PS Modeling Basin Evolution and Assessing Source Rock Potential Within the Orange Basin, Offshore South Africa*

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Abstract

The Passive continental margin basins, the Orange Basin, offshore of the southwestern coast of South Africa is South Africa's largest offshore basin covering an aerial extend of 130 00km^2. This sedimentary basin is relatively under explored, with only 39 wells drilled up to date. The under explored nature of the basin coupled with proven Hydrocarbon (HC) plays, the Kudu and Ibubeshi gas fields, makes it a good platform for frontier HC exploration.

The current study focuses on the southern part of exploration blocks 3B/4B within the Orange Basin. It encompasses a basin analysis study by integrating 40 seismic lines, petrophysical logs and chemical data from 6 wells to model basin evolution and evaluating the source potential of the area to generate HC.

The seismic interpretation was done on the Cretaceous (post-rift) succession that commenced from the 6At1 sequences boundary, excluding the basement and syn-rift intervals. In total, nine sequence boundaries were mapped, seven within the Cretaceous and two Tertiary based on the stratigraphic framework of Brown et al. (1995) and Weigelt and Ünzelmann-Neben (2003). Well correlation across the six wells identified 3 possible source rocks: 1) Lower Aptian, 2) Upper Aptian and 3) Cenomanian.

The source rocks were modeled with varying heat flow histories to assess source rock maturation and HC proliferation within the basin. The first model assumes exponential heat flow decay, with a heat flow of 80W/m^2 at the onset of rifting that decays to 55W/m^2 at present day. The second model takes a constant heat flow of 55W/m^2 in consideration over the whole evolution of the basin.

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1. Introduction

The Orange Basin is a divergent passive margin basin, that developed during the Late Jurassic-Early Cretaceous and is South Africa's largest offshore basin covering an area of 130,000 km^2 out to the 200m isobath. The large areal extent of the Orange Basin, extending from the shelf to the ultra-deep marine, makes it a relatively under explored basin with only 39 wells drilled to date, which equates to ± 1 well drilled per 400km^2. The sparse data set of the Orange Basin with the majority of wells drilled on the shelf and widely spaced seismic data grid in the ultra-deep marine region coupled with proven hydrocarbon plays evidenced by the Kudu and Ibhubesi gas fields, makes the Orange Basin a good platform for frontier hydrocarbon exploration.

The area of study is situated in the southern part of exploration blocks 3B\4B of the South African offshore acreage within the Orange Basin (see Figure 1 (b)). The study encompasses a basin analysis study that integrates 40 seismic lines, petrophysical and chemical data (Figure 5) from 6 wells to model basin evolution and evaluate source rock potential within the southern Orange Basin.

The seismic interpretation, using Schlumberger's Petrel, was done on the Cretaceous sedimentary succession that commences at the 6At1 Hauterivian sequence boundary to present day; the study excludes the basement and syn-rift intervals. Three source rock intervals were identified, but for the scope of the poster only two of the source rocks will be discussed. Source rock modeling, using IES PetroMod, was done using 2 models of varying heat flow histories. The first model assumes a constant heat flow of 55 mW/m^2 at the onset of rifting through to the present day and the second assumes an exponential decaying heat flow of 80mW/m^2 at the onset of rifting decaying to a present day heat flow of ±55mW/m^2.

The study at hand forms part of a bigger umbrella project, the Inkaba Ye Africa research initiative, and aims to contribute toward the research objectives of the South Atlantic Gas System (SAGS), a subsidiary research project of Inkaba Ye Africa, by modeling basin evolution of the Orange Basin and consequent source rock maturation.

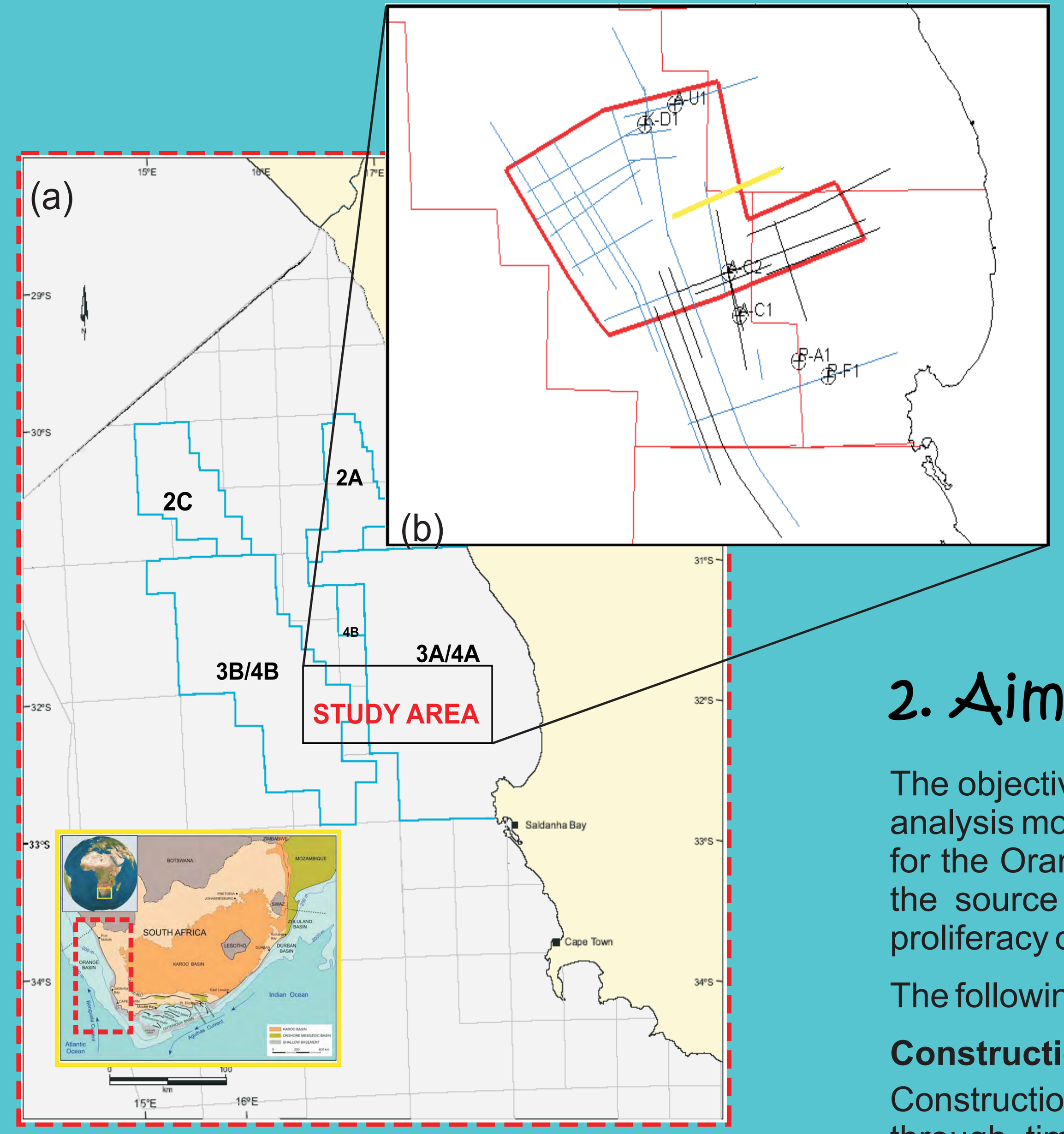

FIGURE 1
(a) The study area with the Orange Basin offshore the southwest coast of South Africa. The study area is bounded to the west and east by geographical coordinates (longitude) 15°E and 18°E and (latitude) 31°S and 33°S.
(b) Gives a detailed outline of the study area, showing well position and seismic line orientation within the basin.

