Recognition of the pre-salt regional structure of Kwanza basin, offshore in West Africa, derived from the satellite gravity data and seismic profiles

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Abstract

Kwanza basin, located on the west coast of Africa and the east side of the South Atlantic Ocean, has the potential for deep-water oil and gas exploration. Previous studies have shown that the pre-salt system within the area has high potential for oil and gas storage. However, due to the shielding effect of the evaporating salt rock during the Aptian period, the quality of seismic reflection profiles of the pre-salt layers is poor. This means that the pre-salt sequences, the main fault, the scale and distribution pattern of the rift are not clear. To clarify the pre-salt regional structure pattern and further guide pre-salt exploration, we carried out a series of analyses and target processing of seismic and gravity data. Further, combining other available geological and lithology data as well as a tectonic model, we put forward a new understanding of the pre-salt structure of Kwanza basin. The research shows that the Kwanza basin can be divided into three uplift belts below the salt layer, which are distributed in the NW–SE trending direction. The three key profiles illustrate the distribution of uplift and depression in detail. The explained structural highs distributed in the outer Kwanza basin may be related to oil and gas reservoir. This study could provide the geophysical basis for the re-interpretation of the pre-salt seismic sequence, the strategic selection of pre-salt oil and gas and the next exploration deployment.

Keywords: gravity data, seismic profiles, Kwanza basin, processing and interpretation, uplift and depression

1. Introduction

The passive continental margins of the globe are mainly located on both sides of the Atlantic and India Oceans, constituting about 60% of the continental boundaries. Today, they have formed very important oil and gas resource areas, such as the West Africa and East South America of the Atlantic Ocean, the northwest continental shelf of Australia and the Mexico Gulf. The basins of passive continental margin were produced by seafloor spread under the control of regional tension when Laurasia and Gondwana broke up after the late Triassic. The opening of the South Atlantic occurred at a different time as well as space, forming four separate oceanic segments (Torsvik *et al.* 2009; Moulin *et al.* 2010). From north to south, they are called the equatorial segment, central segment, southern segment and the Falkland segment, the first three of which are shown in figure 1. There are two fracture zones, namely the Romanche Fracture Zone and Florianopolis Fracture Zone, dividing the first three segments into
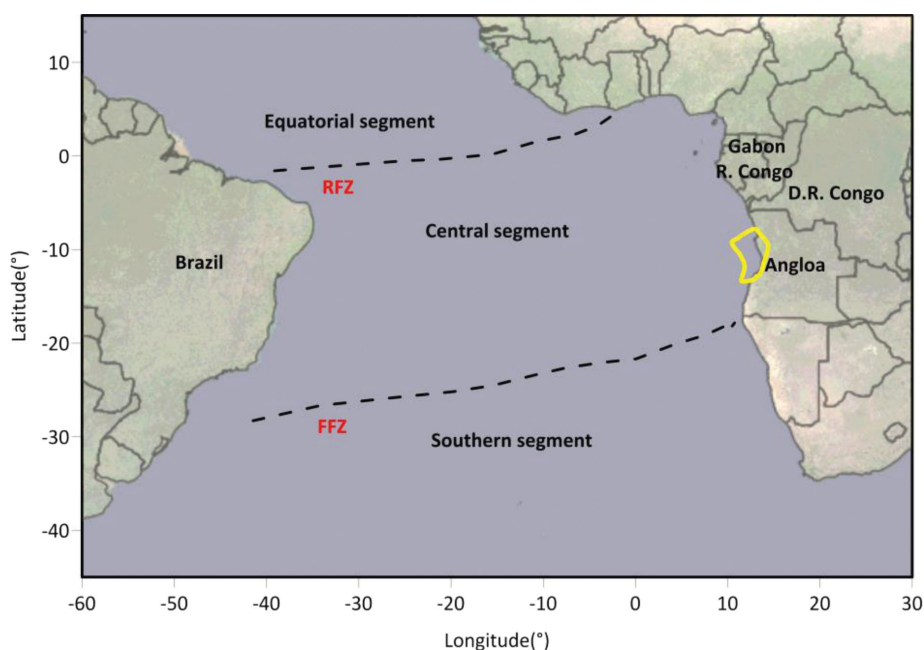
Figure 1. The location map of Kwanza basin (after Nicolai *et al.* 2013). The yellow region represents the Kwanza basin, RFZ is the Romanche Fracture Zone and FFZ is the Florianopolis Fracture Zone.

boundaries. The resulting formed conjugate basins are distributed on the both sides of West Africa and South America.

The Kwanza basin lies on and offshore from Angola, extending from Luanda in the north to the Cape de Santa Maria in the south. In terms of drilling and seismic densities, the basin is mature onshore and immature offshore. Encouraged by positive results in the deep-water Lower Congo Basin to the north, several companies have carried out 2D and 3D seismic surveys and drilled several exploratory wells.

Previous studies of seismic profiles in Angola margin (e.g. Contrucci *et al.* 2004; Moulin *et al.* 2005; Unternehr *et al.* 2010) have shown that the opening of the Central South Atlantic is caused by tectonically controlled crustal thinning. Further, the comprehensive interpretation of seismic profiles and potential field data sets (Blaich *et al.* 2010, 2011; Lentini *et al.* 2010) has illustrated that the thick sag basin is not the generally characteristic of the central segment of the South Atlantic as well as the associated abrupt thinning of the crust. Nicolai *et al.* (2013) presented the results of the deep crustal structure in the Kwanza basin from 3D gravimetric modelling and seismic results and formed a discussion about the implication of the opening of the Central South Atlantic. All these studies contain some knowledge of the deep structure of the Kwanza basin.

