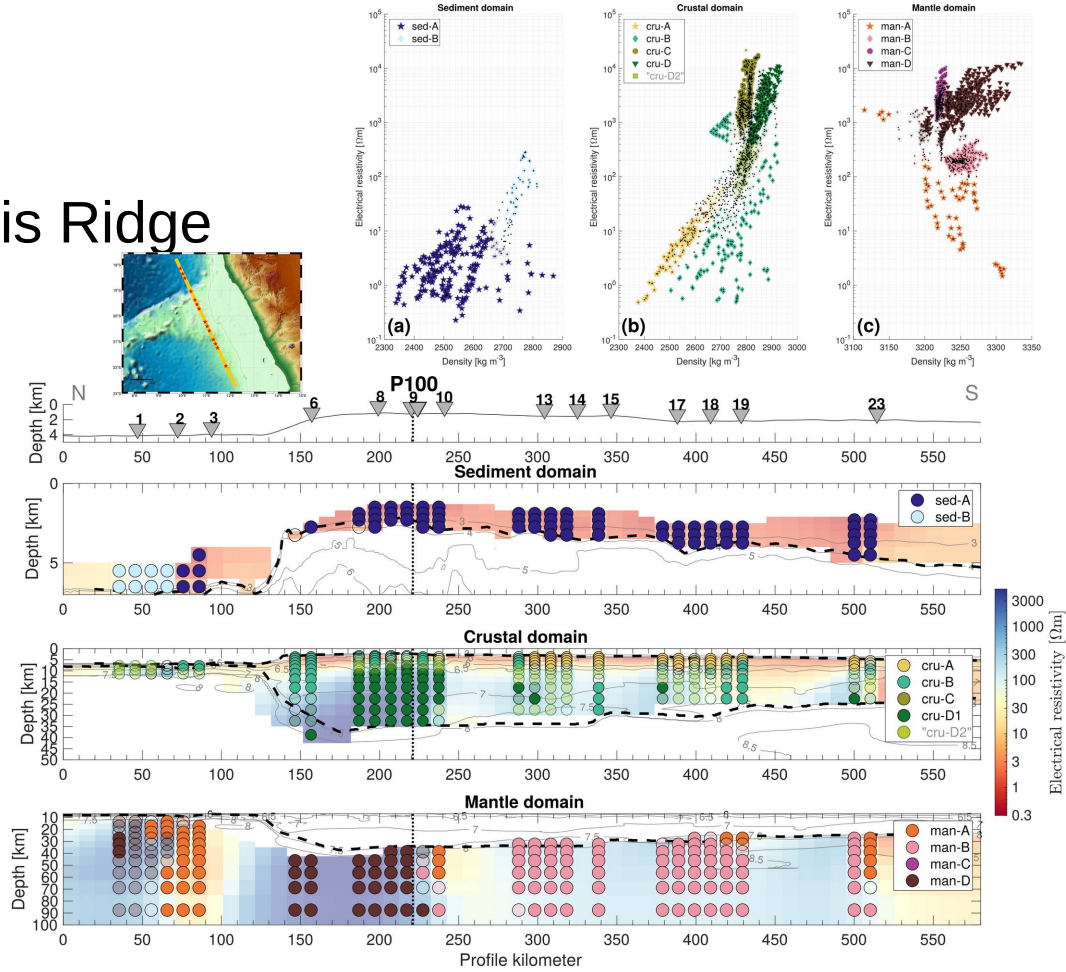
Transitional Crust Along Walvis Ridge

- Sediments: sed-A (near to coast)
  - ➔ thick, coarse, clastic, terrigenous
- Sediments: sed-B (far from coast)
  - ➔ fine, marine, biogenic (?)
- Upper crust: cru-A (near to coast)
- Crust: cru-D
  - ➔ massively underplated, intruded igneous crust
- Mantle: man-D
  - ➔ depleted upper mantle