Wells	Well Data							Petrophysics				
	Completion Reports	Geochemical Reports	Vitrinite Refectance	Well Tops	Check Shots	Pyrolysis Data	Biostratigraphic Reports	Gamma Ray	Spontaneous Potential	Caliper	Bulk Density	Neutron Porosity
A-C1	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
A-C2	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
P-F1	✓	✓	✕	✓	✓	✕	✓	✓	✓	✓	✓	✓
P-A1	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
A-U1	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
K-D1	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

FIGURE 5
Outline of the data used in the study

2. Aims/Objectives

The objective of the study is to generate deterministic basin analysis models, using available physical and chemical data for the Orange Basin to model basin evolution and assess the source rock, to qualitively estimate the hydrocarbon proliferacy of the Orange Basin.

The following approach was employed:

Construction of a Geological Basin Model.
Construction of a geological evolution of the Orange Basin through time to serve as a conceptual input model for petroleum system modeling, by integrating seismic data and petrophysics.

Construction of a Petroleum System Model.
Generation of a Petroleum system model to allow the assessment of hydrocarbon generation potential of source rocks (richness of the source rocks) and the migration and accumulation of hydrocarbons.

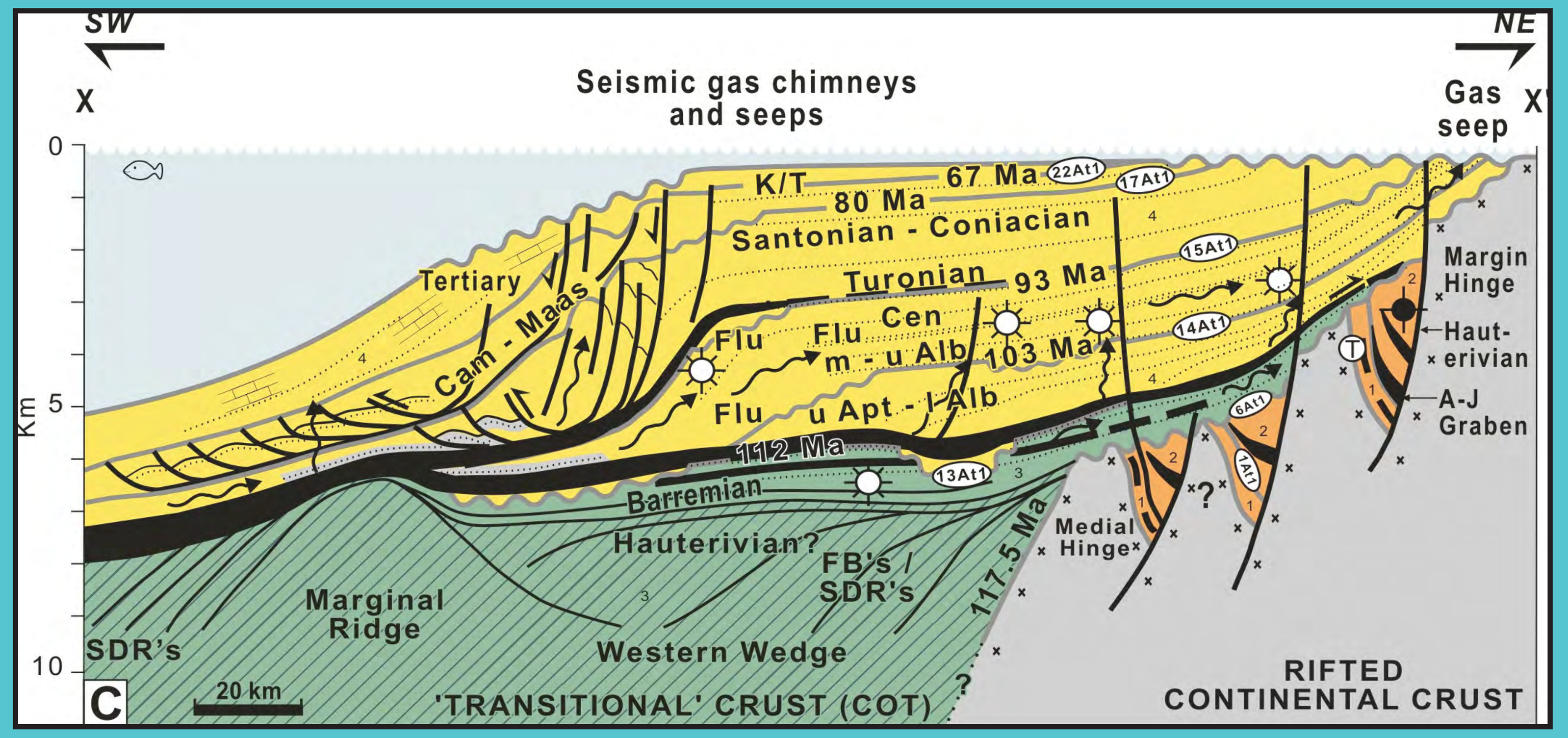

FIGURE 2
Illustration of a generalized composite stratigraphic cross-section through the Orange Basin as proposed by Jungslager (1999), detailing the petroleum systems of the Orange Basin *(Petroleum Agency SA, 2008)*.