Due to the thick evaporate formation during the Aptian period in the transitional stage of structural evolution and the shielding effect of the salt layers, the qualities of seismic reflection of the pre-salt layer are poor. This means that the low research level of the pre-salt sequences and the main fault, scale and distribution pattern of the rift are not clear. To clar-

ify the pre-salt regional structure pattern and further guide pre-salt exploration of the Kwanza basin, based on a series of analyses and processing, combined with seismic and geological data, this paper puts forward a new understanding of the pre-salt structure pattern of the Kwanza basin.

2. Tectonic and geological setting

2.1. Evolution process

The formation of passive continental margin in the South Atlantic was caused by continental rifting and division between the America and Africa plates. The margin has experienced three main phases of tectonic evolution; namely, rifting, transition and drift phases (Teisserenc & Villemin 1990).

The rifting began around the end of the Late Jurassic and first affected the southernmost tip of the African continent, gradually extending to the north. Before the Late Jurassic, the passive continental margin of West Africa was in a stable craton evolution stage. From the Late Jurassic to the early Cretaceous, the Gondwana continent began to crack. Volcanic activity was very intense at this stage, giving rise to the formation of the volcanic chain of Walvis, which was located between North America and the African continent. The Kwanza basin evolved from the continental rifting when the southern Gondwana opened up (Shown in Figure 2).

2.1.1. The rifting phase (from Valanginian age to Barremian age in early Cretaceous). The rifting phase comprises of two stages; the syn-rift stage and post-rift stage. In the syn-rift
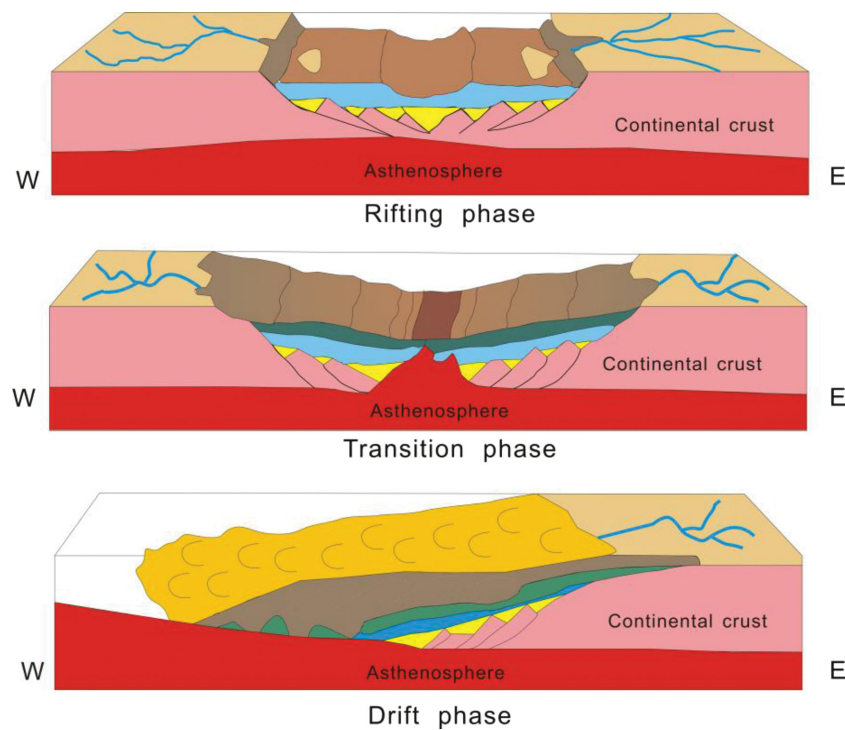
Figure 2. The tectonic evolution of the Atlantic marginal basin (revised after Moulin, 2003), including three phases: the rifting phase, transition phase and drift phase.

stage, a volcanic upwell and the bottom of the basin led to crustal thinning, resulting in an internal rifting in the southern Gondwana continent. The syn-rift stage was characterised by strong volcanism and the development of fault zones. After this time, the basin experienced a short period of denudation. The strata deposited in the syn-rift stage were denuded. In the Barremian age, as the rifting zone extended to the north, it further developed into a rift-sag type basin. This post-rift stage was the peak sedimentary period of continental rifting.

2.1.2. The transition phase (Aptian age in early Cretaceous). By the Aptian age, the rifting phase ends. At this time, the initial ocean crust of the South Atlantic began to form and seawater began to invade. Due to the barrier of the Walvis ridge in the south, the rift system in the north (the edges of the African plate and the South American plate), a huge ocean basin was formed and seawater poured into it periodically. At least seven transgressions occurred during this phase, and a large area of very thick evaporate rock was deposited. The average initial sedimentary thickness was about 600 m (IHS Report 2013).

