

Tectonic Evolution at Musi High and Its Influence to Gumai Formation as an Active Source Rock at Sopa Field, South Sumatera Basin*

Dimas Hendrawan Patra¹, Dardji Noeradi², and Eddy Subroto²

Search and Discovery Article #20125 (2012)

Posted January 16, 2012

*Adapted from extended abstract prepared in conjunction with poster presentation at AAPG International Conference and Exhibition, Milan, Italy, October 23-26, 2011

¹Exploration (G&G South Sumatera), Pertamina-EP, Jakarta, Indonesia (dimas.hendrawan@gmail.com)

²Geology Department Institut Teknologi, Bandung, Indonesia

Abstract

Shale from Lahat and Talang Akar Formations were widely accepted by many geoscientists in Indonesia as general source rocks in Palembang sub-Basin which is part of South Sumatra Basin. The oil from Sopa Field was considered as hydrocarbon accumulation that had been migrated from local and regional deeps around Sopa Field, where Lahat and Talang Akar Formations were deposited.

Based on subsurface physiographic that was obtained from integration of interpretation of well and seismic data, the closest deep is more than 20 km, therefore it is difficult to explain hydrocarbon migration mechanism from kitchen to reservoir. Besides that, Sopa Field is located at paleohigh since Eocene to Middle Miocene; consequently Lahat and Talang Akar Formations were not well developed. With these facts, reservoir carbonates of Baturaja Formation were deposited directly on the top of pre-Tertiary basement.

This thesis is directed to obtain information of other formation potential as a source rock that charge hydrocarbon in Sopa Field, which is Gumai Formation. Not only act as regional seal in South Sumatera Basin, Gumai Formation may also act as active source rock, therefore this hypothesis must be proven with analytical geologic in a simple model.

The result of comprehensive geochemical analysis shows that oils at Sopa wells migrated from source rocks that had been deposited at a transition environment. Oil from Sopa is correlated with bitumen that was extracted from sediment sample of Gumai. The sample of

Gumai Formation was deposited in a lagoon environment. On the other hand, extracted bitumen of Baturaja Formation sample was analyzed as non-indigenous or migrated from other sources. Therefore, the bitumen for the sample from the Baturaja Formation was not valid for further analysis.

Seismic data interpretation is transformed into a geology model that will give explanations of maturity and migration mechanism of shale in Gumai Formation. Tectonic evolution at South Sumatera Basin since Middle Miocene to recent time had been forming a massive number of thrust faults that make some blocks higher, while the others were buried deeper. Some part of Gumai Formation at the fault's footwall reached maturation zone. These tectonic evolutions also tilted the carbonate reservoir helping hydrocarbons to move from the lower part to the shallower part. Hence, Gumai Formation is also acting as active source rock at Sopa Field. Gumai Formation is an active source rock at Sopa Field, and it may open the new vision of hydrocarbon exploration with the same play. The model that resulted from this thesis may be used as an analog to define a source rock younger than its reservoir.

Introduction

South Sumatra Basin is a prolific basin in Indonesia. Reserves of 4.3 billion barrels of oil equivalent have been discovered in reservoirs that range from Tertiary basement through upper Miocene sandstones and carbonates deposited as synrift strata and as marine shoreline, deltaic fluvial, and deep-water strata (Bishop, 2001). The Sopa carbonate complex is located in the Musi Platform, South Sumatra Basin ([Figure 1](#)). The Sopa Field was discovered as stratigraphic trap (carbonate reef) by the exploration well in September 1997, and produced 1,350 BOPD.

The main source rocks of South Sumatra Basin are shales from the Oligocene lacustrine deposits of the Lahat Formation and deltaic fluvial of Talang Akar Formation (Sariono, 1989, Rashid, 1998., Bishop, 2001). However, at Musi Platform these two formations are not well developed. Musi Platform was a paleohigh basement since Tertiary and remained high until Middle Miocene, when carbonate reefs started to develop.

The main part of Sopa field is a tilted carbonate reef. As shown in [Figure 1](#), Sopa field is located in the middle of Musi platform. Carbonate of Baturaja Formation were well spread in these platform, hence, it lies on the top of pre-Tertiary basement. If there is a sand or shale deposit locally on a top of basement, it will be considered as a product of weathered basement. Oil in Sopa field is produced in the Miocene reservoir carbonate reef of Baturaja Formation (BRF), and since Lahat Formation (LAF) and Talang Akar Formation (TAF) were absent in Musi Platform, there must be another source rock that charged and migrated to the reservoir.

Absence of LAF and TAF in Musi Platform, especially in the Sopa field, has been proven by seismic interpretation combined with well data in surrounding area. About six explorations well around Sopa reported the absence of LAF and TAF, although in Sopa-1 well there is less than ten meters of dark brown shale with intercalation of coal shard. This dark brown shale may be considered a shaley facies of carbonate platform, and coal shard may have originated from low-degree of vegetation.