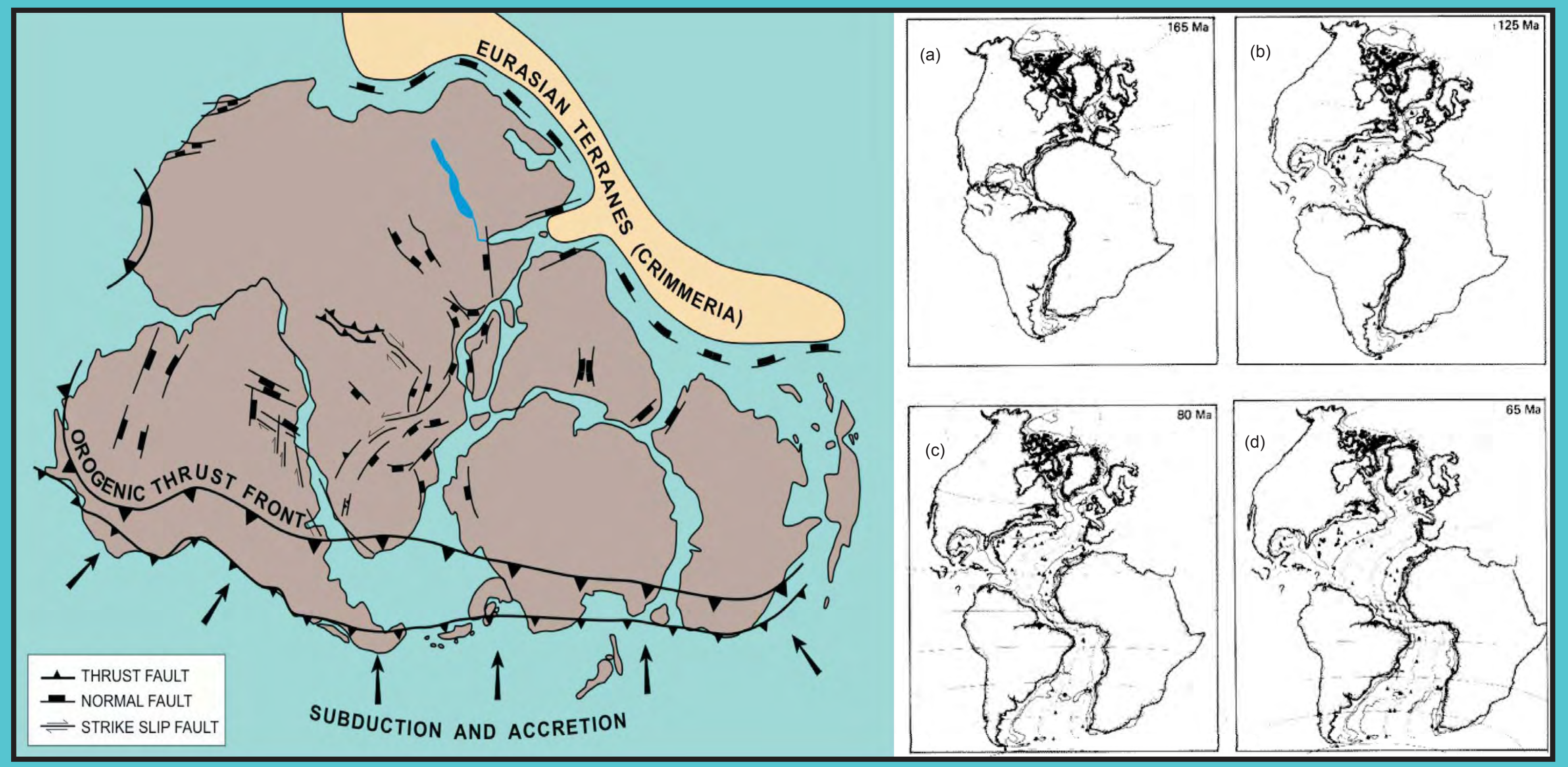

FIGURE 3
An illustration of the impending break-up West Gondwana into the South American and African continental plates. (a) Gondwana in the late Paleozoic-early Mesozoic (pre-rift). (b) An Illustration showing the fragmentation of West Gondwana into the South American and African continental plate, Upper Left image date as 165 Ma (Mid Jurassic) and lower right image dates 65 Ma (Early Cenozoic) *(Figure 3 modified after de Wit and Ransome (1992) and Sclater et al (1977))*

3. Geological Setting

South Africa's western continental margin as described by many involves a passive divergent margin that developed due to the break-up of West Gondwana into the South American and African continental plates during the Late Jurassic-Early Cretaceous (Broad et al, 2006). The resulting continental fragmentation gave rise to the Orange Basin, with present day surface expression stretching between the Kudu Arch (northern boundary) and the Columbine-Agulhas Arch (southern boundary), as illustrated by the isopach map in Figure 9 (Ala and Selley, 1997).

Sediments of the Orange Basin were sourced by the westward flowing Orange and Olifants river systems and accumulated as a post-rift sediment thickness of over 7000 meters in some places, consisting of both terrestrial and marine sediments dated as old as the Hauterivian (Junslager, 1999). These sediments are underlain by a rifted basement consisting of Karoo-age sediments, granite, acid lavas, phyllites and gneisses (Petroleum Agency, 2008).

The underlying rifted basement generally displays isolated north-south trending grabens and half-grabens parallel to the present day shoreline. These grabens are filled with continental sediments interbedded with volcanics east of the medial hinge showwards. There is a large syn-rift wedge characterised by seaward dipping reflectors west of the medial hinge and landward dipping reflectors off the marginal ridge (see Figure 2) (Jungslager, 1999).

The basement is overlain by northward thickening Cretaceous sedimentary succession that has a lower transitional syn-rift sedimentary package, Barremian-Aptian aged, consisting of alternating fluvial and marine rocks followed by a fully developed drift succession consisting of prograding clastics, characterised by a lack of structure on the shelf (van der Spuy, 2003).

Three source rocks occur in the Cretaceous Sediment package a regionally developed syn-rift source rock of Hauterivian age,a Barremian-Aptain source rock and a Cenomanian-Turonian source rock that are directly related to the major stages of basin evolution with in the Orange Basin(see Figure 4) (Jungslager, 1997 and van der Spuy, 2003).

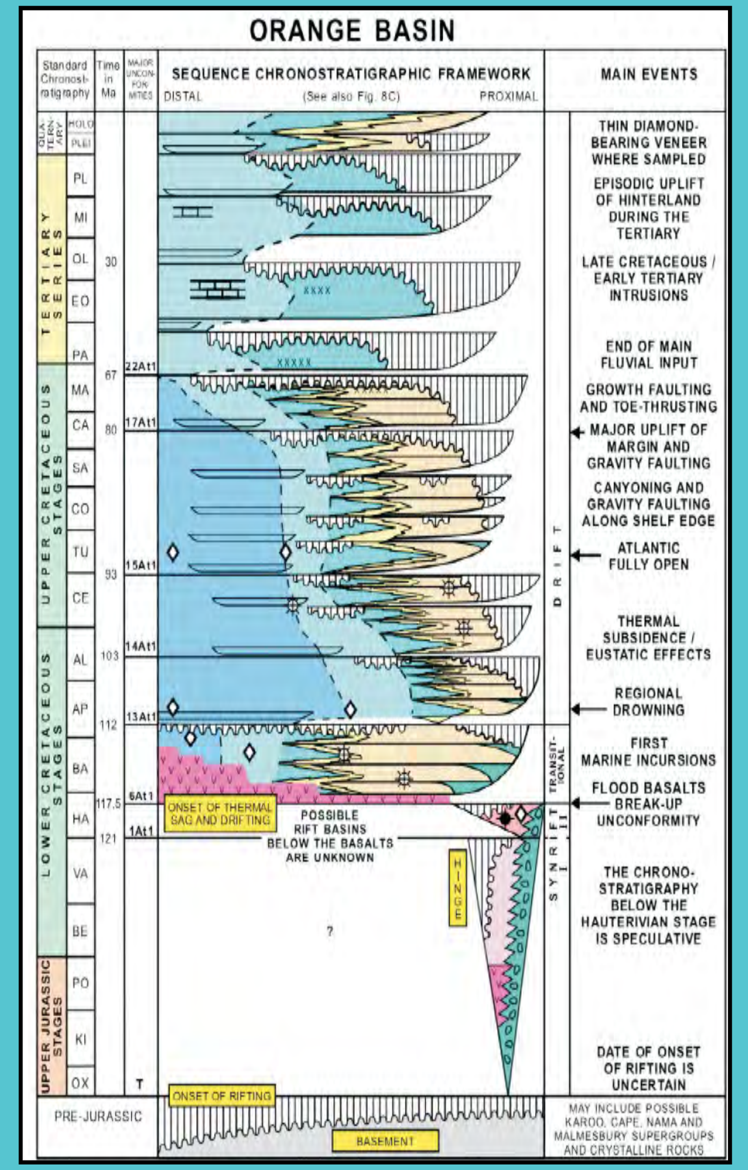

FIGURE 4
Generalized chronostratigraphy of the Orange Basin as per Brown et al (1997).