2.1.3 The drift phase (from the Albian age to now). During the Albian age, with the continuous development of the ocean crust and fault zones, the Atlantic Ocean gradually formed. The ocean crust formed in the early stage gradually cooled and the basin was in a process of rapid subsidence. At this time, the passive continental margin of West Africa became a wide sea environment with marine sedimentary conditions, but the water depth was relatively shallow. By the Cenomanian age, the sea level permanently submerged the Volvis ridge. From the Campanian to Maastrichtian in the late Cretaceous, extensive transgression took place. Then, it was in the stage of global sea-level rise. The Sumble volcanic chain also became active in the Campanian period. The basin is divided into two regions: the main Kwanza and Benguela sub-basins (IHS Report 2013). From the Paleocene to Oligocene, it was in a period of global sea-level reduction. Here, due to the influence of the mantle upwelling in the east of the African continent, the whole African continent tilted to the west, leading to the uplift and erosion of the continental part (Jackson *et al.* 2005). A series of delta systems developed in the west coast of Kwanza basin, while the terrigenous clastic deposits in the coastal area were carried to the deep-water area, forming the deep-water turbidite fan. At the end of the Oligocene, due to the uplift of the eastern part of the basin and the loading of sediments, the intense salt tectonic movement resulted in the formation of salt extension area in the eastern part, salt compression area in the western part and the formation of ground wall in the upper part of the salt system. In the Miocene, transgression occurred, the sea level rose and a large area of marine sediments developed along the coast of West Africa. From the Pliocene to Pleistocene, the sea level dropped significantly (Nicolai *et al.* 2011).
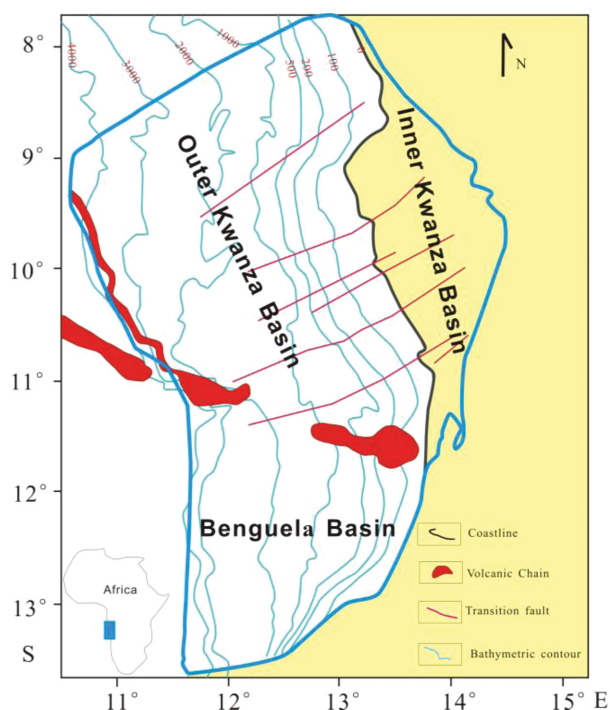
Figure 3. The tectonic framework of the Kwanza Basin (revised from Yang *et al.* 2013). The main part of the figure is the enlargement of the blue area of the map at the bottom left-hand corner.

2.2 The tectonic framework of Kwanza basin

After the evolution of pre-rift, rift, transition and drift periods, the structural pattern of both W–E trending zonation and N–S trending partition have been formed in Kwanza basin, shown in figure 3.

W–E trending zonation was formed by the uplift of the eastern part of the African continent in Paleogene. So the West African edge tilted westward as a whole, and the gravity loading of the overlying sediments caused the salt layers to slip. With regards to this, the main Kwanza area can be divided into a salt extension area and salt extrusion area.

The N–S trending partition represents the structural macroscopic features of Kwanza basin. The Kwanza basin can be divided into three secondary tectonic units; the inner Kwanza secondary basin, the outer Kwanza secondary basin and the Benguela basin. The inner and outer Kwanza basin are roughly bounded by the coastline; the inner and outer Kwanza and the Benguela basins are bounded by volcanic rock chains.

3. Data and methods

3.1. Seismic data processing and interpretation

The seismic data sets are sourced from the China National Ocean Oil Company. There is a total of 30 2D reflection seismic profiles in the study area, including 21 W–E trending lines and 9 N–S trending lines (shown in black in figure 8).

The two specific profiles of depth migration results with different imaging qualities are shown in figure 4. For subsalt formations, the qualities of all the profiles are relatively poor. Only a few parts can identify subsalt formation (figure 4a), whereas most of the profiles do not reflect subsalt information (figure 4b).

According to the analysis of the original data, we believe that there are technical difficulties with accurate removal of multiple waves to solve the problem of subsalt imaging and in improvement of the effective information at low frequencies to better obtain imaging quality. We carried out targeted data processing. First, we suppressed ghost waves and increased low-frequency information energy to obtain the valid signals. Second, we used surface-related multiple elimination to predict and suppress multiple waves as well as multi-channel predictive deconvolution and Radon Transform. Finally, a variety of velocity modelling methods were combined in terms of high-precision imaging, which is also the most important aspect. For strata above the salt, we used the time difference spectrum of the remaining depth along the layer to perform multiple tomographic inversion to iteratively eliminate the time difference of common reflect point gathers, thus ensuring accurate imaging of the formation above the top of the salt. Aiming at the boundary of the salt, the top and bottom of the salt were repeatedly picked on the pre-stacked depth migration data volume, and the migration was performed to obtain the best imaging of the boundary. Regarding the strata below the salt, two interactive pick-up speed methods (both lateral and vertical percentage layer velocity scan) were used to establish an accurate velocity model and further ensured reasonable imaging structure characteristics of subsalt low signal-to-noise ratio formations. Figure 5 shows the comparison of the two processing results of one seismic profile, where the new results show better imaging resolution.