Geological Background

The South Sumatra basin was formed by three major tectonic phases: 1) extension during late Paleocene to early Miocene forming north-trending grabens that were filled with Eocene to early Miocene deposits; 2) relative quiescence with late normal faulting from early Miocene to early Pliocene; and 3) basement-involved compression, basin inversion, and reversal of normal faults in the Pliocene to Recent forming the anticlines that are the major traps in the area. Many of the normal faults that formed the depositional basins in South Sumatra have been reactivated and some have been reversed during Miocene to Plio-Pleistocene compression and basin inversion. The grabens and major faults of the South Sumatra Basin Province are oriented north-northwest to south-southeast. From tectonostratigraphical view, all depositional process in South Sumatra Basin are divided into three phase:

- Pre-rift, when Tertiary depositional fill of the South Sumatra Basin began in the Eocene with deposition of continental sediments derived from local erosion.
- Syn-rift with characteristic half-graben-style locally derived deposits began to fill these basins in response to the half-graben architectural style and subsidence of the basins. From Additional synrift deposits of tuffaceous sands, conglomerates, breccias and clays were deposited in faulted and topographic lows by alluvial, fluvial, and lacustrine processes. Marine transgression occurred in some areas possibly as early as the late Eocene. LAF and Lower TAF were deposited at these phase.
- Post-rift, with widespread marine transgression from the south and southwest in the late Oligocene to Miocene resulted in onlap of clastic deposits onto basement rocks (Upper TAF), development of platform carbonates and carbonate build-ups on fault block highs (Baturaja Formation also called BRF). Maximum transgression in the middle Miocene deposited the marine shale Gumai Formation (GUF) seal across the region before uplift and compression resulted in deposition of shallow marine and continental sandstones and shales. Development of the Barisan Mountains, and possible volcanic islands to the south and southeast, further decreased and then cut off and overwhelmed marine influences and added new clastic and volcanoclastic sources from those directions.

All information above is shown as general stratigraphic column in [Figure 2](#).

Data and Method

Geochemical Method

This article will focus on the other source rock that was charging oil to reservoir in Sopa field and make a simple explanation on how migration mechanism can be done by using well data and seismic data. Geochemical analysis will be focused on possibly source rocks that generate oil to carbonate reservoir.

Geochemical analyses were derived from cutting and oil samples, all plots are based on empirical methods. Geochemical analysis will examine the potential and maturity of the samples. Source rock potency is measured by Total Organic Content (TOC), Production Index (PI), and Hydrogen Index (HI), while maturity of the source rocks are measured by Vitrinite Reflection (Ro), Spore Colorations Index (SCI), and T-max. All those measurements are used to eliminate samples that do not meet minimum requirement as a good quality of source rock. [Figure 3](#) shows plot of several geochemical measurement of cutting samples.

[Figure 3](#) shows some anomalies related to Production Index (PI). PI parameter can be used to check the originality of the source rock whether it is altered or not. High value of PI may be caused of alteration of oil at the cutting samples. Baturaja Formation (BRF) act as reservoir in Sopa field, hence the cutting samples may be altered, and it is shown in [Figure 3](#). Because of that, cutting samples from BRF may considered as invalid samples, therefore further geochemical analysis for this sample must be taken carefully.

Depositional environment can be determined by using a plot template of carbon isotopes as shown in [Figure 4a](#). Carbon isotope ($\delta^{13}\text{C}$) values of crude oils and source rock extract may be used to distinguish marine from freshwater/ terrestrial sources (Sofer, 1984 op.cit. Satyana, 2006). From the template, all samples including oil and source rock extract showing the same depositional environment which is marines. Even coaly shale is determined as marine environment; it may come from small vegetation that grew around the carbonate platform while it was deposited. Another template is using carbon isotopes and combines with ratio of Pristane and Phytane (Pr/Ph) as shown in [Figure 4b](#). Pristane-Phytane ratio is an isoprenoid (biomarker component) that most commonly used to distinguish facies of the source rock. High Pr/Ph ratios (>3) are associated with terrestrially influence oxic sediment, including coal, while Pr/Ph ratios ranged between 1-3 are associated with suboxic marine sediment. Below 1, Pr/Ph ratios are associated with anoxic marine sediment.

Other sophisticated method in geochemical analysis is using biomarker that can be used to correlate oil to oil and oil to source rocks extract. At this article, the using of biomarker will be focused to value the similarity of the “fingerprint” pattern of mass

chromatogram and to identify deposition environment of the source rock. Mass chromatograms that are commonly used in geochemical analysis of Indonesia Basin are m/z 217 and m/z 191 (Subroto, 2009). Mass chromatogram m/z 217 is showing sterane distribution and used to value diasterane (C_{27} - C_{29}) that associated with clay content, high clay content will be interpreted as marine source. In [Figure 5](#), diasterane on a mass chromatogram is marked by a circle.

Mass chromatogram m/z 191 (also called Triterphane pentacyclic) is showing the distribution of Hopane. One of specific characteristic of Hopane is oleanana, a matter that is produced from higher plant, can be used as a special mark of terrestrial influence.

As shown in [Figure 5](#), mass chromatogram m/z 217 can be interpreted qualitatively. It is shown that oil in Sopa-1 well has a low value of diasterane, hence is associated with non-marine source. Oppositely, the interpretation of m/z 191 shows that the oil and extract samples have low values of oleanana, hence it is not associated with a terrestrial source. With this fact, biomarkers show that oil in Sopa field may be produced by a source rock deposited in a transition zone between terrestrial and marine. We think that depositional environment of the source rock was a lagoon.

Because Talang Akar Formation (TAF) is absent in Sopa field and cutting samples of Baturaja Formation has been altered with oil, we may conclude that Gumai Formation may be act as source rock in Sopa field. From geochemical analysis, Gumai Formation has good quality to be the main source rock for Sopa structure because it has all the values to be qualified as an active source rock

Structural Method

To understand how a source rock became mature and migration mechanisms have taken place, we need to trace a structural evolution of the Sopa field and surrounding area. Sopa field is covered by 2D and 3D seismic, all interpretation has been made to create a simple model that may explain structure evolution in that area.

