Gravity and magnetic constraints and limitations in defining basin structure, offshore Senegal

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Introduction

The Senegal portion of the MSGBC Basin has become highly prospective following the recent deepwater discoveries by Cairn and Kosmos. On seismic the visible sequence is dominated by a Jurassic to early Cretaceous carbonate bank and a westwards prograding wedge of mainly younger clastics. Minimal information is available on the underlying fabric. In this study we utilize the latest satellite potential field datasets to constrain the syn-rift and early drift geometries of Senegal, both for the onshore and offshore. Specific objectives were to determine the boundary between oceanic and continental crust and to locate the eastern onset of rifting. The result is a much clearer picture than previously available on the factors determining prospectivity. The results are fully consistent with seismic.

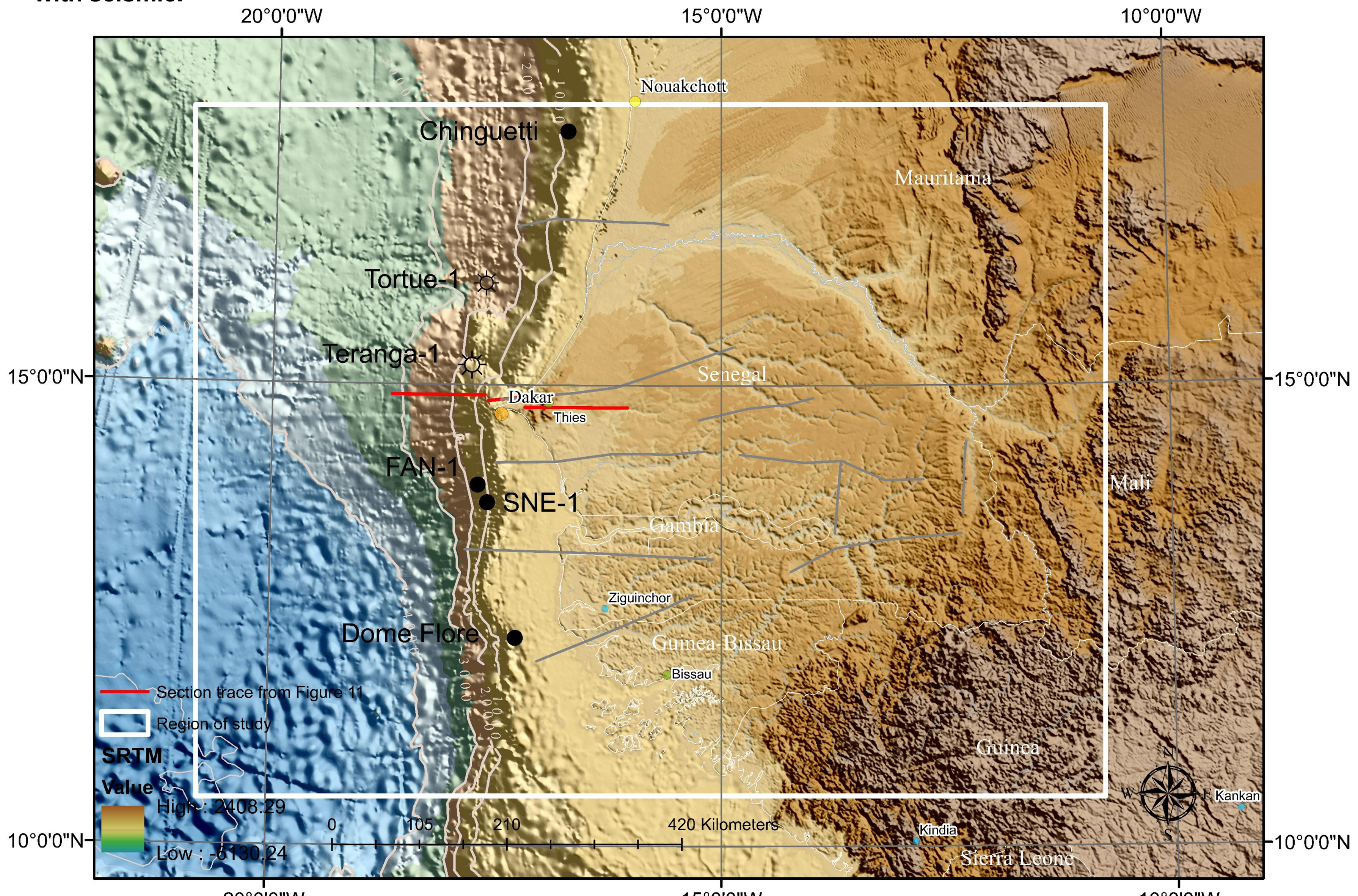

*Figure 1: Region of study with SRTM topo-bathymetry base, and key offshore wells, plus **Figure 11** section trace (red), mapped onshore deep crustal faults (grey) from magnetics in **Figure 9**.*

Geomorphology

The Senegalese climate straddles the semi-arid Sahel in the north, to the tropical and verdant zone of the southern highlands of Guinea. The geomorphology varies from the western Rio de Oro lowlands and Senegal floodplain, defined by the Cenomanian marine transgression, towards the east and south eastern highlands of Mali and Guinea respectively, from which present day water courses converge into the Gambia and Senegal river systems (**figure 1** above). The present day river courses suggest palaeo-topographic influence. Water depths are shallower to the north of the Dakar Peninsula. This northern region contains a thicker sedimentary cover which originated from the focusing of progradation during the Cretaceous into this region.

Geological Setting

Senegal's basins have developed through several tectonic evolutions: Palaeozoic suturing of Laurentia-Gondwana, Triassic rift phase, Jurassic-Cretaceous drift, and Tertiary uplift and around Dakar magmatism. The host MSGBC Basin is delimited to the north by the Reguibat-West African Craton, to the east by the Mauritanides, and to the south by the Palaeozoic Bové Basin.

Onshore Palaeozoic basins record the deepest known structural inheritance arising from the initial suturing of Senegal and Mauritania to Gondwana in Ordovician times (LeCorche, 1980). Early Triassic rifting marked the break-up of Laurentia and Gondwana, with early rifts expected to be filled by red beds. Salt accumulated in the Casamance Failed Rift Arm. The Central Atlantic Magmatic Province (CAMP) was emplaced at 200 Ma(Davison, 2005). Drift commenced at the end of the early Jurassic (Davison 2005). Growth of a carbonate bank dominated the subsequent Jurassic and early Cretaceous histories. The younger Cretaceous is characterised by delta fed progradation into deepwater. In contrast, slower rates of deposition define the Tertiary. From the Eocene onwards mantle derived magmatism emplaced the Cayar and Dakar domes. There was associated tectonism, uplift and offshore canyon cuts. **Figure 2** below summarizes the stratigraphic facies, and important events.