The previous research results showed that the subsalt filling sequence in the West African rift basin can generally be divided into three periods. (i) Syn-rift period-basin filling in the extensional period, which is characterised by the development of rampart structures and syn-sedimentary faults. (ii) The sag period, where after the fault ceases to be active, a set of overlying strata is filled. This set of strata plays the role of 'filling up', filling in the slab structure formed during the rifting period. It is basically not affected by faults, but its overall pattern is still controlled by the strata in the rifting period. It appears in the form 'thick in the middle and thin on both sides', generally called depression basin filling. (iii) The regional filling period, which is characterised by a set of thin and stable transgressive fillings. This set of strata also plays the role of 'regional filling up', quasi-plainizing the strata in the previous rift and depression periods, followed by salt deposition. Therefore, this set of formations can be classified into 'transitional' formations.
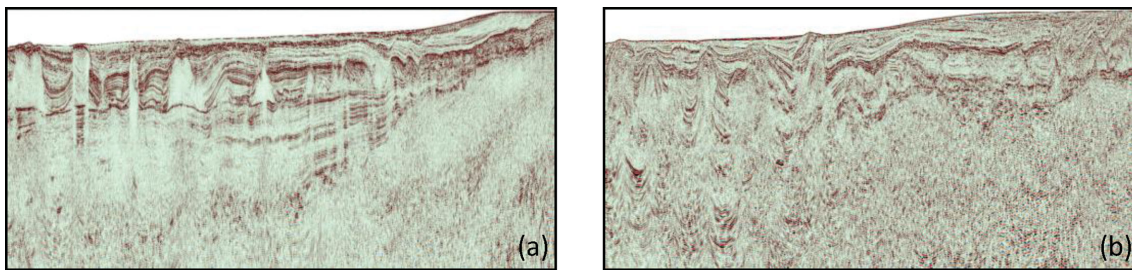
Figure 4. Two representative seismic profiles: (a) relatively high quality shown in figure 8a with a red line and (b) relatively low quality shown in figure 8a with a yellow line.
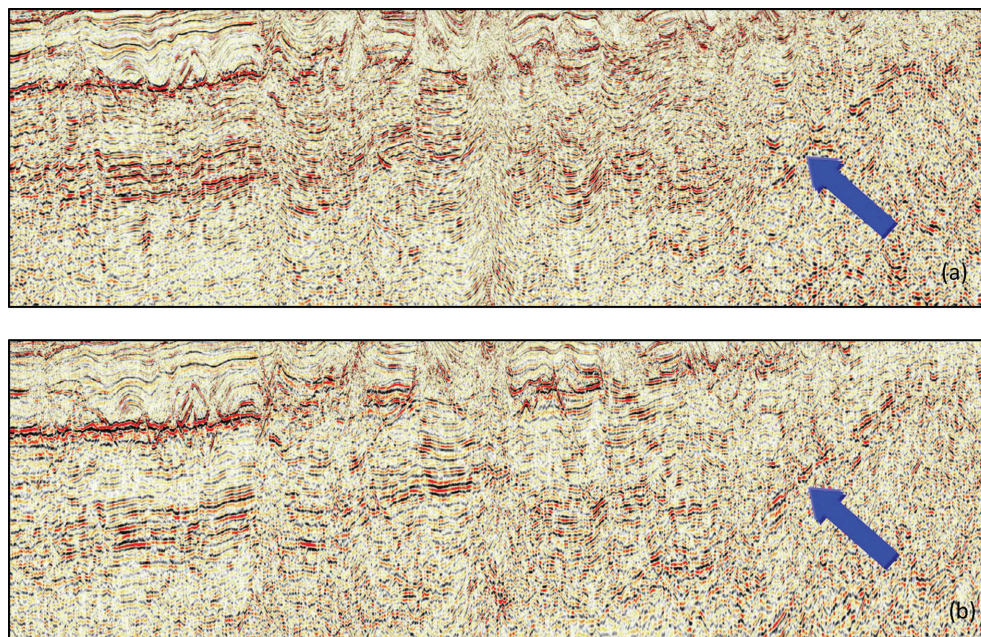
Figure 5. The comparison of two results of one seismic profile: (a) the basic processing result and (b) the new targeted processing result.
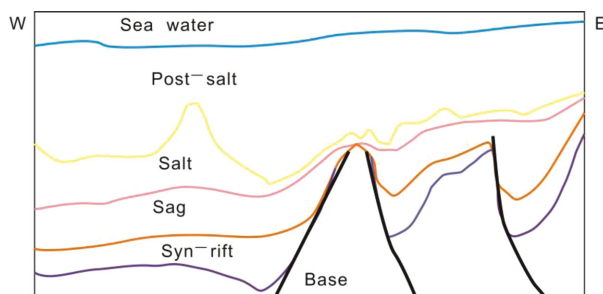
Figure 6. The basic layer pattern by seismic interpretation in the Kwanza basin (based on IHS Report 2013; Nicolai *et al.* 2013).

Based on the sedimentary filling sequence described here, this study of subsalts explained four tectonic horizons. From the bottom to top, there are the bottom interface of the rifting period (base), the bottom interface of the sag period, the bottom interface of the salt layer and the top interface of salt layer. This is shown in figure 6.

The quality of seismic data in the study area is generally poor, and the structural interpretation is inherently highly multi-solvable. Therefore, it is difficult to entirely determine the uplift and depression pattern only based on the interpretation of seismic data. The gravity method is an important auxiliary method for this study and an important basis for determining the basement uplift and depression pattern. The gravity data can be effectively processed, and the influence of overlying strata from the structural interpretation of seismic profiles can be eliminated by forwarding modelling. Finally, the residual gravity anomaly that reflects the basement uplift and depression pattern can be obtained (more details later). In the case where the uplift and depression pattern on the seismic profile is uncertain, reference can be made to gravity results. The high and low residual anomaly has a good guiding significance for structural interpretation. In the meanwhile, the depth variation of the basement can be obtained by 2.5D modelling for gravity data based on both seismic interpretation and lithology references. The corresponding density parameters in 2.5D modelling are listed in Table 1. This reflects the upward or downward trend of the base surface, which can in turn guide the structural

Table 1. The density parameters of different layers

Layer name	Density value (g/cm³)
Sea water	1.03
Post-salt	2.50
Salt	2.16
Sag	2.45
Syn-rift	2.55
Base	2.67

interpretation of seismic profiles. Structural interpretation and gravity studies are repeatedly combined and finally the best fitting and most reasonable results can be reached. Figure 7 shows the seismic interpretation results (top) and gravity fitting results (bottom) for the profile (purple line in figure 8). In figure 7c, the interface between the brown strata (rift) and the pink stratum (base) is the basement plane. It can be seen that the gravity-fitted basement and the seismic interpretation of the basement plane change trends and the overall pattern are basically consistent. Therefore, the combined results of seismic structural interpretation and gravity fitting are credible to a certain extent.

3.2. *Gravity data processing and method*

The satellite gravity data was collected from the gravity anomaly database (Topex V18.1) of the global satellite geodetic website (Sandwell & Smith 2009, 2013, 2014). The database uses the newly released EGM 2008, and provides the spatial gravity anomaly data global network of 1′ × 1′. The Bouguer anomaly is obtained from free air anomaly and elevation data at global scale in spherical geometry (see figure 8). Here the results are consistent with the release of WGM2012.