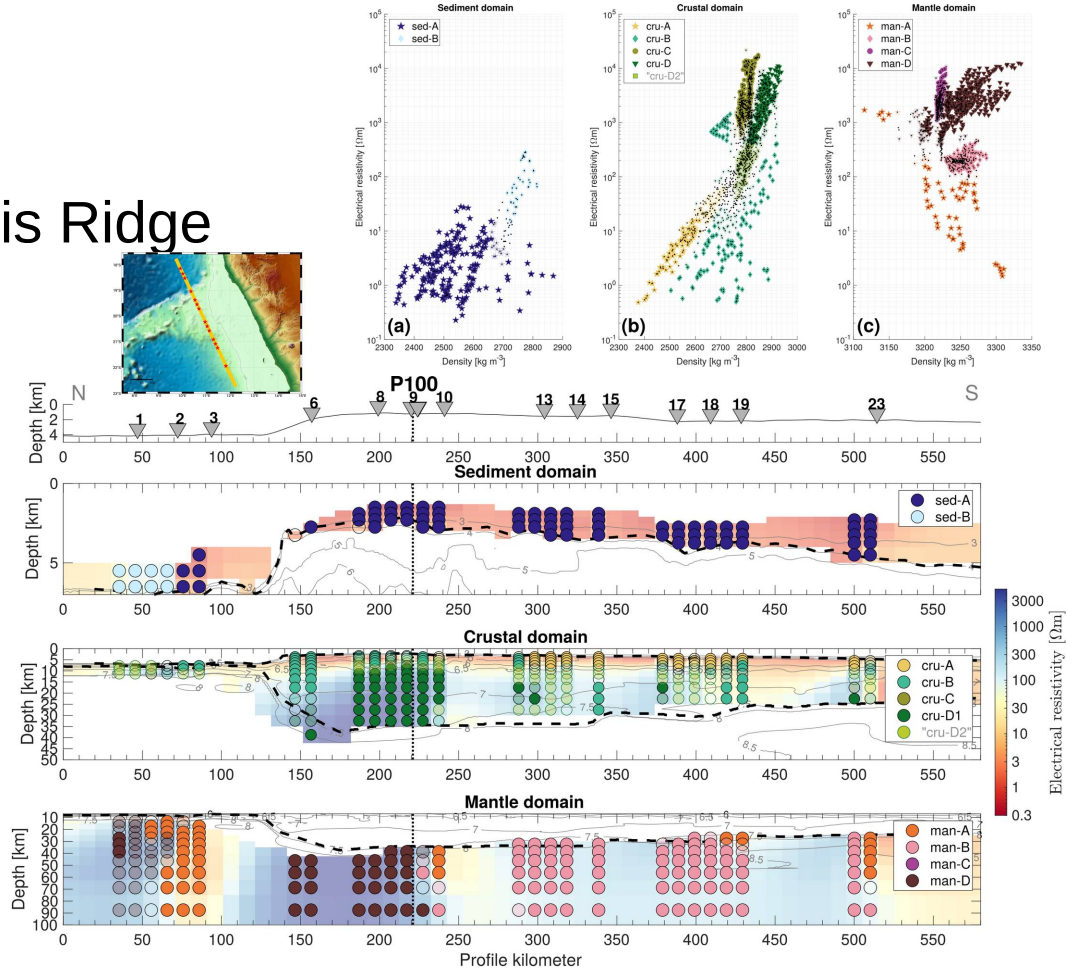
Oceanic Crust North of Walvis Ridge

- Sediments: (mostly) sed-B
  - ➔ fine, marine, biogenic (?)