Epoch	*Age*	*Basin primary lithologies*	*Event*		*Epoch Base (Ma)*
Quaternary	Holocene	Deep marine		onshore uplift and tectonism terrestrial erosion Dakar volcanics	0.01
	Pleistocene				2.6
Neogene	Pliocene				5.3
	Miocene				23
Paleogene	Oligocene			↑	34
	Eocene	Shelf carbonates and marls, deepwater cherts	Progradation ceases	Cayar, Dakar Dome magmatism	56
	Paleocene				65.5
Cretaceous	Late	Deepening marine	Progradation	Leona Dome Santonian unconformity	
	Early		carbonate bank forms		145.5
Jurassic	Late				161
	Middle			Onset Atlantic spreading (190Ma)	175.6
	Early				199.6
Triassic	Late	Red beds, Casamance salt	↑ Syn-rift	CAMP (200Ma) Central Atlantic Magmatic Province	228.7
Palaeozoic structural inheritance					

Figure 2: Stratigraphic column

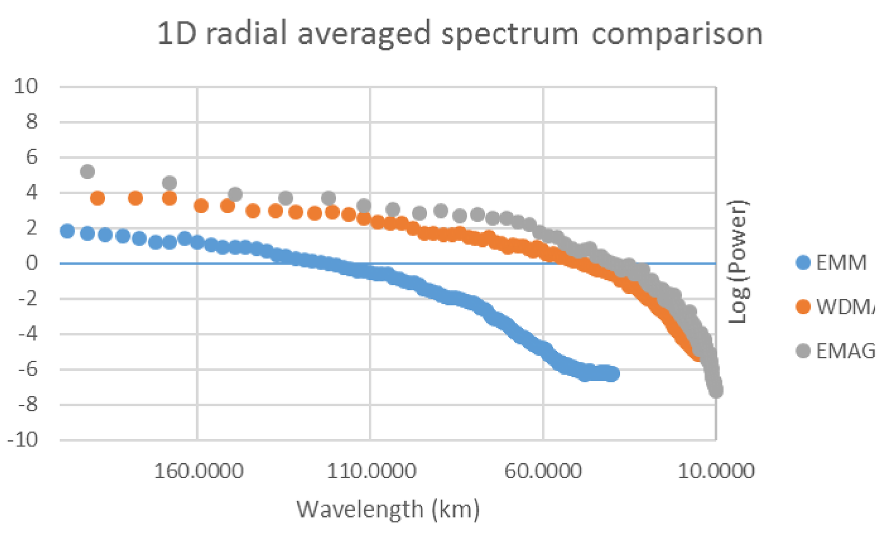

Figure 3: Radial averaged spectra comparison of magnetic datasets. EMAG2 not used in this study.

Data sets scope

Satellite data have been utilized to demonstrate the low cost, efficient value they can yield when processed and presented in useful residual form. Sandwell v23-1 Free-air gravity (Sandwell et al 2014) and the World Digital Magnetic Anomaly Map (W.D.M.A.M., Maus et al, 2007) combined with the Enhanced Magnetic Model 2015 (E.M.M., Chulliat et al, 2015) model data have been selected in this study. Sandwell gravity has recently been updated to include new satellite altimetry for increased accuracy. The E.M.M. incorporates E.S.A. Swarm satellite data that provides short wavelength detail to degree and order 720 (derived from available ground, air and marine survey), that translates to resolution of magnetic anomalies as short as 56 km. There are limitations in their use, both in spatial resolution and seamless coverage, however the datasets continue to evolve and become more useful. Sandwell onshore interpolation is well documented, and is presented at a lower resolution of 5 minutes, versus offshore 1 minute resolution. It has a vertical datum at effectively sea level (EGM 2008 geoid). However, it provides very good coherence to shipborne survey data as noted by (Sandwell et al 2013) and (Fairhead et al, 2009) for example. The WDMAM data provides 3 minute resolution and has a vertical datum at 5 km altitude above the WGS84 ellipsoid. **Figure 3**, above right shows comparative radial averaged spectra for the two magnetic datasets, including the Earth Magnetic Anomaly grid (EMAG2 Maus et al, 2009). The lower resolution of the EMM set offshore is clearly seen in **figure 6**.