The observed gravity anomalies contain all the gravity response of geological bodies with density contrast at different depth in the subsurface. One must separate the local 'target' anomaly caused by the specific geologic bodies from the total gravity anomalies. In the previous study, many different kinds of valid separation methods have been proposed, including upward continuation, matching filtering, polynomial fitting, Wiener filtering, preferential continuation, wavelet transform multiple-scale decomposition and nonlinear filtering (Guo *et al.* 2013).

Here we use preferential continuation to divide the regional and residual gravity anomaly from Bouguer anomaly. The preferential continuation has the advantage of complete anomaly separation. When performing the conventional upward continuation, the short wavelength signals caused by the shallow source and the long wavelength signals by the deep source are both performed upward continuation at the same time. As a result, both the signals are attenuated. Here we obtain the residual signals by subtracting the
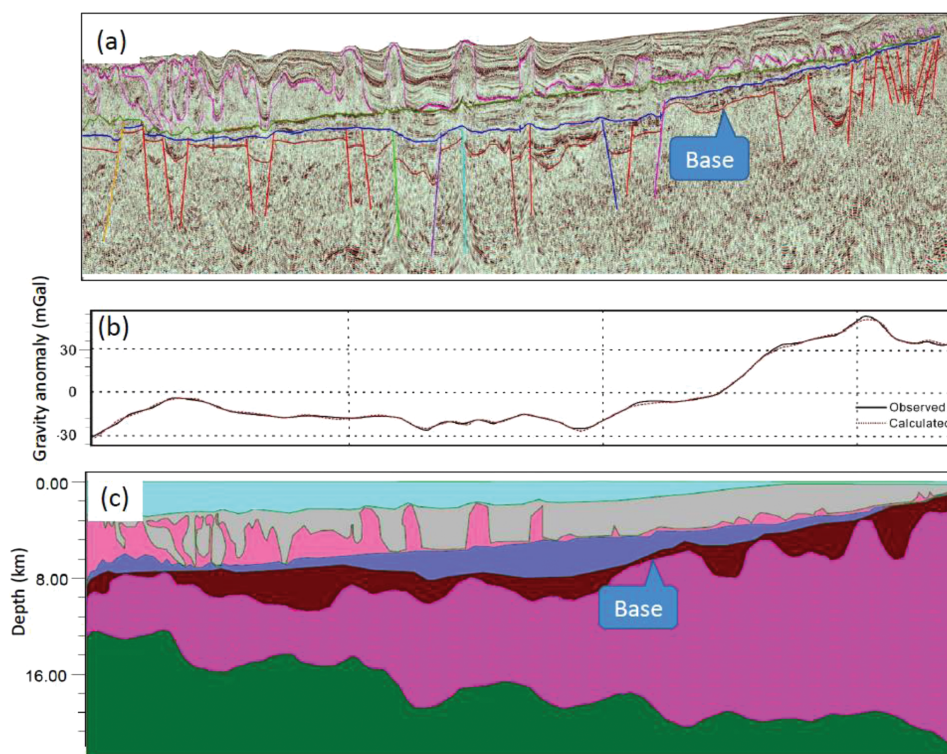
Figure 7. Combination interpretation of one seismic profile and gravitational forward modelling. (a) Seismic profile interpretation; (b) 2.5 D gravity forward modelling and (c) gravitational forward modelling based on the seismic interpretation.
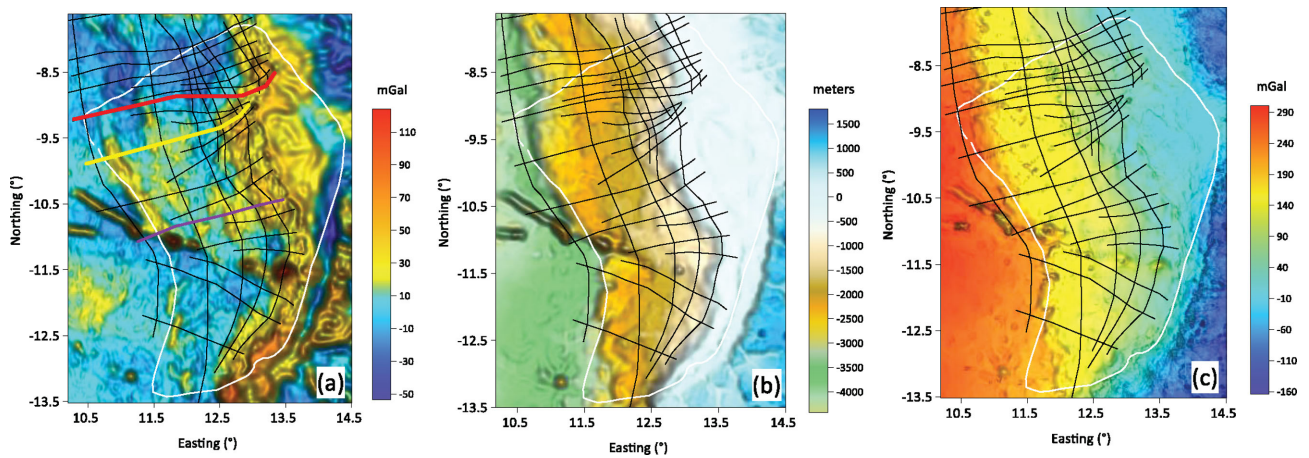
Figure 8. The free air (a), elevation (b) and Bouguer gravity anomaly (c) maps of the Kwanza basin. The black lines represent the distribution of seismic reflection profile, the white lines show the region of the Kwanza basin.
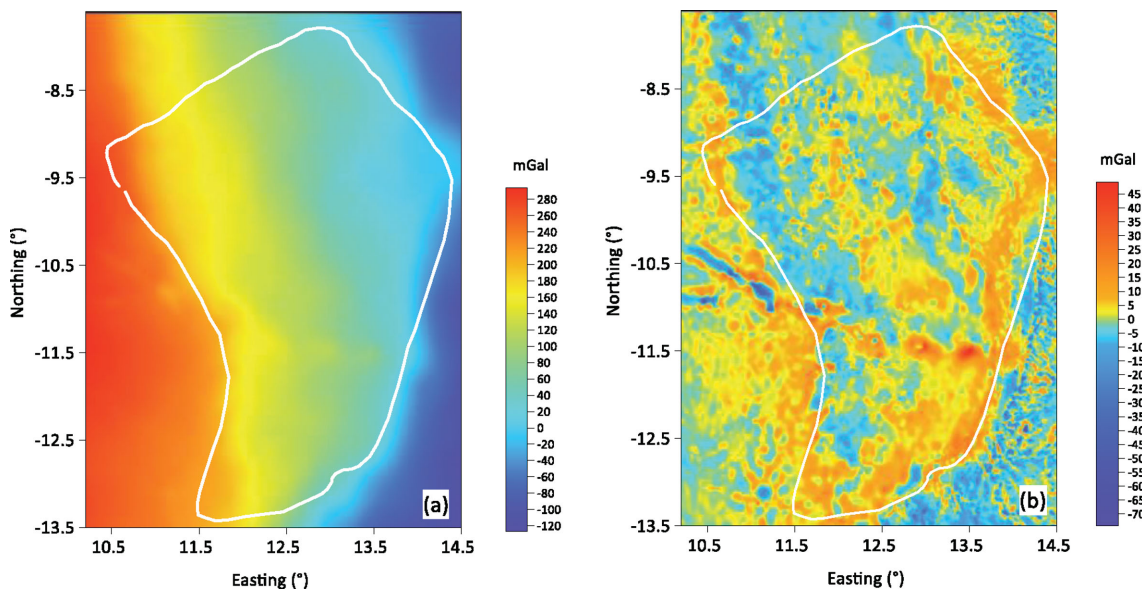
Figure 9. The separation of Bouguer gravity anomaly: (a) regional gravity anomaly representing the effect of Moho interface and (b) residual gravity anomaly.