A model has been built by using flattening method of some horizons related to time of deposition of several formations respectively ([Figure 6](#)). Paleo-structure is assumed and can be approached by a flattening method. Hence, a structural model will show step by step with considering to depositional environment and regional tectonic in South Sumatra Basin.

At a local scale, tectonic evolution that worked in Sopa field can be trace as follow:

1. First stage: Pre-Tertiary extension that may form half graben structure and create accommodation space for Eocene-Oligocene sediment. At higher part (horst), deposition was not taken place, hence it can explain why LAF & TAF were absent in Musi High/platform.
2. Second stage: no significant change of tectonic force at time range Oligocene to early Miocene, in other word tectonic force at this stage was relatively calm. Sea level was relatively increase, at Musi high carbonate platform was start to formed and in several places carbonate build up might be grew.
3. Third stage: continued of the second stage where tectonic force was relatively still, but sea level was increase rapidly through the edge of the basin. Marine shale was covered the entire basin who became regional seal.
4. Fourth stage: dextral movement of wrench fault system was causing massive deformation at middle Miocene trough late Miocene. Great Sumatran Transform Fault was moving along direction of northwest to southeast creating compression effect in some part while another part was being stretch. At this stage old system fault was rejuvenated with different force direction.
5. Fifth Stage: massive compression has taken place as caused by subduction of volcanic arc Barisan Mountains at Plio-Pleistocene. This compression force creating independent fold/fault or even to reconfirm older fold or asymmetrically changing fold that already exist form previous wrenching system.

Gumai Formation Maturation and Migration

At the late stage of tectonic evolution, massive deformation was taking place in South Sumatra Basin creating a big thrust fault named Lematang Fault. The Sopa structure is located at the foot wall part and is buried deeper and tilted. This thrust fault gives significant impact to Gumai Formation around Sopa, as it was buried deeper and entered a maturation zone due to increasing thermal gradient.

Oil might be generated if the source rocks entered the “oil window”. Zone of oil windows in Sopa structure are measured by vitrinite reflectance (R_o) and spore coloration index ([Figure 7](#)), indicating that 2,000 meters is critical depth of maturation. If we bring that critical depth to the seismic section, it is equal to 1,740 milliseconds.

As mentioned before, the Sopa carbonate reef laid on the top of pre-Tertiary basement, and this structure was tilted due to compression of Plio-Pleistocene. The tilted geometry allowed bitumen or hydrocarbon generated from the Gumai Formation source rock to move into the adjacent reservoir rock. Hence Gumai Formation not only acts as seal rock but also act as an active source rock.

Primary migration of hydrocarbons from marine shale of the Gumai Formation to the reservoir Baturaja Formation is one-way direction movement ([Figure 8](#)). This system is similar to a membrane system that allows fluid to go through the membrane but

prevents the fluid to coming back. This particular system might be caused by permeability contrast between GUF and BRF. Hydrocarbons generated from marine shale GUF will easily move to porous limestones of BRF; on the other hand GUF will also act as seal rock that prevents hydrocarbon from moving back.

Conclusions

Structural evolution of the Sopa Field caused petroleum systems to work well. At this moment we can say that at the local scale, GUF can be a good source rock as well as regional seal of the South Sumatra Basin. With structural evolution due to system tectonics, secondary migration was taking place as the geometry of the reservoir became tilted.

With this article, we hope to open new ways of thinking that seal rocks as the younger sediment may also have a good potential as source rocks. From the view of hydrocarbon exploration, other basins may have a chance to find similar ways of thinking as Sopa field, as long as basic requirements of petroleum systems are fulfilled.

Selected References

Barber, A.J., M.J. Crow, and J.S. Milsom, 2005, (eds.), Sumatra: Geology, Resources, and Tectonic Evolution: The Geological Society of London, 290 p.

Bishop, G.M., 2001, South Sumatra Basin Province, Indonesia: The Lahat/Talang Akar-Cenozoic Total Petroleum System: USGS Open-File Report 99-50-S, 22 p.

Ginger, D., and K. Fielding, 2005, The Petroleum System and Future Potential of The South Sumatra Basin: Proceedings of the Indonesian Association of Petroleum Association, 30th Annual Convention, The Urgency of Building Competitiveness to Attract Oil and Gas Investment in Indonesia, p. 67-89.

Pertamina BPPKA, 1996, Petroleum Geology of Indonesian Basins; Principles, Methods and Application, Volume III, West Java Sea Basins.

Rashid, H., I.M. Sosrowidjojo, F.X. Widiarto, 1998, Musi Platform and Palembang High: A new look at the Petroleum System” IPA 26th Annual Convention Proceedings, v. 1, p. 265-276.

Riadhy, S., A. Ascaria, D. Martono, A. Sukotjo, D. Hernadi, D. Kurniawan, and N. Luthfi, 1999, Carbonate Play Concept in Sopa and Surrounding Areas: An Alternative Model For Hydrocarbon Occurrence, Musi Platform, South Sumatra Basin: IPA 27th Annual Convention Proceedings, p. 1-13.

Ryacudu, R. (2005). Studi Endapan Syn-rift Paleogen di Cekungan Sumatra Selatan, Disertasi Program Doktor, Institut Teknologi Bandung, Indonesia, p. 40-52.

Sarjono, S. dan Sardjito (1989). Hydrocarbon Source Rock Identification in the South Palembang Sub-basin: IPA 18th Annual Convention, p. 427-467.

Subroto, E. A. (2009). Kuliah Sistem Petroleum, Progam Studi Magister Teknik Geologi ITB.