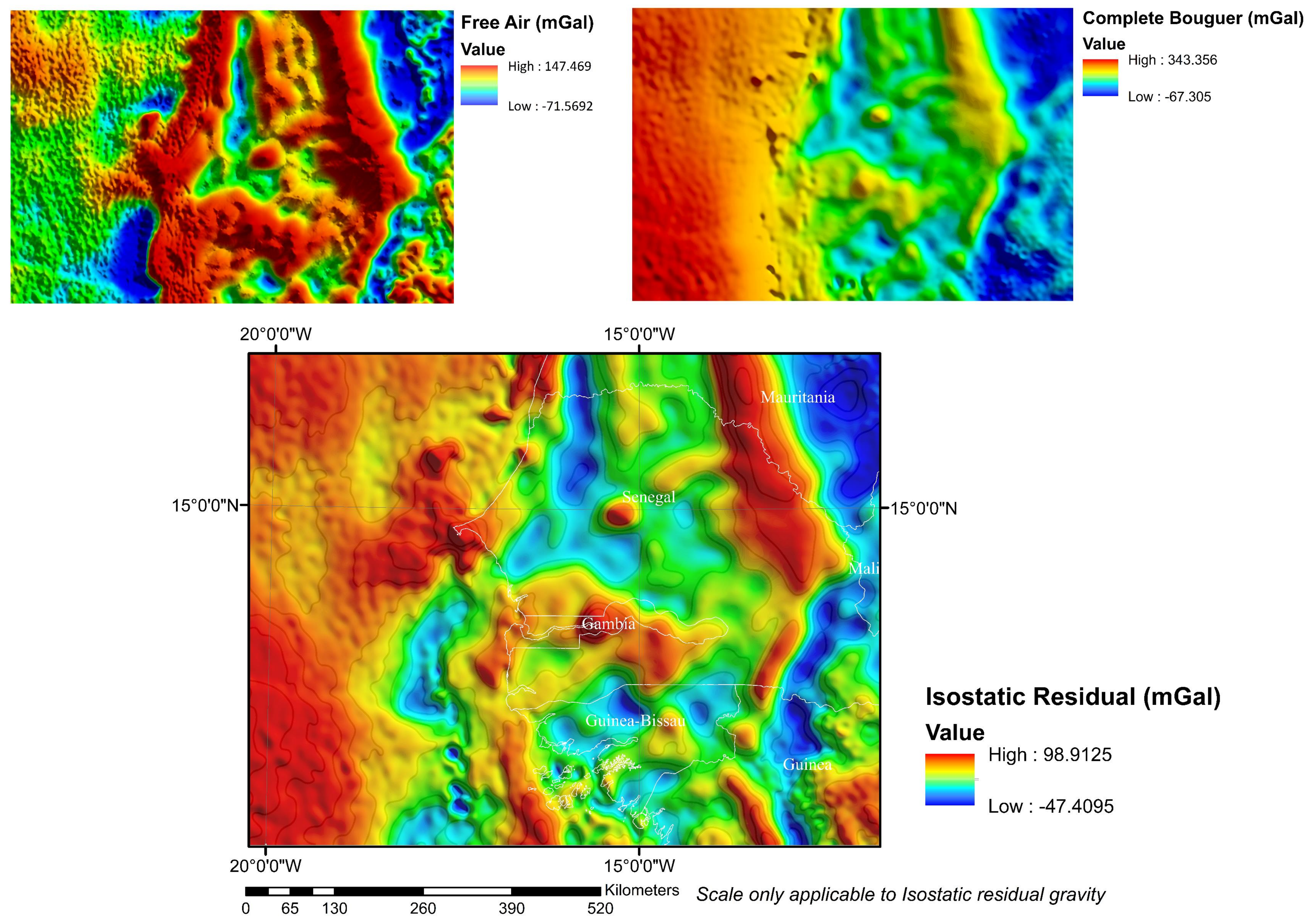

Figure 4: Sandwell Free Air gravity (top left), Bouguer gravity (top right), and isostatic residual gravity (bottom)

Shallow structure and residual gravity derivatives

The Free Air gravity has been corrected for terrain, Bullard curvature, 3-D Bouguer corrections and isostacy to yield a residual isostatic gravity product shown in **figure 4** above. By looking at conventional filter derivatives of the residual gravity it is possible to interpret some structural components of the shallow sequence within the Senegal basin.

Several prominent onshore residual lows identify basin features within the broader onshore component of the Senegal basin with the western border of the Mauritanides defined by a prominent north north west striking residual gravity peak. Rift and drift period, igneous bodies are evidenced as obvious circular peaks with steep gradient margins, for example the Leona plug 150 km north north east of Dakar and the Gasane plug 250 km east of Dakar.

Offshore, there is evidence of several fault-bound crustal domains which correlate with previously described provinces delineated by fracture zones. Younger Tertiary magmatic upwelling in the vicinity of known volcanic outcrops is expressed in the Dakar Peninsula region by broad positive peaks, and shorter wavelength peaks identify some of the outcrop.

The vertical derivative of the residual gravity (**figure 5**, below left) provides higher resolution by naturally filtering shorter wavelength features. It has been possible to identify the front of the carbonate bank from this vertical gradient filtered residual. However, it is not possible to differentiate between the shape of the carbonate bank and faulted margins at this resolution, neither whether the signal discretely represents the bank, ramp front or a karst zone.

To the north of Dakar, the carbonate bank is defined by a western limit of a frontal peak signal which is believed to be folded\inverted disturbed beds lying west of the faulted ramp front. The bank front appears to strike fairly consistently north north east, but leaves the Dakar Peninsula east of a prominent lobe peak anomaly that appears to express its faulted margin. Through the Peninsula resolution is lost due to igneous emplacement, but also due to the aforementioned loss of resolution in the onshore satellite gravity.

South of Dakar, the carbonate structure's signal is perturbed possibly by the influence of diapiric salt features which mask the slope morphology. These are defined by blue trough anomalies. In essence, the bank's structure does not exhibit sufficient density contrast with the surrounding units to provide further insight. However, just south of Dakar, a 'dog-leg' in the carbonate bank's edge is evident by concordant movement on an apparent dextral slip, fracture zone, mapped from magnetics and described later.

Calculating the second vertical derivative filter of the isostatic gravity (**figure 5**, below right) enables even shorter wavelength anomalies to be identified without detriment to the signal integrity. Salt structures, known to exist south of Dakar may be interpreted from the deep gravity anomaly lows, representing a range of structures (pillows, tongues, detachments) as described by Tari et al. (2003). However, it is evident at this resolution consistent mapping, or further definition of the structures that have been identified from seismic interpretation is not possible.