upward continued regional signals from the observed anomalies. The residual signals tend to have parts of regional anomalies (Guo *et al.* 2013). Using the Moho results in Nicolai *et al.* (2013) as a reference, we obtained the regional gravity anomaly and residual gravity anomaly (figure 9). The regional gravity anomaly represents gravitational response caused by the variation of Moho interface, whereas the residual gravity anomaly means the response of other density variations expect Moho.

To obtain the pre-salt regional structural framework, we must also remove all layers above salt. With the combination of seismic interpretation and density parameters, we first compile the thickness map of salt and above salt layers, then use 3D forward modelling based on grid residual node (Zhang *et al.* 2018) to further calculate the resid-

ual gravity anomaly caused by subsalt layer (Shown in figure 10). The residual gravity anomaly in figure 10b reflects the pattern of uplift and depression to some extent.

3.3. *The workflow of the comprehensive interpretation*

In the previous two sections, we focused on the main key parts involved in gravity data and seismic profiles. In fact, in the process of comprehensive interpretation, we also consider other aspects of the data available, such as the comparison with South America results, known oil field data, HIS database, guidance of tectonic model and regional tectonic background. The comprehensive interpretation process is shown in figure 11.
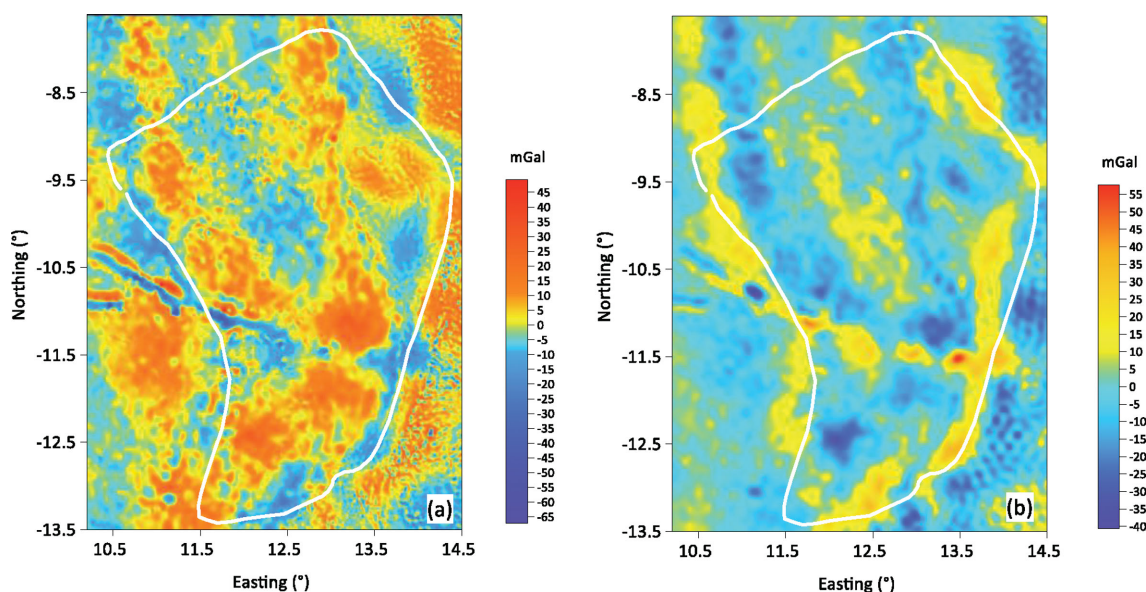
Figure 10. The further separation of residual gravity anomaly: (a) gravity response caused by salt and post-salt layer and (b) gravity response representing the subsalt variation.
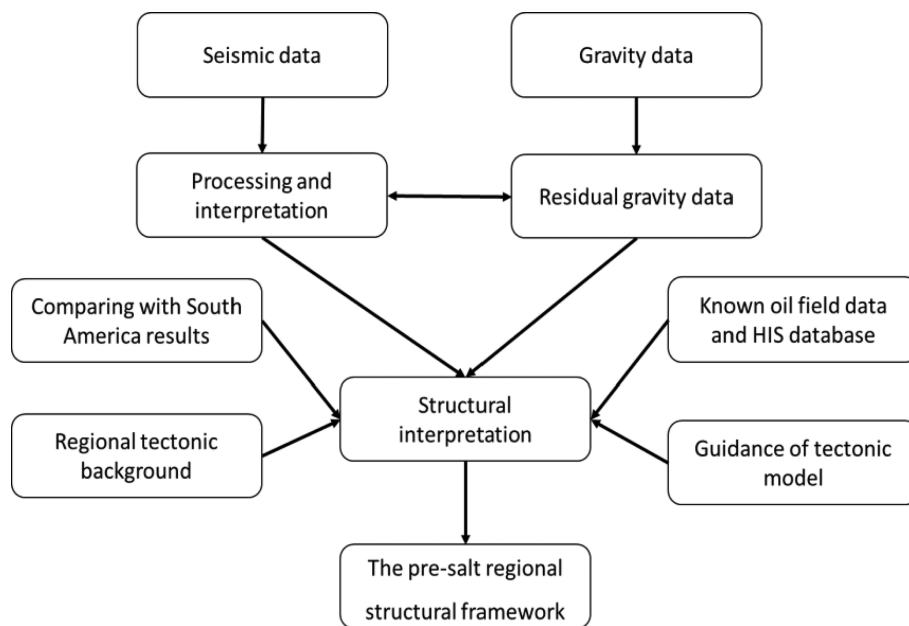
Figure 11. The workflow of comprehensive interpretation using various kinds of available information.