Part 1

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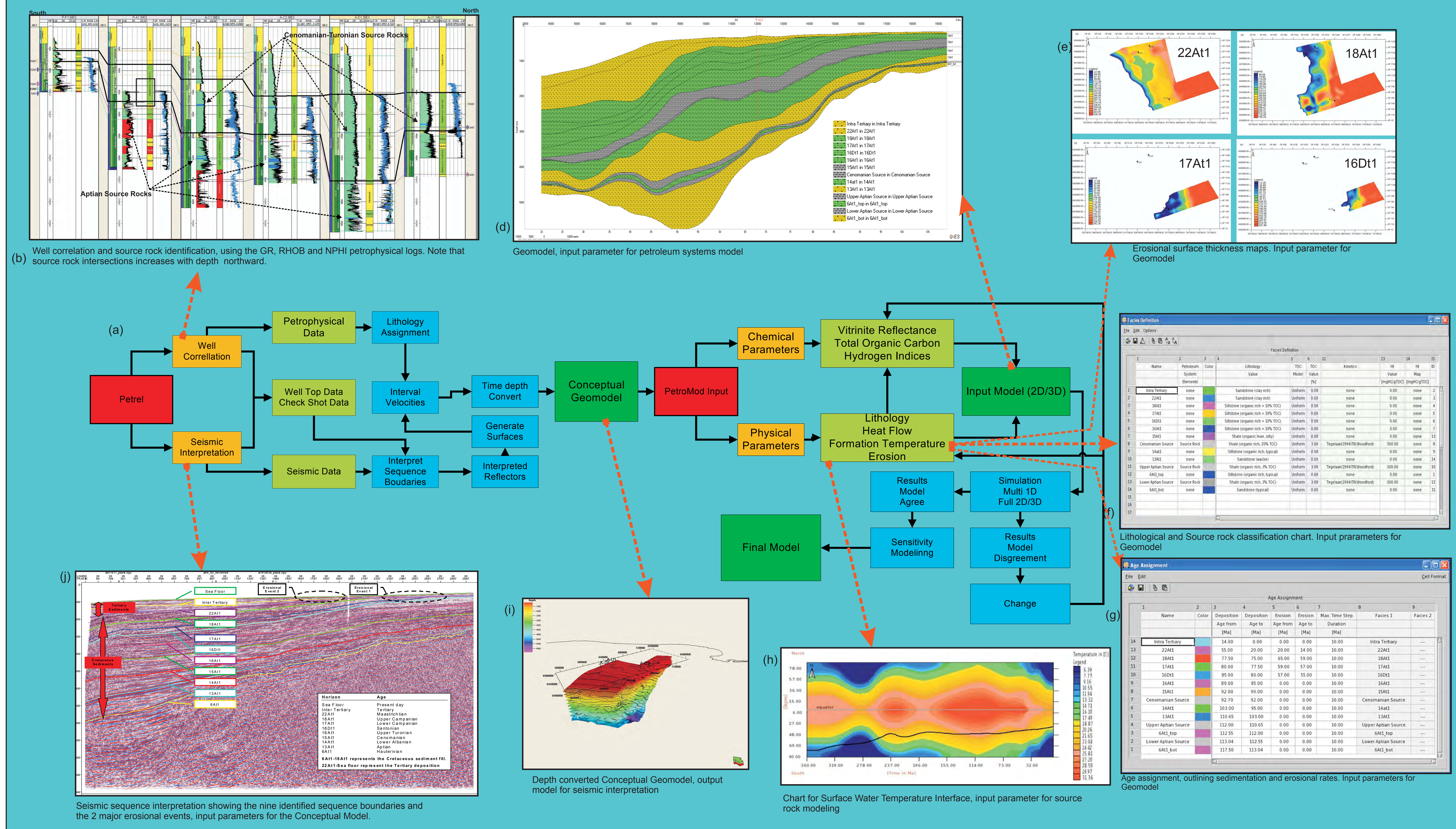
4. Work Flow/Methodology



(b) Well correlation and source rock identification, using the GR, RHOB and NPHI petrophysical logs. Note that source rock intersections increases with depth northward.

Geomodel, input parameter for petroleum systems model

Erosional surface thickness maps. Input parameter for Geomodel

Lithological and Source rock classification chart. Input prarameters for Geomodel

Age assignment, outlining sedimentation and erosional rates. Input parameters for Geomodel

Chart for Surface Water Temperature Interface, input parameter for source rock modeling

Depth converted Conceptual Geomodel, output model for seismic interpretation

Seismic sequence interpretation showing the nine identified sequence boundaries and the 2 major erosional events, input parameters for the Conceptual Model.

FIGURE 6

Illustrates the general workflow followed for the seismic interpretation and basin modeling, outlining the various input parameters required, processes applied and the various output models.

5. Basin Evolution Modeling

Modeling the basin evolution of the southern Orange Basin was constricted to the Cretaceous sedimentary succession and Tertiary sediment and excludes the basement and the rift-drift sedimentary succession.

Forty seismic lines of varying vintage and quality were interpreted and integrated with petrophysical well log data to produce the depth converted Conceptual model for the Petroleum systems modeling (see Figure 6 (h)).

Applying the principles of sequence stratigraphy 9 sequence boundaries were identified within the Cretaceous sedimentary succession following the framework of Brown et al (1997) (see Figure 7(b)), as listed below;

- Sea floor — Present Day
- Inter-tertiary — Tertiary
- 22At1 — Maastrichtian
- 18At1 — Upper Campanian
- 17At1 — Lower Campanian
- 16Dt1 — Santonian
- 16At1 — Upper Turonian
- 15At1 — Cenomanian
- 14At1 — Lower Albian
- 13At1 — Aptian
- 6At1 — Hauterivian

Two erosional events were identified within the Upper Cretaceous succession based on the interpretation of truncating erosional sequence boundaries identified on seismic data (see Figure 6 (i)).

Event 1

This event is dated Maastrichtian in age and is a fairly significant erosional event, eroding a total of thickness of 1285m as it eroded the 18A, 17A and 16D successions in a very short span of time.

Event 2

This event is dated as Oligocene in age. It is interpreted to have eroded total thickness of 430m of the 22A1 succession .

Depth converted seismically interpreted sequence boundaries were used to generate sediment thickness maps. These maps were then are used to model migration of the sedimentary depocenter through time.

Figure 7 (a) details the migration of the Orange Basin depocenter from the onset of drifting to present day as the basin undergoes constant evolution due to tectonics and sediment influx.

Sediment thickness maps of the interval between the 6At1 and 15At1 show the depocenter migrates shoreward, coinciding with the global sea-level curve that shows a relative rise in sea-level.

Sediment thickness maps of the interval between 15At1 to present day show a basinward shift in the depocenter and an overriding northward migration of the depocenter, that coincides with the isopach map of Jungslager (1999), showing that the thickest accumulation of sediments occur in the Northern Orange Basin (see Figure 9).

Based on the sediment thickness maps in Figure 7(a) the overall trend shows a north-ward migration of the depocenter.