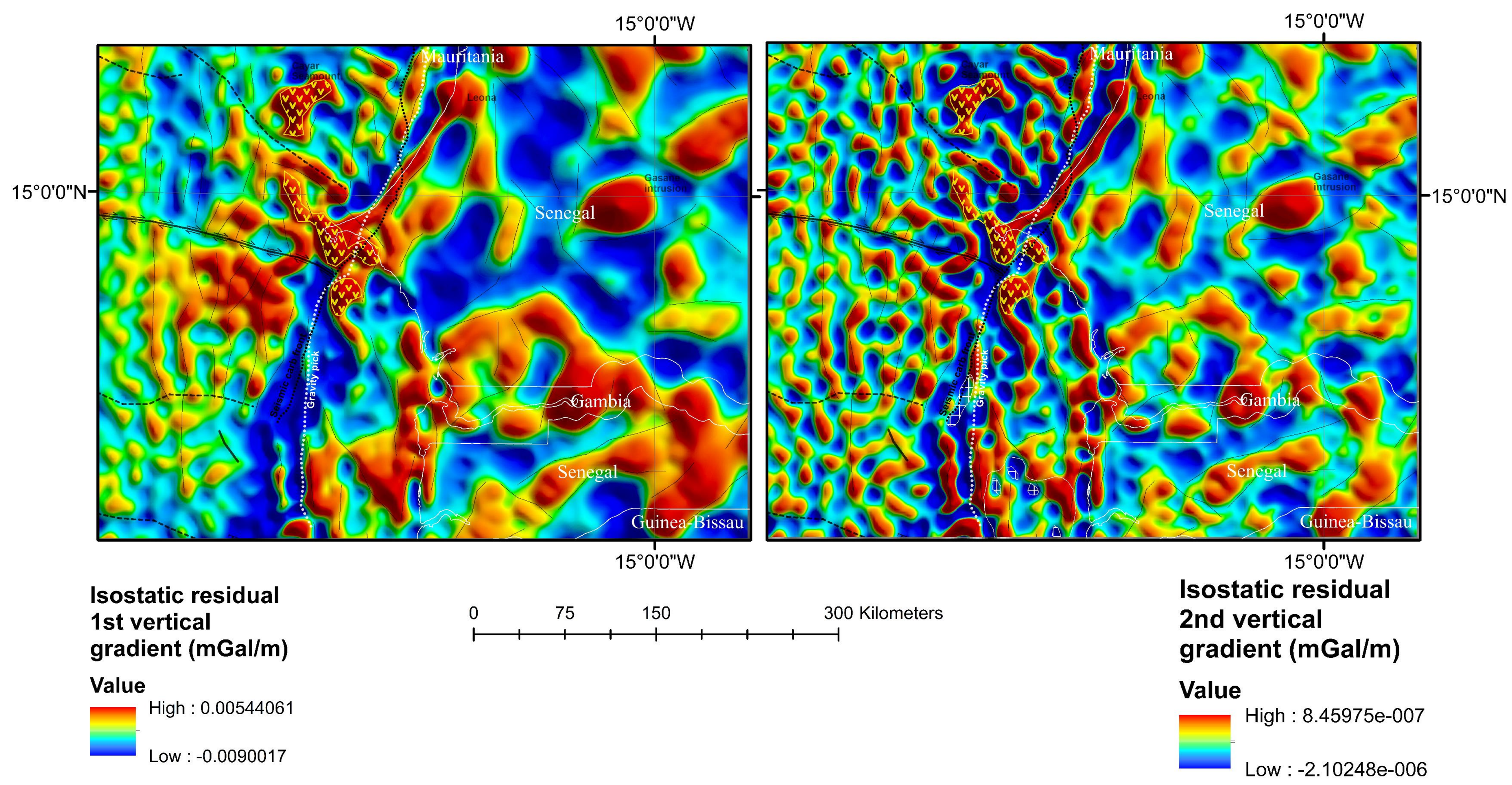

Figure 5: Isostatic residual vertical derivatives. 1st (left), 2nd order (right)

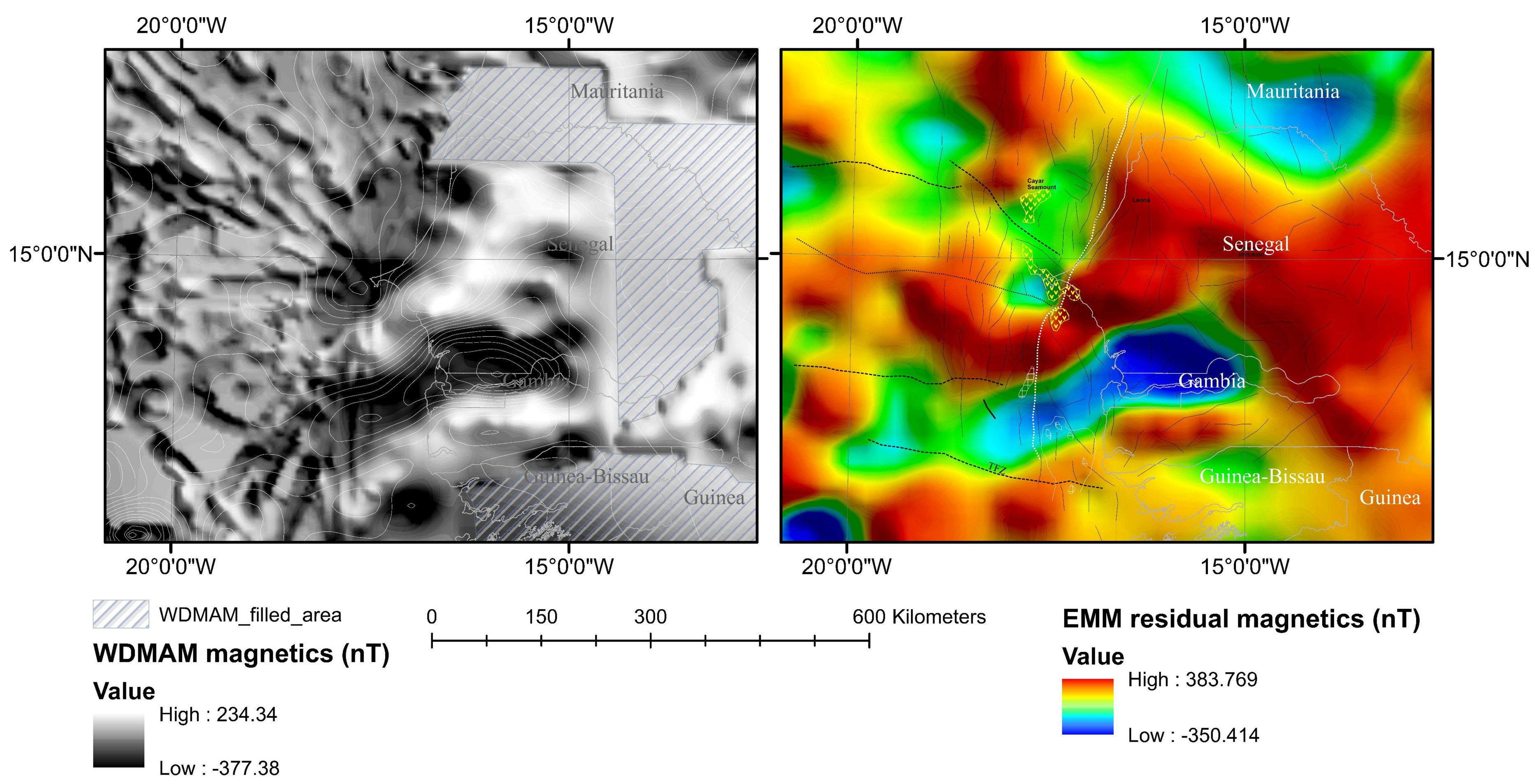

Figure 6: Left: World Digital Magnetic Anomaly Map (WDMAM) showing areas of interpolated field. White contours of Enhanced Magnetic Model (EMM). Right: EMM residual magnetics with gravity interpretation overlain from above.