4. Results and discussion

Limited by the data conditions, this paper focuses on the subsalt tectonic characteristics of the Outer Kwanza basin, which is more or less the offshore portion. By interpreting the seismic profiles of different structural locations in the study area and combining the results of gravity data processing, we identify the uplift and depression pattern of the subsalt in the Kwanza basin, which also can be regarded as horst and graben/half-graben structures. That is to say, the Kwanza basin can be divided into three uplift belts under the salt, and they are distributed in NW-SE direction (shown in figure 12).
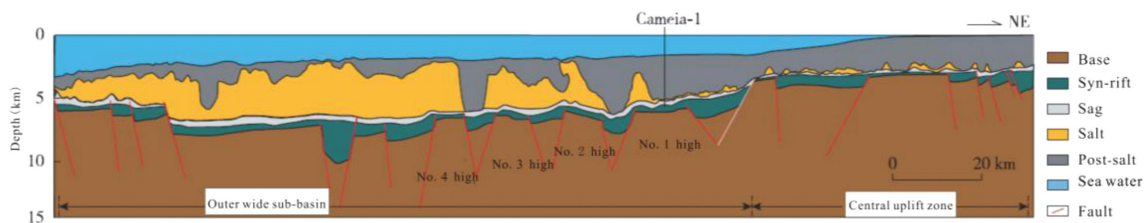
Figure 13 is the interpretation of 2D seismic profile combined with gravity data across the central and southern part of Kwanza basin (the location of the profile A-A' in figure 12). From this section, the central uplift zone and the outer wide sub-basin can be identified and secondary depressions are developed on the central uplift zone. The Atlantic hinge zone (pink fault) is the boundary between the central uplift zone and the outer wide sub-basin. In the outer wide zone of
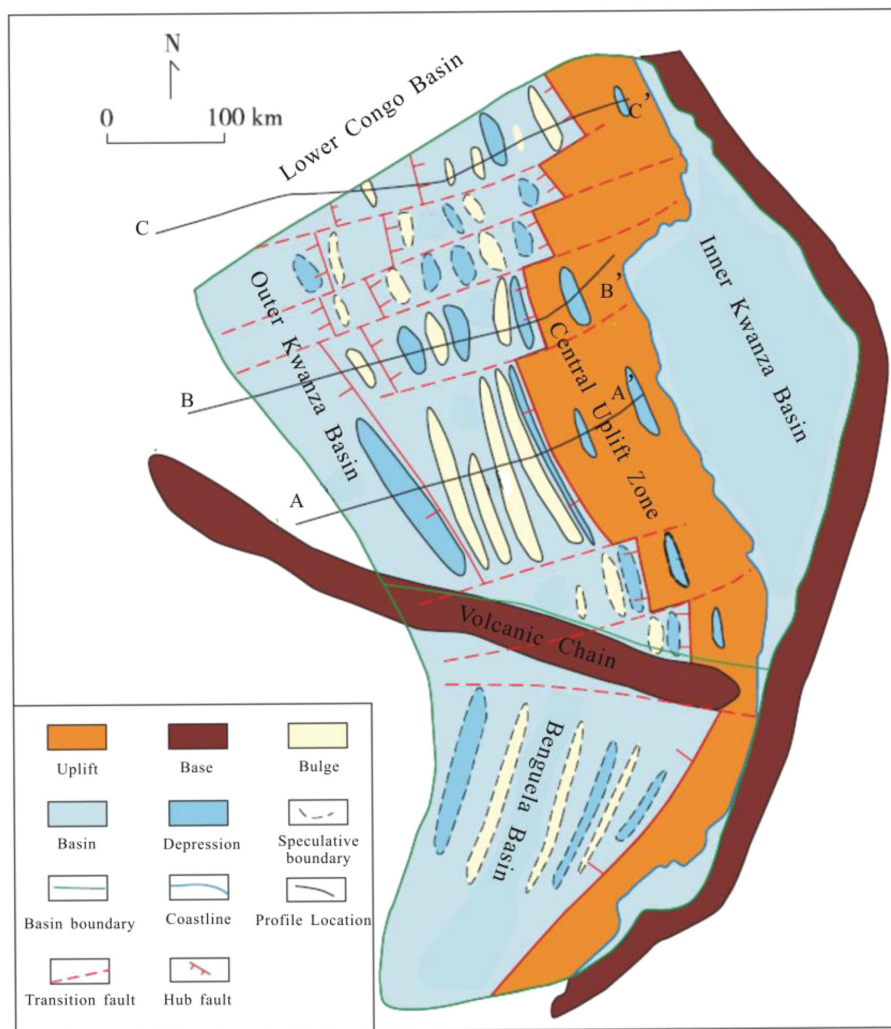
Figure 12. The uplift (including structural highs) and depression distribution of Kwanza basin based on comprehensive interpretation.
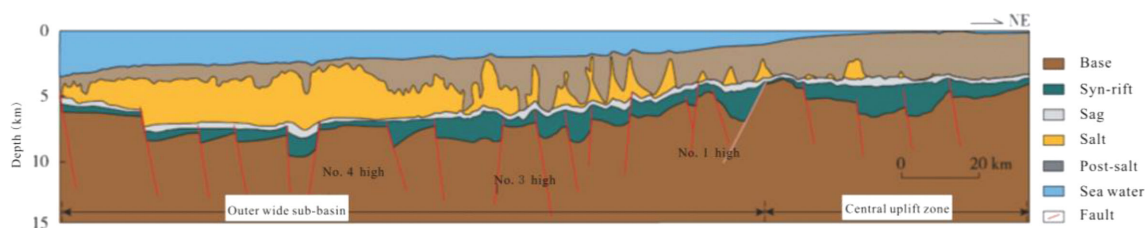