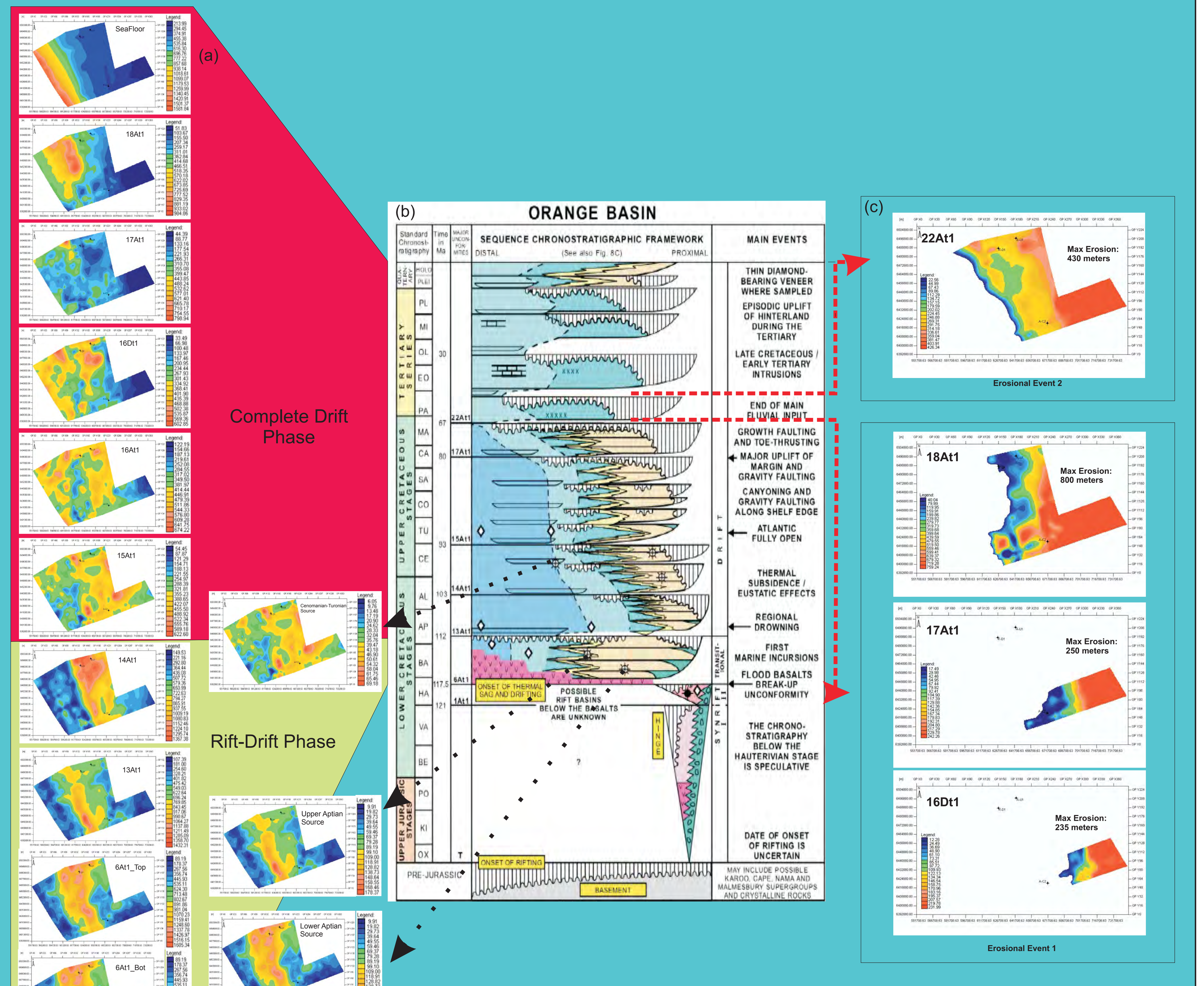


FIGURE 7

Outline of the Orange Basin evolution over time. (a) A series of sediment thickness maps from the rift-drift unconformity (6 At1) to the present day sea floor, showing transition of the depocenter of the Orange Basin through time. (b) Generalised chronostratigraphy chart as per Brown et al (1997). (c) Displays the generated erosional maps to suffice for sediment loss during the two identified erosion events on the shelf, at different level in the stratigraphy.

Part 2

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6. Source Rock Characteristics

Rock-Eval Pyrolysis data together with TOC and Depth data gives a quick and reliable measure of the source rock's hydrocarbon generation potential by assessing the quality (kerogen type), quantity (TOC) and maturity (T_{max}) of the source rock, when Rock-Eval measurements are cross-plotted against one another.

Figure 8 (a) is a cross plot of TOC vs Depth showing TOC concentrations relative to depth for wells across the study area. From the cross plot it is evident that the highest TOC's occur at 2000m, 2800m and 3200m depths. These depths on average indicate respectively the Cenomonian/Turonian and Aptian source rocks intervals as reported by Junslager (1999) and van der Spuy (2003) and evident from well correlation analysis (see Figure 6 (b)).

The Aptian-Albian source is divided into the Upper Aptian and Lower Aptian source interval based on well log interpretations, literature and reports. The Source rock interval gets progressively more deeply buried from south to north across the study area due increasing thickness of the overburben.

Figure 8(b) is a cross plot of Hydrogen Index vs Oxygen Index that gives an indication of the quality of the source rock. From the cross plot its evident the majority of the sample set plots in the Type III kerogen region.

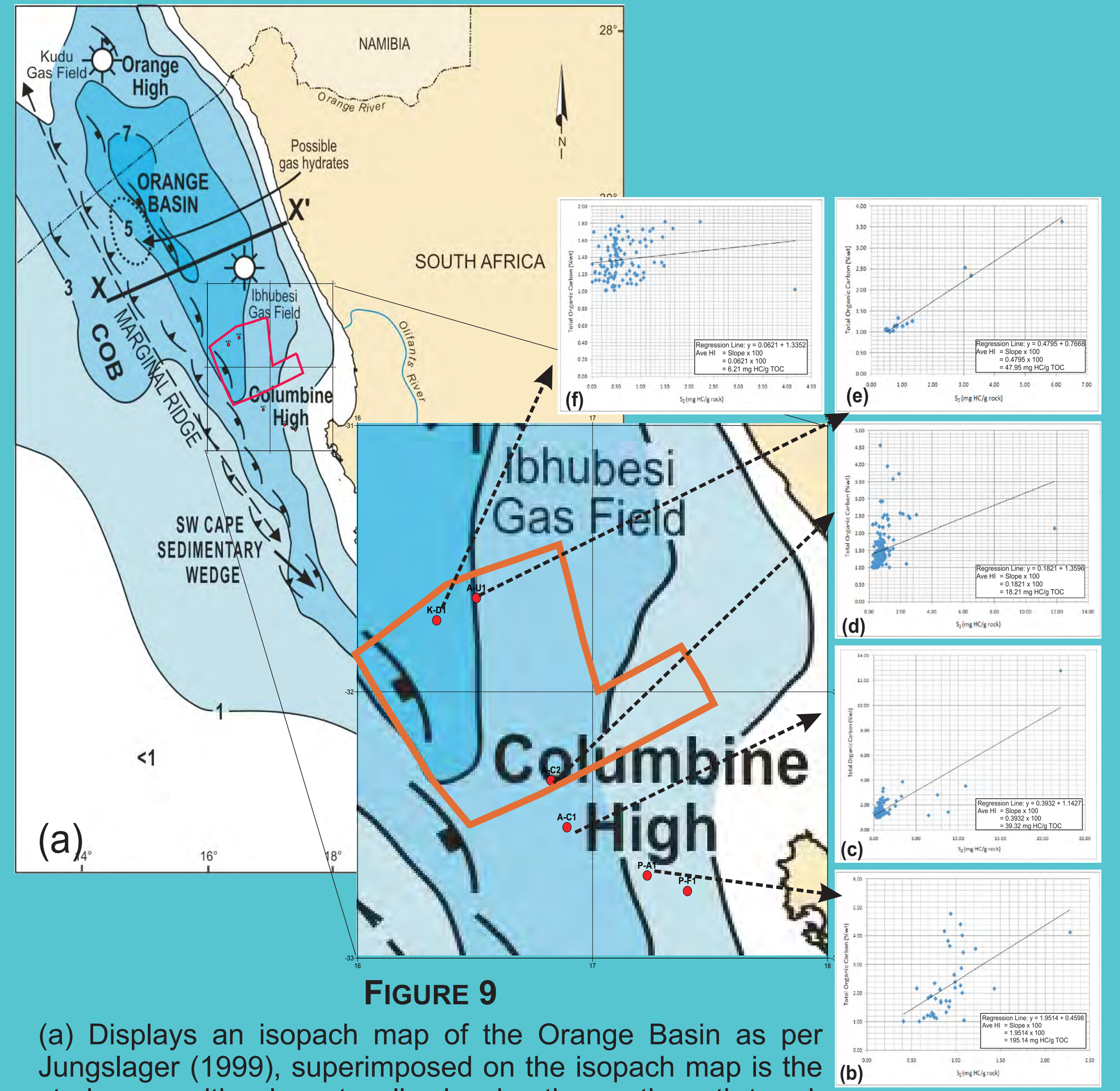

FIGURE 9

(a) Displays an isopach map of the Orange Basin as per Jungslager (1999), superimposed on the isopach map is the study area with relevant wells showing the south-north trend. (b)-(f) Displays a series of S_2 vs TOC cross plots of the relevant wells plotting samples of >1wt% TOC.