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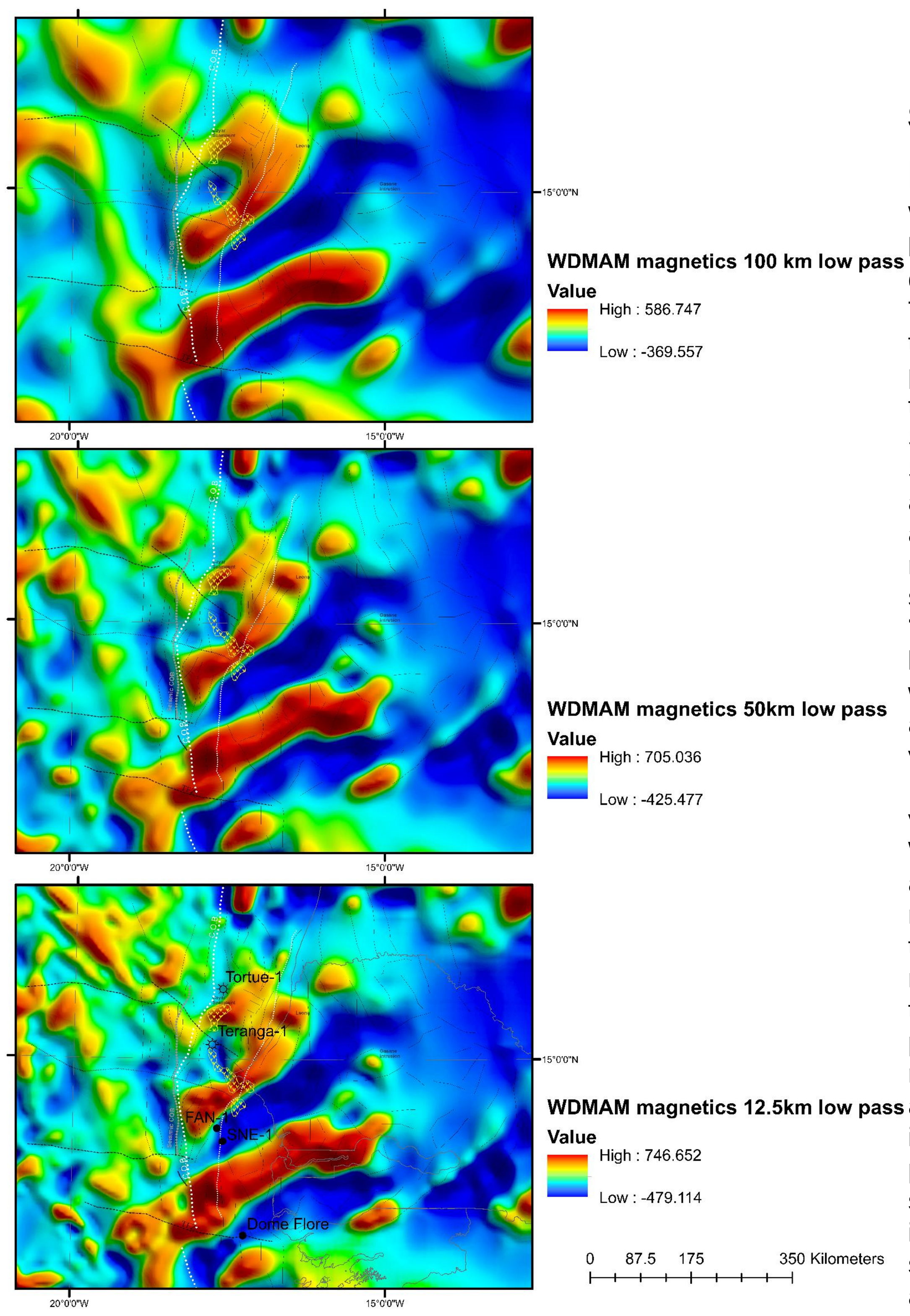

Figure 7.5 (a) – top, (b)-middle, (c)-bottom. WDMAM magnetic anomaly low passes. These are filtered at 100 km (7.5a), 50 km (7.5b) and 12.5 km (7.5c) respectively

Deep Mesozoic structure from the magnetic record

WDMAM magnetic data enables the identification of long wavelength crustal anomalies and a means to delineate the ocean\continental crust boundary. This is normally described as a transition zone, but the broad wavelength features of the reduced to pole transformed magnetic signature suggests there is a termination of coastal (NE-SW, and ENE-SSW striking) magnetic anomalies offshore Senegal. Progressive shorter wavelength filters applied to the satellite magnetic data (after Spector and Grant's 1970 1-D power spectral method), reveal continuity of the boundary through successively shallower depth slices (see left, **figure 7**), corresponding to 100 km, 50 km and 12.5 km low pass filters respectively. The filter wavelengths were chosen from the 1-D power spectrum according to changes in the gradient of the energy versus wavelength.

The EMM provides continuous coverage versus areas of onshore interpolation in the WDMAM (see **figure 6**) . The data were extracted at a vertical datum of the WGS84 ellipsoid. The magnetic field at ground level is a combination of the main magnetic field (outer core), the crustal magnetic field, and the rapid temporal variation of the external magnetic field. The EMM was processed to create a residual magnetics product to resemble residual crustal magnetization source anomalies by removing an approximation of the inducing field strength. The resultant anomaly pattern, reduced to pole, (**figure 9**, left) indicates some very deep structural trends that potentially indicate the Variscan-Alleghenian suture belt striking north east, due east of the Dakar Peninsula, as described by Villeneuve et al (2015). The basement high under the annotated suture represents the large horst block on which Dakar lies. There is furthermore good coherence between the broad continental crust anomaly footprint and the C.O.B. mapped above from the WDMAM.

Assessment of crustal thinning and the Moho structure

An initial depth to the Moho root was calculated assuming regional Airy isostacy over a passive rift margin setting. The Moho structure was low pass filtered to reflect the broader wavelength structure of the crust \ mantle boundary and exclude localized topographic effects. This root model does not take into account thermal corrections or elasticity properties. However, a broad correlation of the magnetics mapped C.O.B. with the edge of shoreward dipping Moho surface is evident (see below, left **figure 8**).

In order to improve the deep structure, a simple parametric model is used to fit the Moho structure to the Free Air gravity, using an algorithm introduced by Parker [1973]. A three-layer parametric model was constructed between the sea-level and onshore topography, offshore bathymetry, and the Moho derived from the isostatic root calculation. The forward Free Air model was calculated and then differences observed between calculated and measured Free Air gravity. From the resultant error the objective was to inverse fit only the long wavelength Moho structure to the Free Air gravity signal. This assumes the residual gravity error's broad wavelength component is caused by misplacement of the deep crust-mantle structure, and that the error is not derived from regional lateral density variation.