Figure 13. The interpretation of 2D seismic profile combined with gravity data across the central and southern part of the Kwanza basin (the location of the profile A-A' in figure 12).

the Kwanza basin, four secondary uplifts are developed. The No. 1 structural high is the drilling block of the Cameia-1 well, which has been proved to be a favourable drilling site. The eastern side of the uplift is close to the Atlantic hinge zone, where the descending wall is a favourable hydrocarbon-generating depression. The high is an up-dip barrier block of the wedge-shaped structure in the rift basin. There is an overlying salt rock cap, so this block is a favourable oil and gas accumulation area. The No. 2, No. 3 and No. 4 structural highs

have the same structural background as No. 1, both of which are structural high barriers formed by the faulting in the rifting period, and both sides are adjacent to the deep sag, which is presumed to be a potential favourable exploration site.

Figure 14 is the interpretation of 2D seismic profile combined with gravity data across the central part of Kwanza basin (the location of the profile B-B' in figure 12). This section is similar to figure 13, showing the structural features of the central uplift zone and the outer wide sub-basin. An

Figure 14. The interpretation of 2D seismic profile combined with gravity data across the central part of the Kwanza basin (the location of the profile B-B' in figure 12).
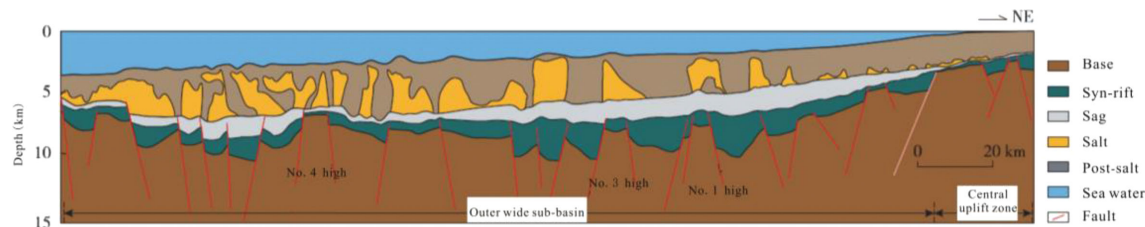
Figure 15. The interpretation of 2D seismic profile combined with gravity data across the northern part of Kwanza basin (the location of the profile C-C' in figure 12).

obvious secondary depression is developed in the central uplift zone. The Atlantic hinge zone (pink fault) separates the central uplift zone from the outer wide sub-basin. It should be noted that three secondary structural highs are developed in the outer wide sub-basin. Compared with figure 13, No. 2 structural high is absent in this section and No. 1, No. 3 and No. 4 structural highs correspond to figure 13 in the location. In particular, No. 1 structural high is a more typical upward block with a wedge-shaped structure. In view of the significant breakthrough made in the Cameia-1 well, it is speculated that this block has great exploration potential. No. 3 and No. 4 structural highs are also controlled by faults, and both sides are depressed and connected with each other, which are presumed to be potential exploration breakthrough areas.

Figure 15 is the interpretation of 2D seismic profile combined with gravity data across the northern part of Kwanza basin (the location of the profile C-C' in figure 12). Affected by the transition fault, the scale of the central uplift zone on this profile has become smaller, and the Atlantic hinge zones and secondary structural highs have shifted to the land side. Nonetheless, three secondary structural highs can be identified in the outer wide sub-basin, but the scale of the structural highs is not as large as those shown in figures 13 and 14, which may be related to the nature of the basement, structural location and transfer faults.

5. Conclusions

A series of analysis and processing of seismic data can improve the resolution and provide a good data basis for further identification and interpretation of the post- and pre-salt horizons. Target processing of gravity data can obtain a gravity response that can only be produced by the uplift and depress patterns, and also can give auxiliary materials for seismic interpretation. The comprehensive interpretation results show that the Kwanza basin can be divided into three uplift belts under the salt, and they are distributed in a NW–SE trending direction. The three key profiles illustrate the distribution of uplift and depression in detail. The explained structural highs distributed in the outer Kwanza basin may be related to oil and gas reservoir. This study can provide the geophysical basis for the re-interpretation of the pre-salt seismic sequence, the strategic selection of pre-salt oil and gas as well as the next exploration deployment.

Conflict of interest statement None declared.

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