Suseno, P.H., Zakaria, N. Mujahindin, E.A. Subroto, E.A., 1992, Contribution of Lahat Formation as hydrocarbon source rock in South Palembang area, South Sumatera, Indonesia: IPA Proceedings, v. 1, p. 325-337.

Waples, D.W., 1985, (ed.) Geochemistry in Petroleum Exploration: International Human Resources Development Corporation, Boston, 232 p.

Williams, Harold (2006), Geochemistry Malacca Strait, Course Material Kondur Petroleum, Special Publication.

Wirawan, A. (1998). Laporan Studi Cekungan Sumatera Selatan, Publikasi Internal. Pertamina EP.

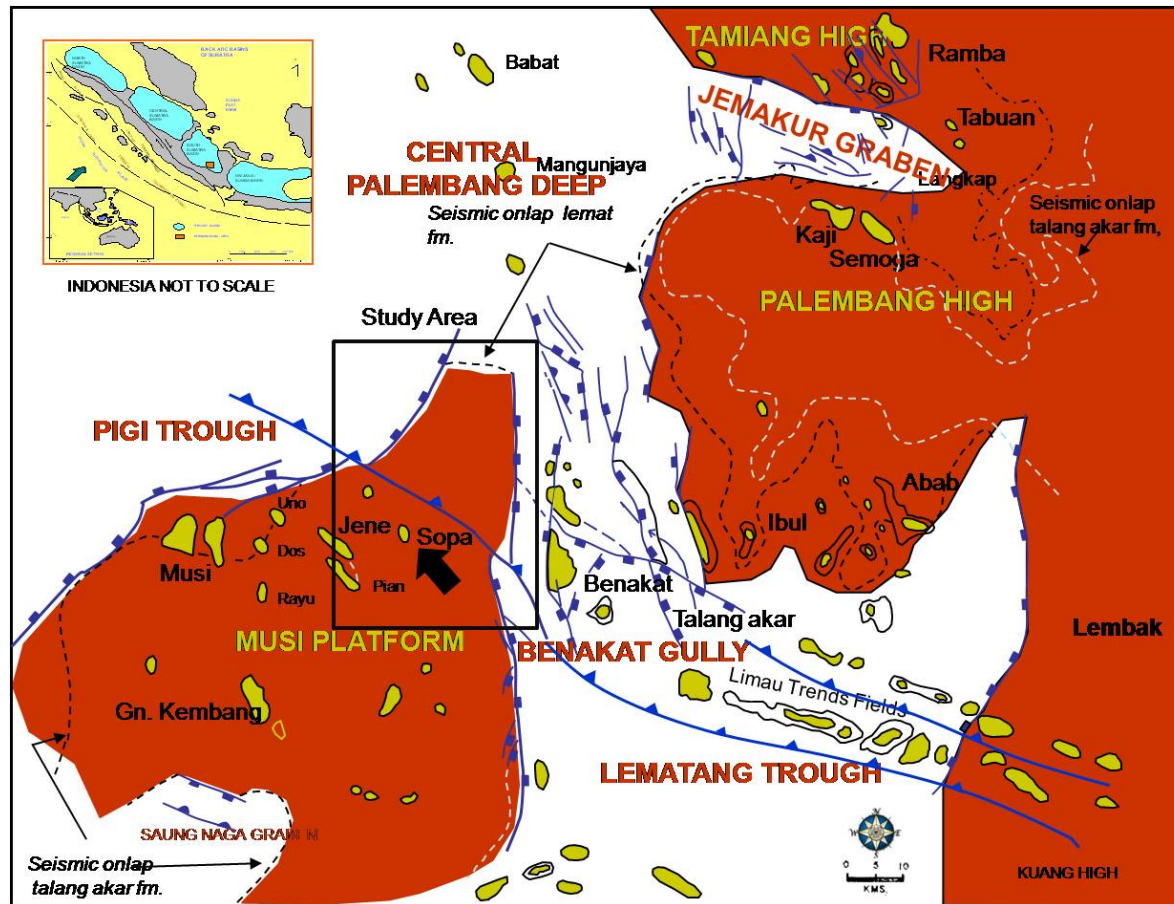


Figure 1. Sopa Field is located at Musi Platform (indicated by arrow), massive thrust fault of late Pleistocene were causing reef become tilted.