With these assumptions, the new Moho structure provides evidence of crustal thinning in the transform compartments offshore Senegal. Previous research has suggested that the Dakar Peninsula is underlain by oceanic basement, and this work supports this (for example Roussel and Liger, 1983), at least within a transition between continental to oceanic crust. This study indicates the Peninsula occupies a horst block, initiated within oceanic deep basement, and subsequently supported by the magmatic upwelling that produced the volcanism at Dakar. To the north of the Peninsula there is evidence of crustal thinning given by the depression in the Moho surface (see below right, **figure 8**). The local discontinuity in crustal thickness is clear in regional context to the nearshore N-S strike trend of the Moho's surface and towards the westerly transition to the magnetic COB. The timing of this assumed ductile deformation may be related to the magmatism associated with the 200 Ma Central Atlantic Magmatic Province (C.A.M.P.) emplacement. The Cenozoic magmatism appears to have used brittle faulted margins of this anomaly as channels for emplacement. This supports the concept of long lived magmatism related to C.A.M.P. as described by the work of Oyarzun (1997), and lithospheric channelling by Ndiaye (2014) for example. Early crustal stretching and C.A.M.P. magmatic upwelling may have propagated the early Triassic rifting onshore.

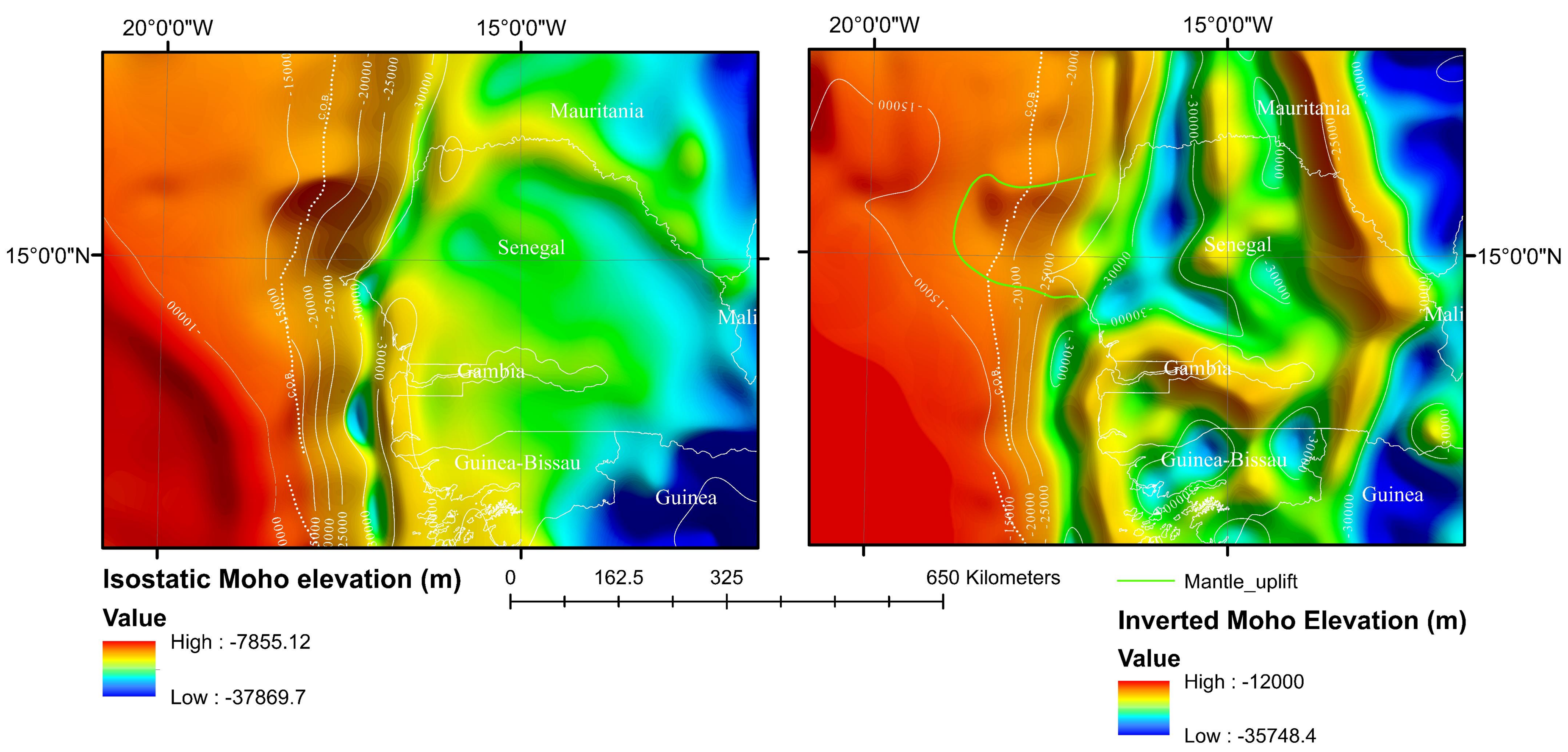

Figure 8: left: Airy isostatic Moho elevation, contours in white. Right: Structural inversion of Moho elevation