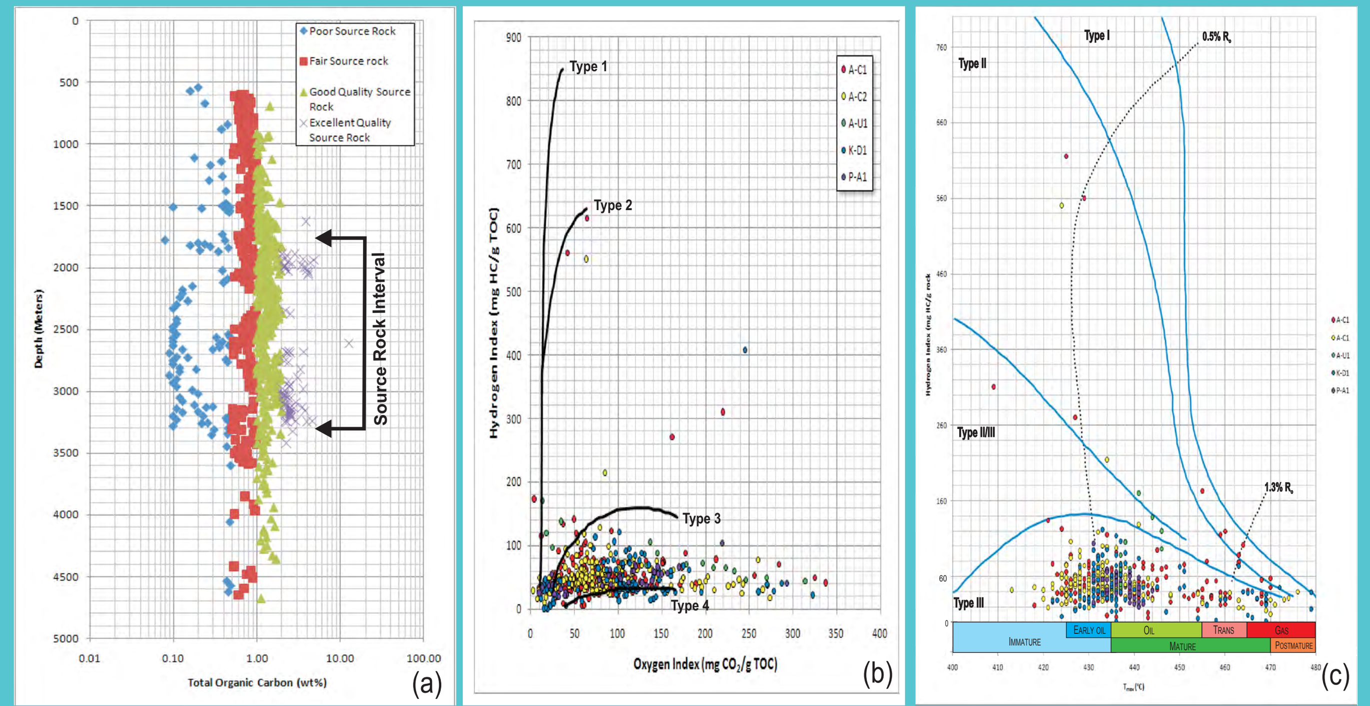

FIGURE 8

Cross plots of various Rock-Eval, TOC and Depth data plotted to assess source rock quality, quantity and maturation.
(a) Cross plot of TOC (wt%) vs depth, assessing the TOC abundance.
(b) Cross plot of Hydrogen Index vs Oxygen Index, assessing source rock quality.
(c) cross plot of Hydrogen Index vs Tmax, assessing source rock quality and degree of source rock maturation

Figure 8(c) is a cross plot of Hydrogen Index vs T_{max}, this cross plot gives an indication of the quality of the source rock at its present maturity level. From the plot it can be deduced that the source rock is within the early oil window, with some samples plotting well with in the mature oil/gas and window

The results above indicate that the source intervals for the Createaceous sedimentary succession across the study area are characterised by a Type II/III kerogen, that has a relatively high TOC (ave TOC= 3 wt%) and the source rock display a maturity level of a immature to early mature stage in the oil window.

Figure 9 (a) shows an isopach map of the Orange Basin, showing the general trend of a northward thickening of the post-rift succession and the basin depocenter. It is overlain by the outline of the study area and shows the well locations.

Figures 9 (b)-(f) shows cross plots of S_2 vs TOC. The cross plot of S_2 vs TOC assumes TOC as a linear function of S_2, that produces a regression line where the slope of the curve gives the average Hydrogen Index value for a source rock sample suite (Dahl et al (2004)).

The cross plots follow the south-north trend of the wells (Figure 9 (b)-(f)) and show the reduction in kerogen quality from south to north. The southern most well, well P-A1 has a average HI value of 195.14mg HC/g TOC and the northern most well, well K-D1, has an average HI value of 6.21mg HC/g TOC for all the samples with a TOC >1wt% over the identified source rock interval (see Figure 8(a)) .

It can be inferred from the above results that with increasing sediment thickness there is a decease in the quality of the source rock due to influx of less rich organic sediments, thus lowering the TOC of the source rocks, or that the northen part of the Orange Basin was higher concentration of land derived organic matter (higher order plant material) making it more Type III/IV kerogen prone source rock having lower Hydrogen Index values.