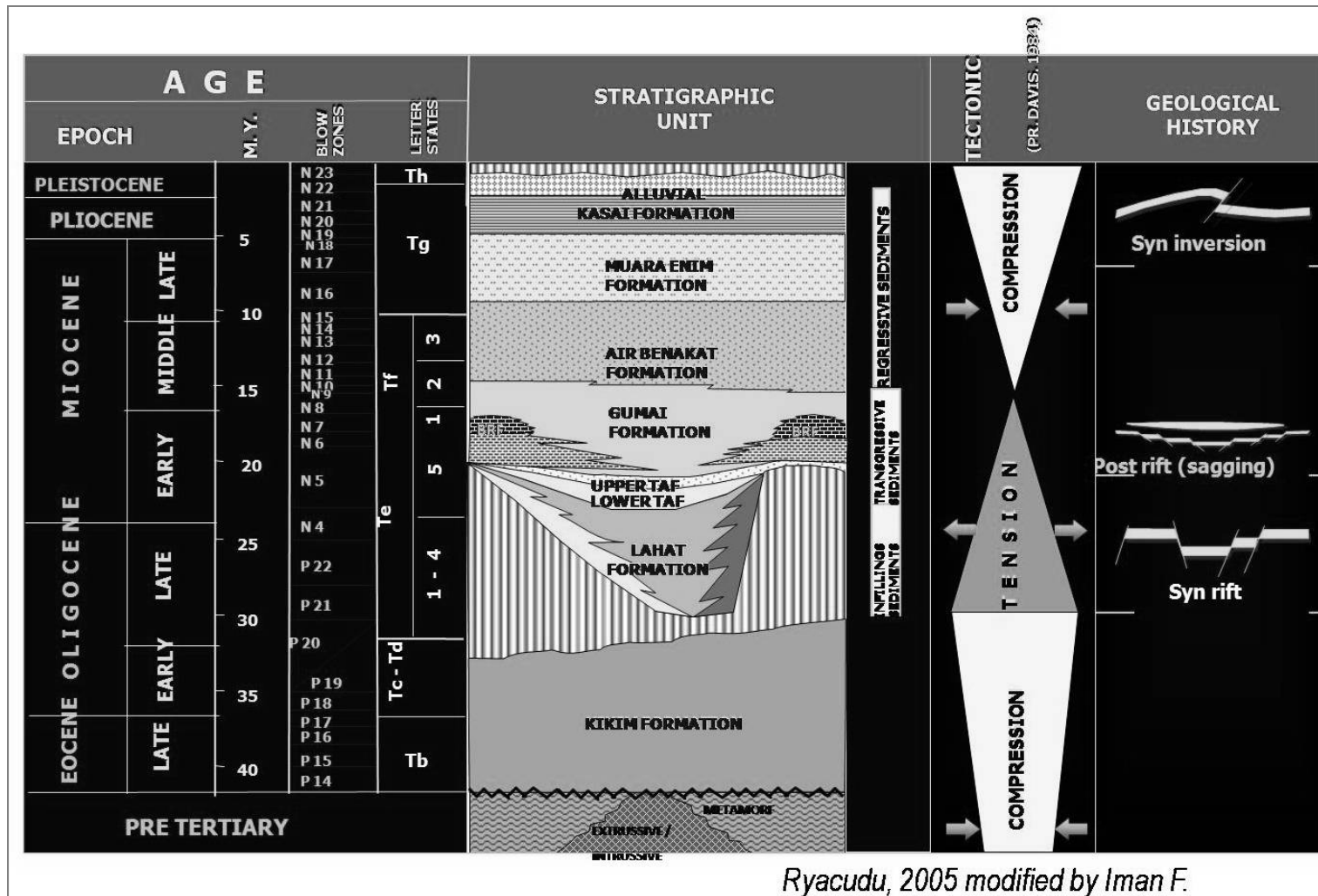


Figure 2. General stratigraphic of South Sumatra Basin.

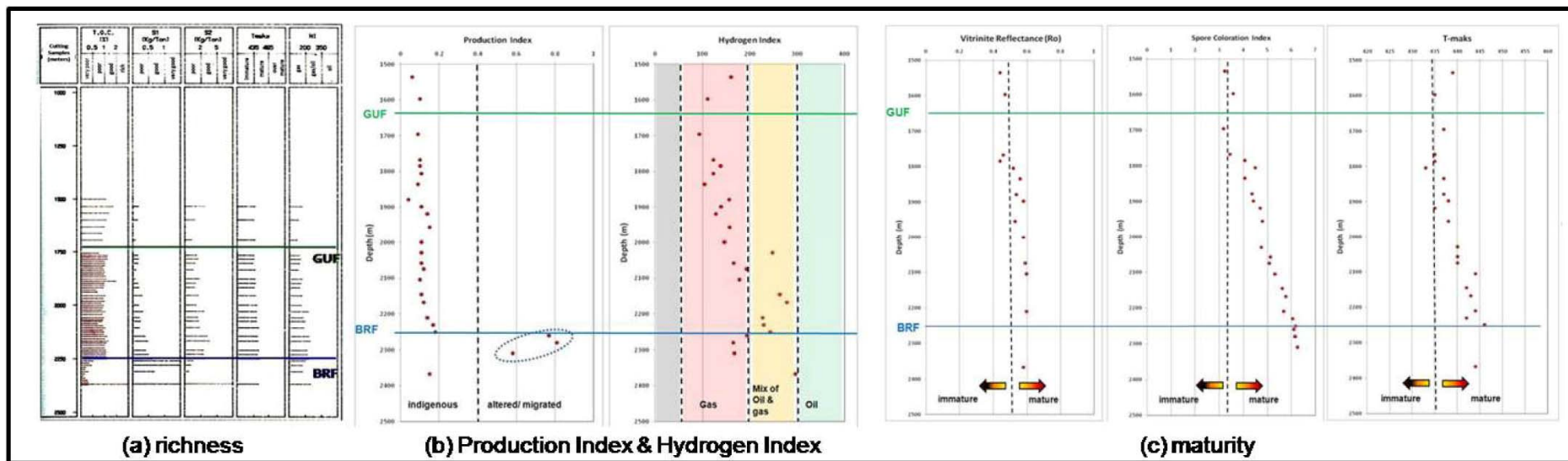


Figure 3. Few parameters of geochemical analysis showing GUF as potential source rock, while BRF samples are assumed to be impregnated/altered.