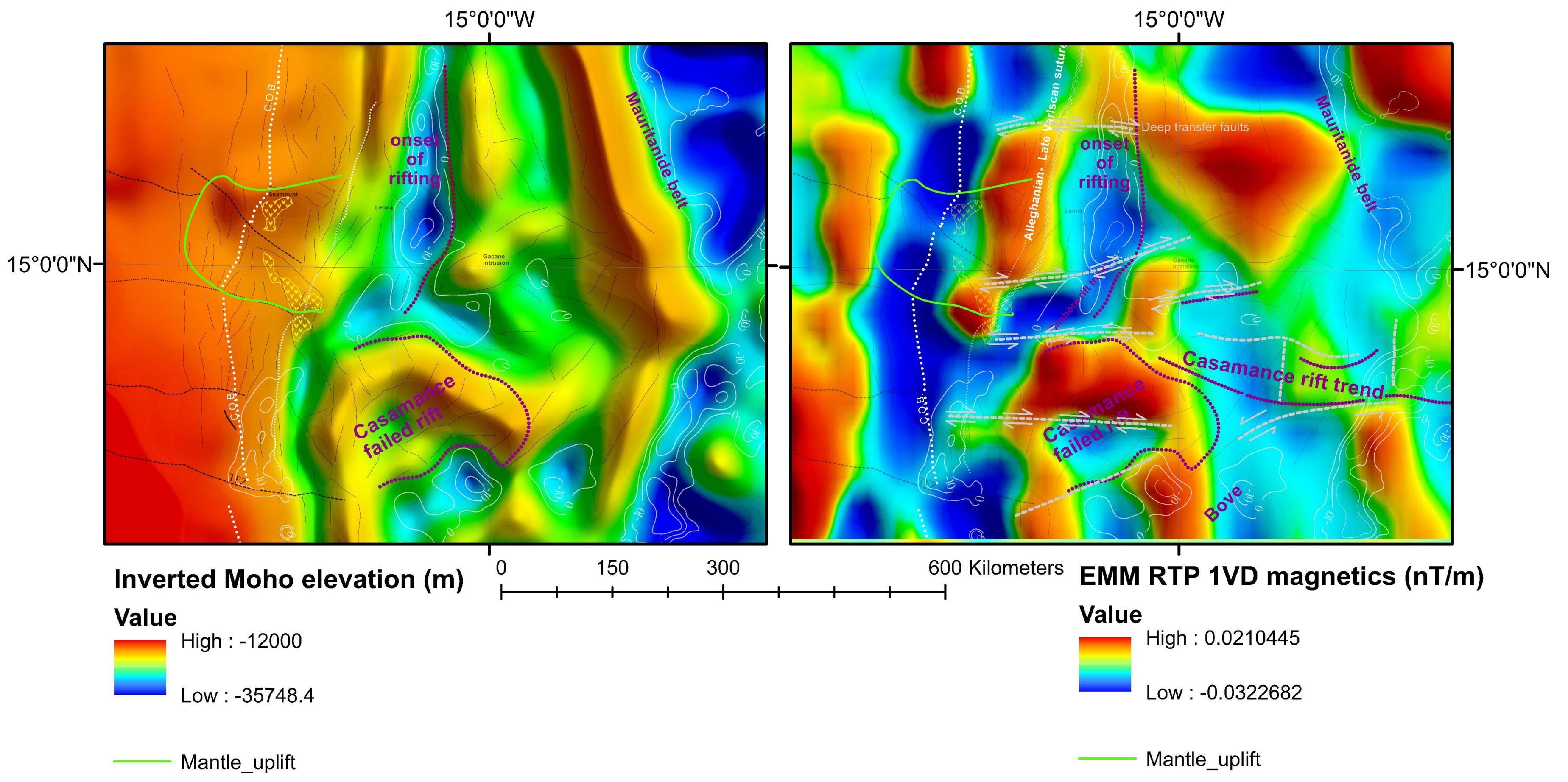

Figure 9: Left: Inverted Moho with key rift structures (purple), isostatic residual contour lows (0, -10, and -20 mGal, white) and gravity interpretation. Right, EMM residual magnetics vertical gradient, with transfer faults (grey) and the same features annotated.

The eastern limit of rifting

An eastern limit of the onset of rifting is suggested by the longer wavelength components of the residual gravity. Readily apparent from them is the outline of the failed Casamance rift arm in the residual isostatic gravity. It is also seen in the Moho structure, **figure 9**, above left, as previously documented by others (see Davison, 2005 for example). The interpreted onshore limit broadly agrees with the boundaries mapped by Chanut and Micholet (1988). It is defined by a north-south striking line, prominently delineated by a broad peak to trough transition in the residual gravity signal and a more subtle transition further south marked by a transition from parallel north south striking lineaments in the west to north west striking lineaments to the east. The EMM vertical gradient, **figure 9**, above right, shows a similar trending trough that extends into the northern Casamance sub-basin. The trace of major deep transfer faults indicate the original rifting was assisted by detachment faults after Lister (1986). The sense of movement on the faults are consistent with uplift of the broad Dakar basement. The early transfer movement set up the compartments for rifting to proceed onshore. The carbonate front shows a dog-leg consistent with sinistral movement on the Dakar transfer.