7. Maturation Modeling

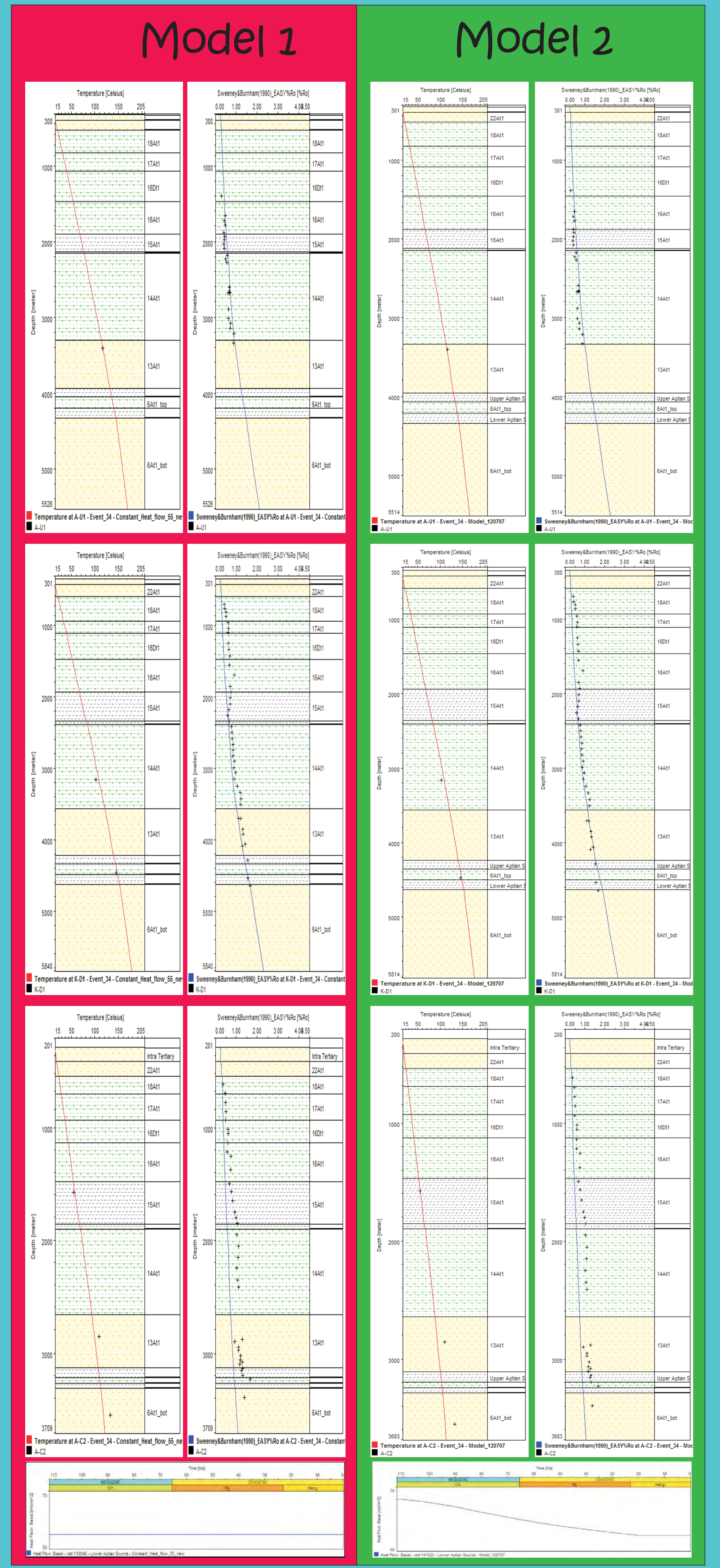

FIGURE 10

Comparison of the two heat flow models to compare how well the measured maturation data, Vitrinite Reflectance and Formation Temperature, correlate with the calculated outputs of Model 1 and 2 as a measure calibration.

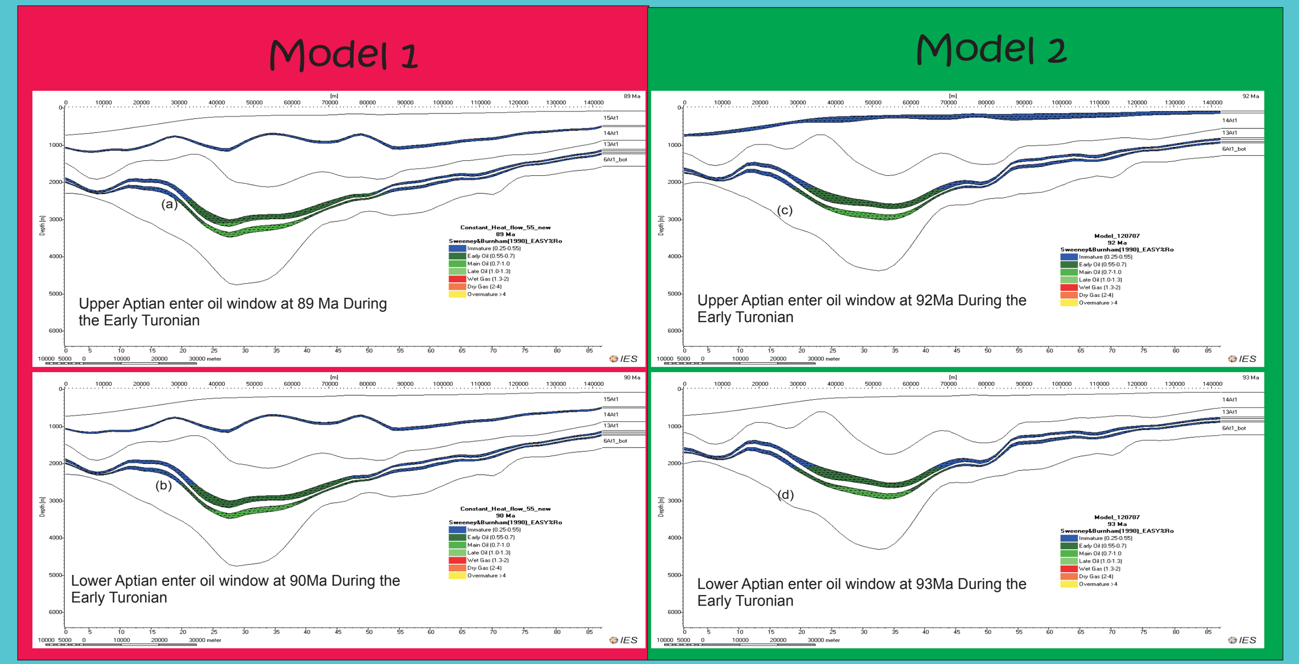

FIGURE 11

East- West aligned cross section for Models 1 and 2 showing first entry of source rock into the oil window of the Upper Aptian and Lower Aptian source rocks, based on the calculated transformation ratios for each model.
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For the purpose of the poster only maturation modeling results of the Upper and Lower Aptian source rocks are displayed and discussed as they show a much higher degree of thermal maturation, indicated by high transformation ratios.

For the purpose of modeling the source rock maturation within the study area, two maturation models with different heat flow histories were applied. Aside from this, identical input parameters were used for both models.

Maturation Model 1 assumes a constant heat flow of 50 mW/m^2 for the study area throughout basin development. Maturation Model 2 assumes a exponentially decaying heat flow for the study area throughout basin development, with an initial heat flow of 80mW/m^2 at the onset of rifting decaying to present day heat flow estimated at 50mW/m^2 (Goutorbe et al (2007)).

The input parameters include: organic rich siltstone to clay-rich sondstone lithologies (Figure 6 (f)), a computed Surface Water Temperature Interface, (Figure 6 (h)), TOC of 3 wt% for source rocks, erosional and sediment thickness maps, sedimentation and erosional rates (Figure 6 (g)) and a Stretching Factor (Beta) of 1, 5.

The calculated Maturation Models need to be verified against maturation data,(e.g. Formation Temperature and Vitrinite Reflectance data) measured from boreholes.

Figure 10 shows the comparison of the calibration between the calculated maturation models against measured Vitrinite Reflectance and Formation Temperature data for both heat flow model 1 and 2 across three boreholes within the study area. The borehole are A-C1, K-D1 and A-U1 trending from south to north.

Comparing maturation models 1 and 2 against the measured maturation data across the 3 boreholes shows no significant difference between the results of maturation models 1 and 2. An exception is borehole K-D1 that shows a better fit to the measured Vitrinite Reflectance calibration data for Model 2.