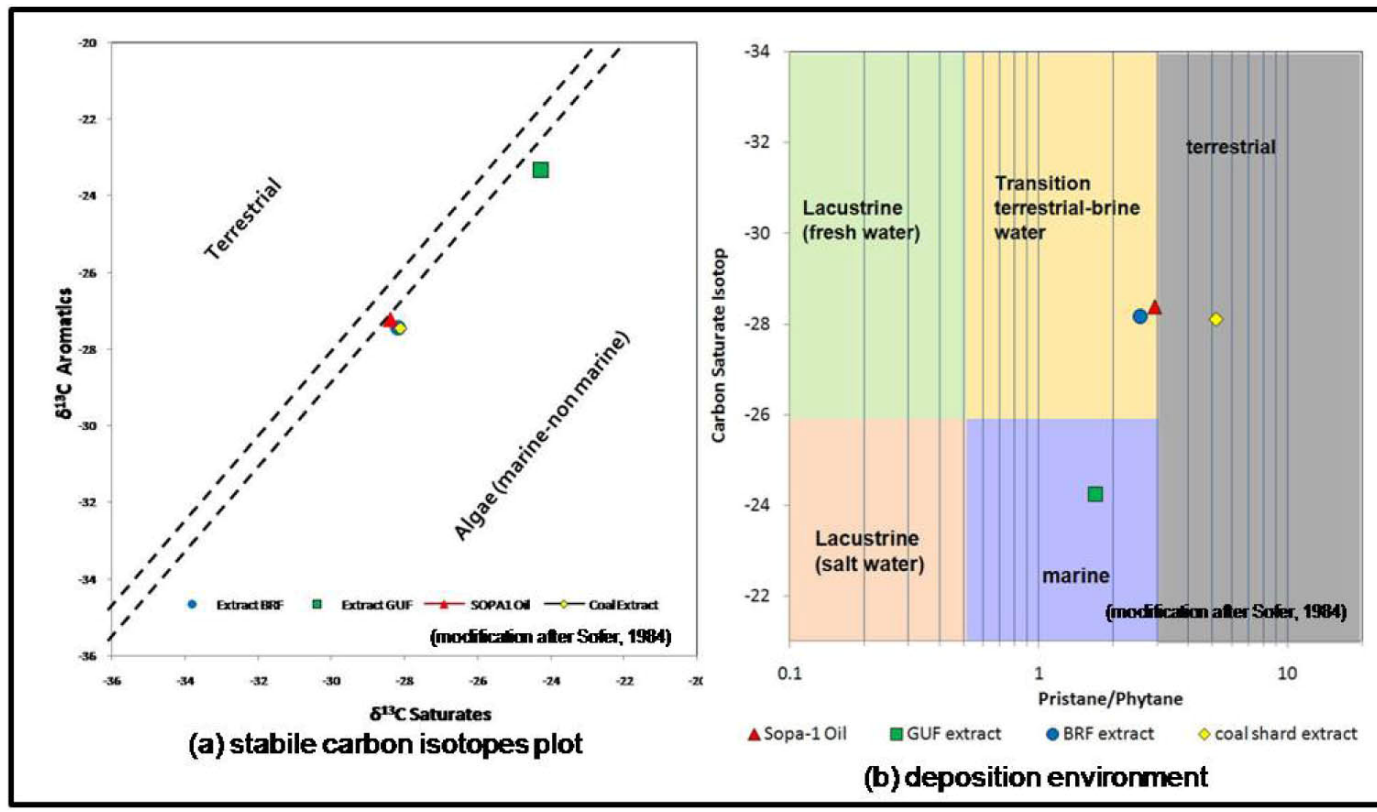


Figure 4. Depositional environment of the source rock can be determined by using plot of stable carbon isotope (a) all samples showing that algae (marine or non-marine) have dominant influence; (b) combined with Pr/Ph ratios, a more distinctive scope of the depositional environment is made.