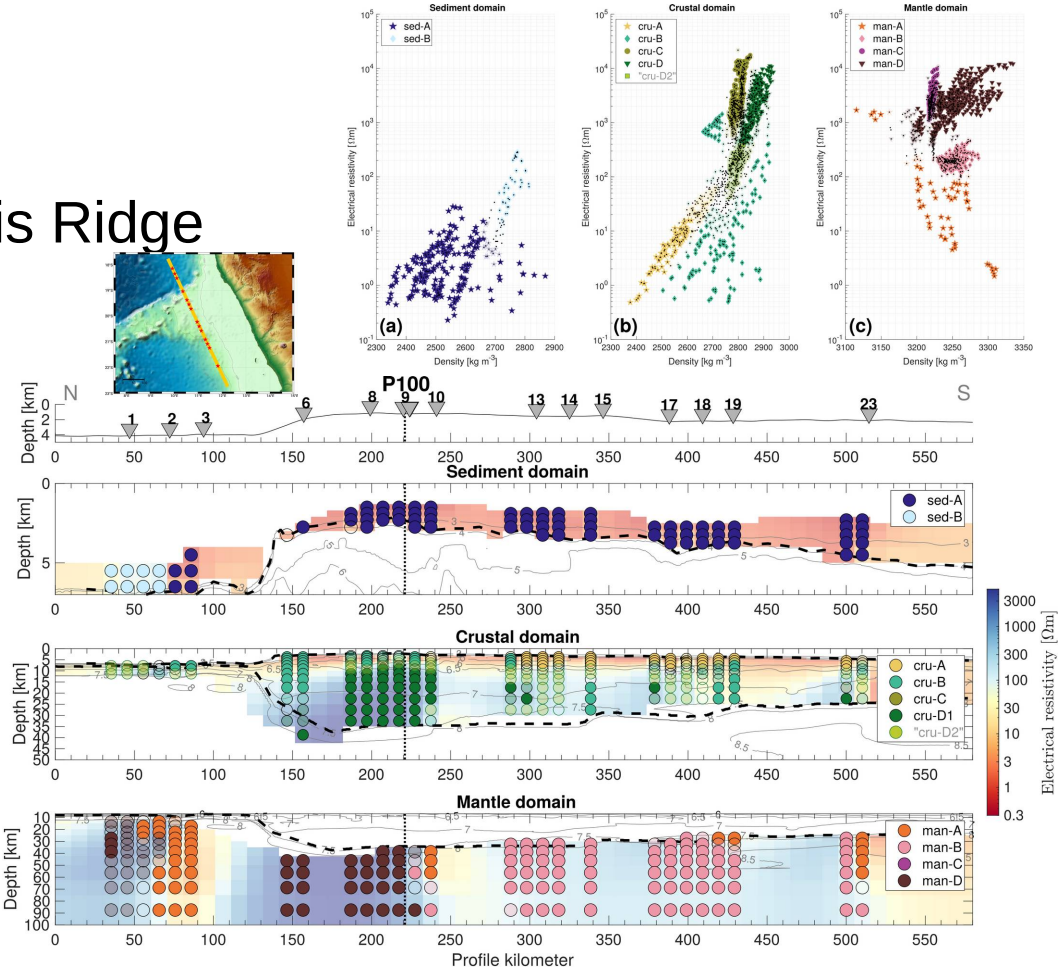
Oceanic Crust North of Walvis Ridge

- Sediments: (mostly) sed-B
  - ➔ fine, marine, biogenic (?)
- Crust: cru-B/cru-D (very shallow)
  - ➔ transition to normal, thin oceanic crust



Oceanic Crust North of Walvis Ridge

- Sediments: (mostly) sed-B
  - ➔ fine, marine, biogenic (?)
- Crust: cru-B/cru-D (much shallower)
  - ➔ transition to normal oceanic crust
- Mantle: man-A/man-D, lower probability = higher uncertainty
  - ➔ FFZ and vertical smearing is an artifact from drastic topography/crustal thickness change



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Part III: Conclusion

Summary Cross-Gradient Coupled Joint Inversion

- Cross-gradient coupling of MT inversion with fixed structural model **(JI1)** helped to
  - partially suppress a vertical artifact
  - emphasize need for upper crustal conductors
  - emphasize high mantle resistivity

- Joint inversion of Gravity and MT **(JI2)**
  - did not alter resistivity model
  - enabled passive margin parameter analysis

Implications for the Geological Interpretations at the Namibian Passive Margin

Differentiation in a southern & along Walvis Ridge domain

- mainly rift driven southern domain, typical volcanic margin features
- plume center below Walvis Ridge, increased magmatic input & halted break-up
- Massively underplated lower crust and depleted upper mantle lead to striking high resistivity anomaly


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Questions? gfranz@geomar.de
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References

Berndt, C., Planke, S., Teagle, D., Huismans, R., Torsvik, T., Frieling, J., ... & Hong, W. L. (2019). Northeast Atlantic breakup volcanism and consequences for Paleogene climate change-MagellanPlus Workshop report. Scientific Drilling, 26, 69-85.