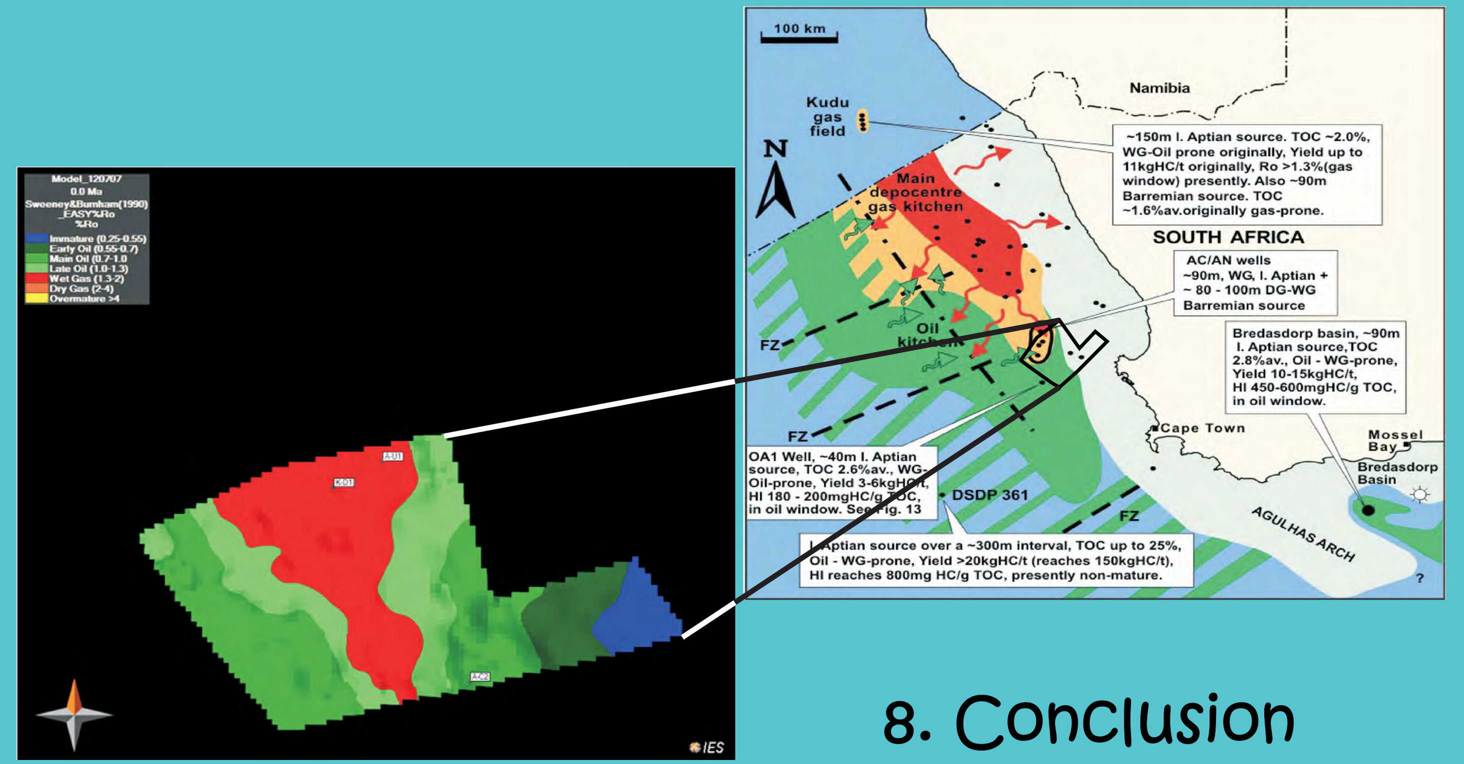

FIGURE 13

Comparision of modeled hydrocarbon generation zones map with a published map of Jungslager (1999)

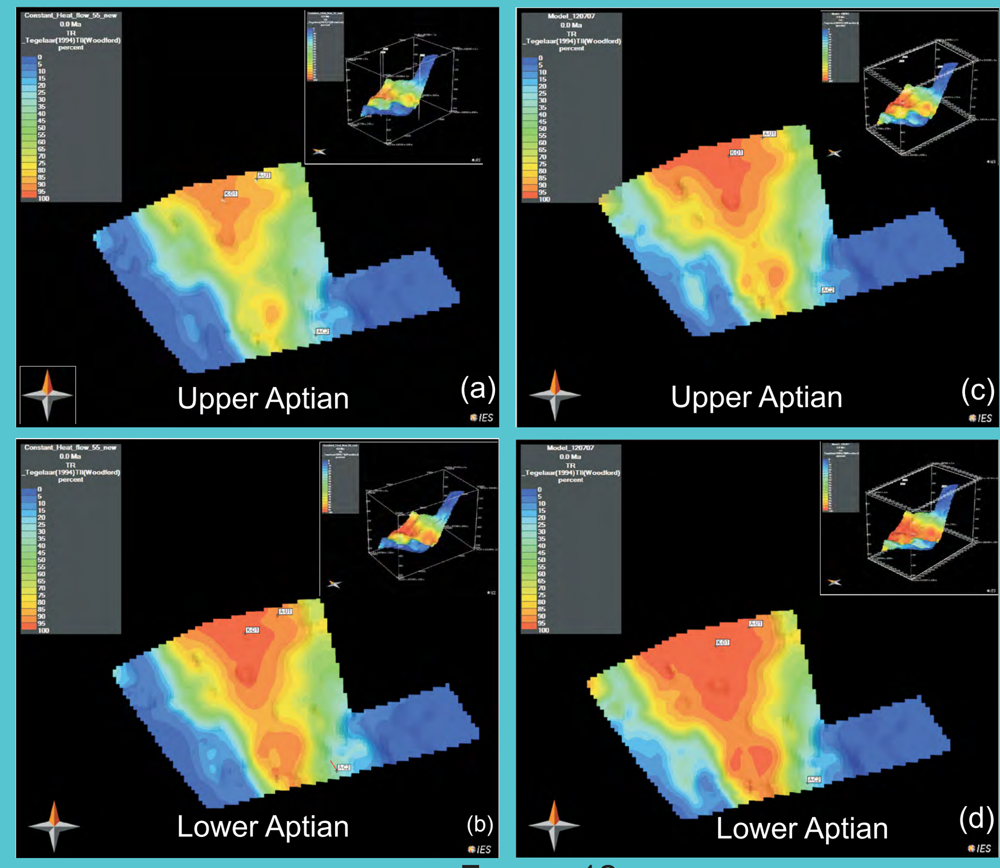

FIGURE 12

Maps of Transformation Ratio for Models 1 and 2 across the study area for the respective source rocks identified.

8. Conclusion

Based on the data acquired and the modeled results the following conclusions can be drawn with respect to source rock characteristics and maturation modeling.

Source Rock Characteristics

The Source rocks of the study area in general display a mixture of Type II/TypeIII kerogen , with average TOC's of 3 wt% across the basin, with maturity levels varying from immature to early oil maturation based on T_{max} values (Figure 8 (c)) at the respective source interval across the study area. Based on the S_2 vs TOC cross plots (Figure 9 (b)-(f)) there is diminishing source quality from south to north within study area, from Type II to Type III, making the southern part oil prone and northern part gas prone.

Maturation Modeling

The modeled transformation ratio maps, Figure 12, for both Models 1 and 2 show a more mature central basin getting less mature deeper and south-ward into the basin, with respect to the study area. This makes the northen central Orange Basin source rocks gas mature and the deeper southern source rock oil mature. The maturation models of Model 1 and 2 concur with the proposed hydrocarbon generation zones mapped for the entire Orange Basin as suggested by Jungslager (1999), see Figure 13.

In conclusion, modeling of the Upper Aptian and Lower Aptian source rocks at different heat flow histories throughout basin development shows no significant difference across the respective source intervals with regards to hydrocarbon generation , but has an effect on the timing of when the source rocks enter the oil window, as seen in Figure 11. The early or later exposure of source rocks to the oil window can largely impact hydrocarbon migration and accumulation.

Part 3

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