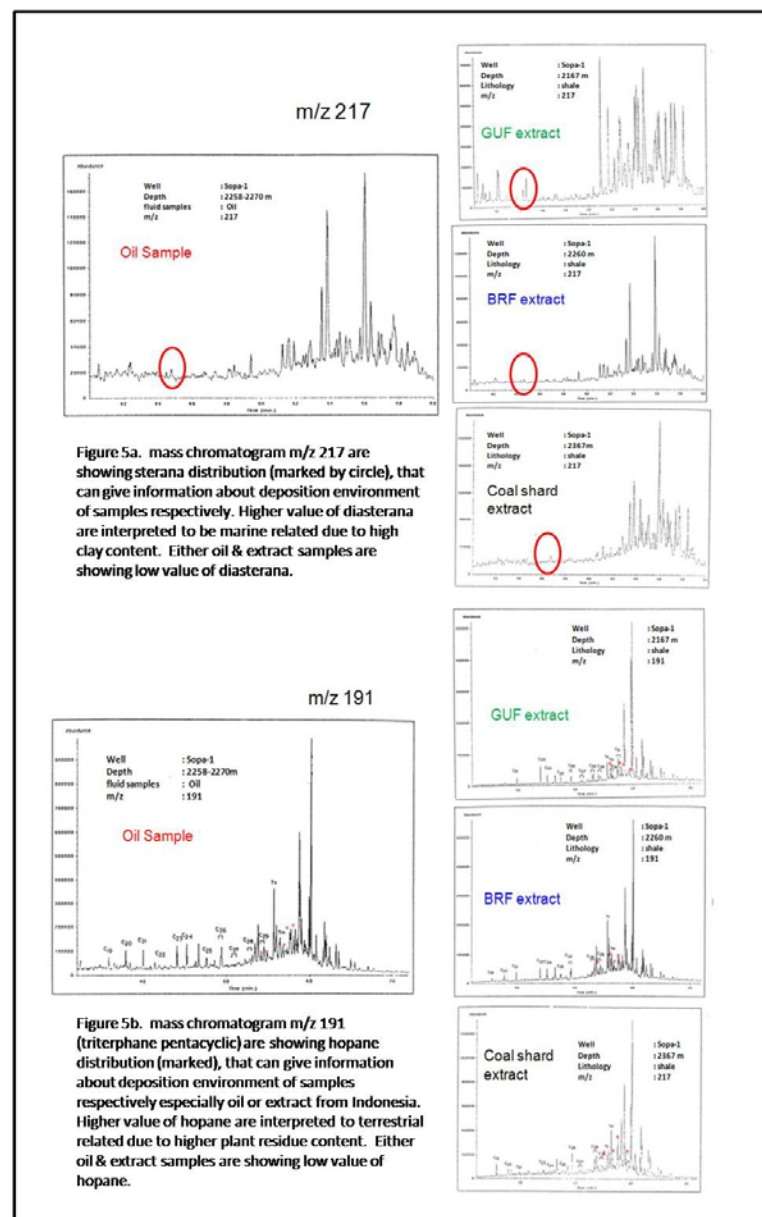


Figure 5. (a) Mass chromatograms m/z 217 are showing sterana distribution (marked by circle) that can give information about depositional environment of samples. Higher values of diasterana are interpreted to be marine-related due to high clay content. Both oil and extract samples are showing low value of diasterana. (b) Mass chromatogram m/z 191 (triterpane pentacyclic) are showing hopane distribution (marked), that can give information about depositional environment of samples, especially oil or extract from Indonesia. Higher values of hopane are interpreted as terrestrial-related due to higher plant residue content. Both oil and extract samples are showing low values of hopane.

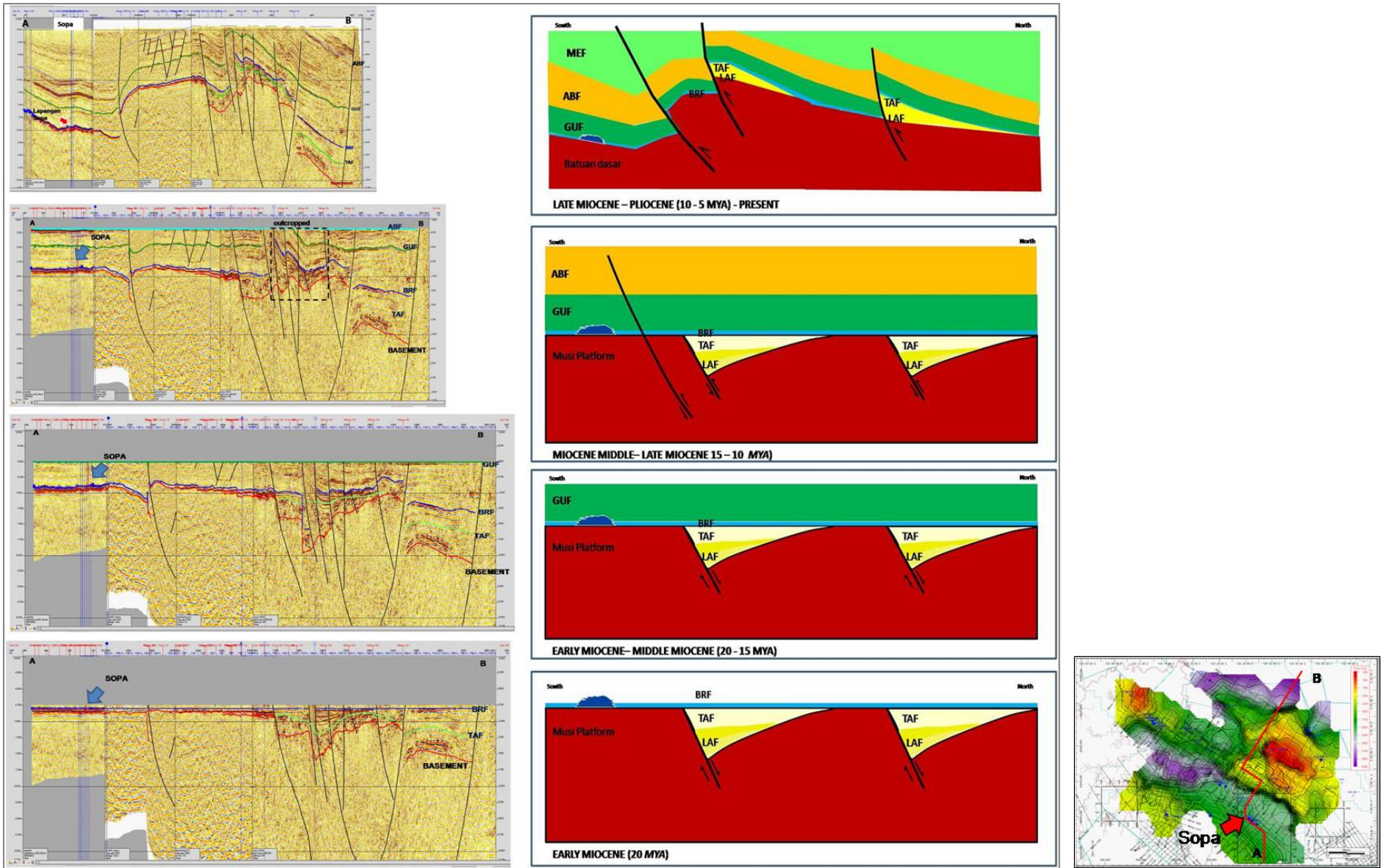


Figure 6. North-south seismic section through Sopa field and its respective model. On the left side are seismic sections flattened at several times that are significant to basin establishment (locally). The critical moment took place at Late Miocene-Pliocene, where tectonics formed several thrust faults, forcing some blocks higher, while others were buried deeper. This tectonic event also tilted the carbonate reservoir.