Franke, D. (2013). Rifting, lithosphere breakup and volcanism: Comparison of magma-poor and volcanic rifted margins. Marine and Petroleum Geology, 43 , 63–87.

Fromm, T., Jokat, W., Ryberg, T., Behrmann, J., Haberland, C., & Weber, M. (2015). South Atlantic opening: A plume-induced breakup? Geology, 43 (10), 931–934.

Fromm, T., Jokat, W., Ryberg, T., Behrmann, J., Haberland, C., & Weber, M. (2017). The onset of Walvis Ridge: Plume influence at the continental margin. Tectonophysics, 716 , 90–107.

Gallardo, L. A., & Meju, M. A. (2003). Characterization of heterogeneous near-surface materials by joint 2D inversion of dc resistivity and seismic data. Geophysical Research Letters, 30 (13).

Gladczenko, T. P., Skogseid, J., & Eldhom, O. (1998). Namibia volcanic margin. Marine Geophysical Research, 20 (4), 313–341.

Gladczenko, T. P., Skogseid, J., & Eldhom, O. (1998). Namibia volcanic margin. Marine Geophysical Research, 20 (4), 313–341.

Götze, H. J., & Pail, R. (2018). Insights from recent gravity satellite missions in the density structure of continental margins–With focus on the passive margins of the South Atlantic. Gondwana Research, 53, 285-308.

Koopmann, H., Schreckenberger, B., Franke, D., Becker, K., & Schnabel, M. (2016). The late rifting phase and continental break-up of the southern South Atlantic: the mode and timing of volcanic rifting and formation of earliest oceanic crust. Geological Society, London, Special Publications, 420 (1), 315–340.

Maystrenko, Y. P., Scheck-Wenderoth, M., Hartwig, A., Anka, Z., Watts, A. B., Hirsch, K. K., & Fishwick, S. (2013). Structural features of the Southwest African continental margin according to results of lithosphere-scale 3D gravity and thermal modelling. Tectonophysics, 604 , 104–121.

McCormick, C. (2014): Gaussian Mixture Models Tutorial and MATLAB Code. https://chrisjmccormick.wordpress.com/2014/08/04/gaussian-mixture-models-tutorial-and-matlab-code/

Moorkamp, M. (2017). Integrating electromagnetic data with other geophysical observations for enhanced imaging of the earth: a tutorial and review. Surveys in Geophysics, 38(5), 935-962.

Moorkamp, M., Heincke, B., Jegen, M., Roberts, A. W., & Hobbs, R. W. (2011). A framework for 3-D joint inversion of MT, gravity and seismic refraction data. Geophysical Journal International , 184 (1), 477–493.

Moulin, M., Aslanian, D., & Unternehr, P. (2010). A new starting point for the South and Equatorial Atlantic Ocean. Earth-Science Reviews, 98 (1-2), 1–37.

Owen-Smith, T. M., Ashwal, L. D., Sudo, M., & Trumbull, R. B. (2017). Age and petrogenesis of the Doros Complex, Namibia, and implications for early plume-derived melts in the Paraná-Etendeka LIP. Journal of Petrology, 58 (3), 423–442.

Planert, L., Behrmann, J., Jokat, W., Fromm, T., Ryberg, T., Weber, M., & Haberland, C. (2017). The wide-angle seismic image of a complex rifted margin, offshore North Namibia: Implications for the tectonics of continental breakup. Tectonophysics, 716, 130–148.

Salomon, E., Passchier, C., & Koehn, D. (2017). Asymmetric continental deformation during South Atlantic rifting along southern Brazil and Namibia. Gondwana Research, 51 , 170–176.

Teklay, M., Wirth, K., Mezger, K., & Thole, J. (2020). Picrites of the Jungfrau and Sargdeckel, central Namibia: Relative roles of mantle and crust in the Southern Etendeka large igneous province. Lithos, 354-355 , 105283.

Trumbull, R. B., Vietor, T., Hahne, K., Wackerle, R., & Ledru, P. (2004). Aeromagnetic mapping and reconnaissance geochemistry of the Early Cretaceous Henties Bay-Outjo dike swarm, Etendeka Igneous Province, Namibia. Journal of African Earth Sciences, 40 (1-2), 17–29.