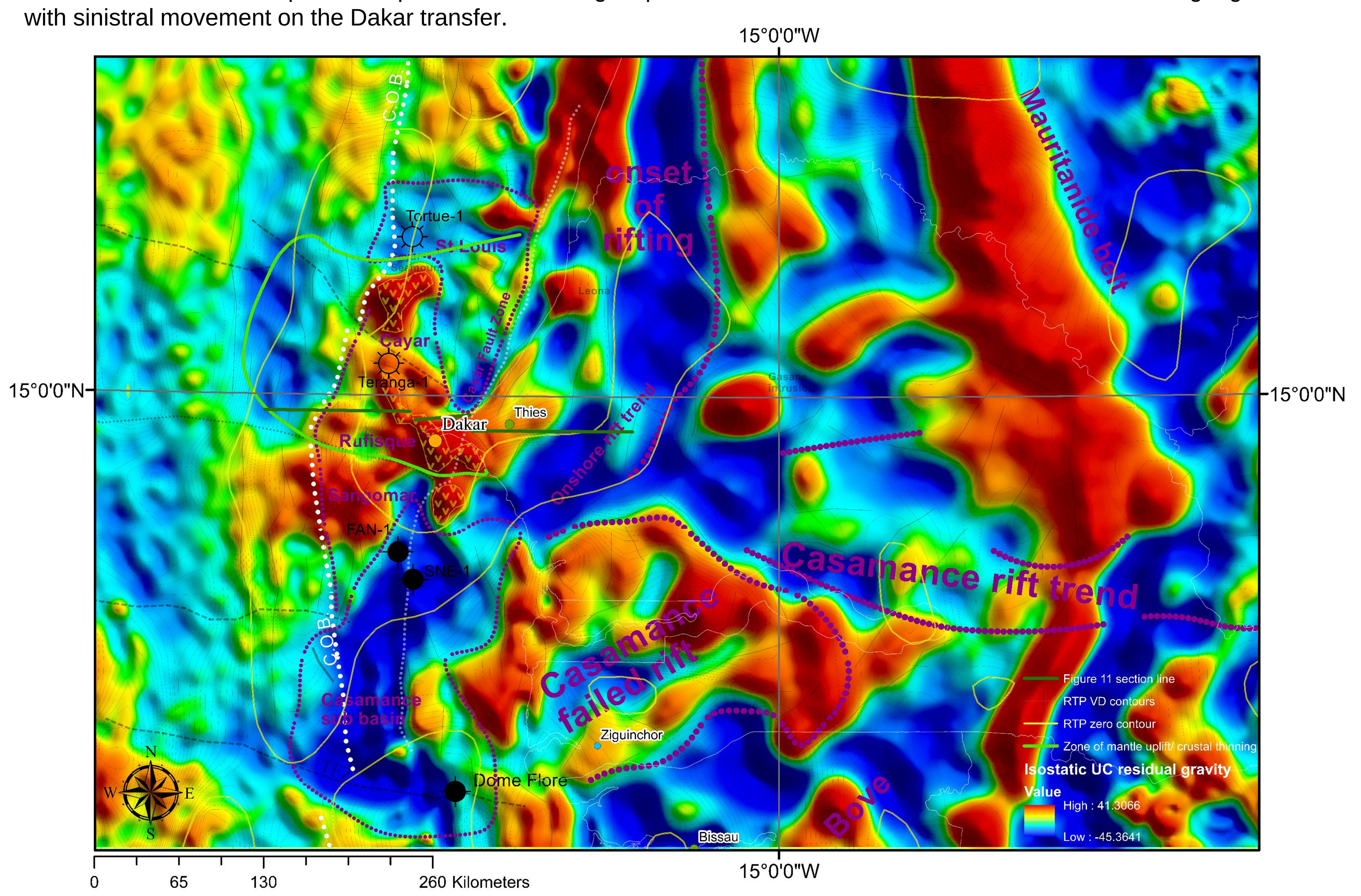

Figure 10: Residual of upward continuation (20km) of isostatic gravity with key interpretation features. COB (dotted white line), Senegal basin compartments (purple dotted lines), gravity pick of front of carbonate structure, residual magnetic RTP vertical gradient contours, the RTP zero line (yellow) and region of crustal thinning (light green). Figure 11 section line in dark green.

Exploration consequences

The satellite magnetics derived continental-ocean boundary (COB.) has been delineated using the signature of long wavelength components, and this interpretation is supported by the gravity-derived Moho structure. These results provide the heat flow control for basin modeling and defining the early Mesozoic geology in the Dakar region. There is evidence that the Peninsula rides on a major horst block, underpinned by crustal thinning. The Dakar horst appears to be a deeper crustal feature also seen in the magnetics and may have formed at the onset of onshore rifting, restricting both extensional movement of the onshore trend and the Casamance rift arm.

The fracture zones seen in the magnetic signature support the COB interpretation and the derived Moho depth indicated from the gravity. The EMM residual anomalies may indicate the earliest Variscan collision and suggest major thrust-fold belts are associated with the larger broad residual magnetic anomalies with strike of the Variscan structure trending north east to north, north east, against the later Triassic rifting episode that strikes north. The EMM residual magnetic gradient clearly indicates the early Triassic onshore rift trend connecting with the Casamance sub-basin, versus the north-south trend in the Jurassic foreramp post-rift basin sequence.

Assuming the onset of crustal thinning was coeval to CAMP emplacement, the Dakar horst formed in consequence to deeper detachment faulting, restricting extensional Triassic rifting onshore, and Casamance rifting further to the south. Triassic salt would then have been restricted to shallow embayments due south of the horst (and the Dakar transfer compartment), and perhaps partially into the main NE rift arm onshore. The subsequent Jurassic drift phase, characterized by marine transgression would have initiated the carbonate build up on the Dakar horst and south along the western front of the Casamance failed rift. Marine transgression restricted by the western front of the detached basement high, is marked by the contrasting Dakar horst gravity high to onshore rift gravity low trend. Cretaceous sources would have reached gas generation following the later Cenozoic magmatism across Dakar and Cayar, versus in the south where only oil generation is achieved by verse of their depth of burial (Cameron et al, 2016). The residual upward continuation of isostatic gravity structure and basin compartments are shown above in **figure 10**. An excellent fit exists with the seismic as illustrated on **figure 11**. Prominent from west to east on the profile are the COB, the Cayar Fault Zone and the onshore rifting; more information on this profile is provided by Cameron et al, 2016. The Cayar-Rufisque, Sangomar compartments show gravity highs associated with the magmatic doming, and horst footprint. Casamance sub-basin shows clear residual lows, with the oil discoveries on the margins. Other onshore gravity troughs, offset to the north and east from the eastern limit of Triassic rifting, most likely represent Palaeozoic basins as demonstrated by Villeneuve et al (2015),. Given they are Palaeozoic basins, Mesozoic maturation will be an issue since the depth of burial and sediment thickness will be less in this proximal setting, but the Palaeozoic section is likely inverted, and thus at higher levels of maturity.

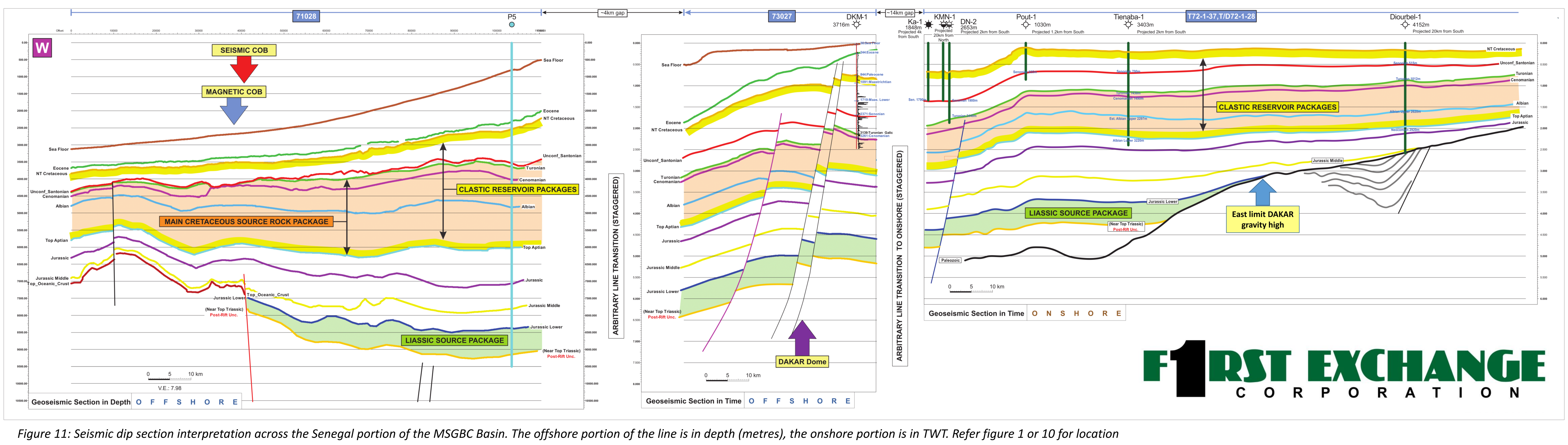

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Figure 11: Seismic dip section interpretation across the Senegal portion of the MSGBC Basin. The offshore portion of the line is in depth (metres), the onshore portion is in TWT. Refer figure 1 or 10 for location

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