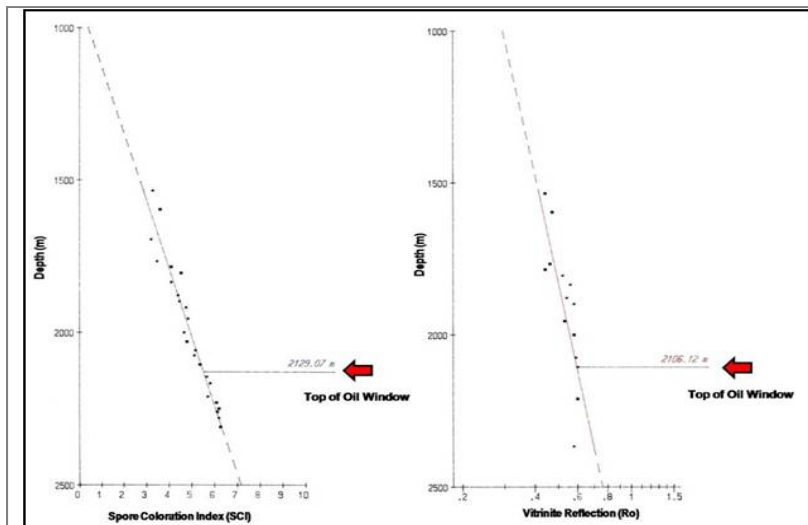


Figure 7. (left) Top of oil window are acquired from Vitrinite Reflection and Spore Coloration Index, these two plots showing that source rock reach the maturation zone approximately at 2000-2100 meters. Seismic section below are showing relative north south section traversed Sopa Field. At the section we can see that some part of GUF in Sopa field has reached mature zone based on the depth line or top of oil window at 2000 meters (which is converted to time domain as 1740 millisecond).

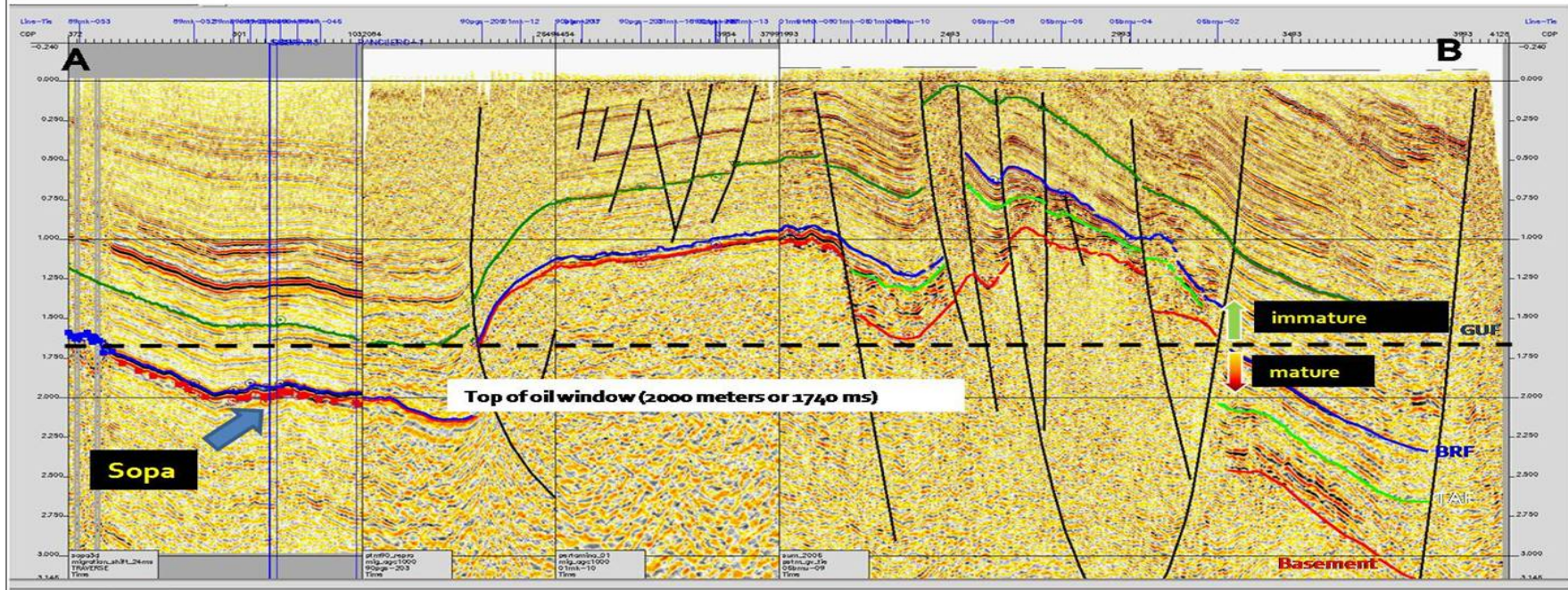
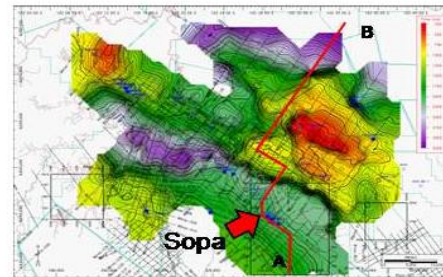


Figure 7. Top of oil window acquired from vitrinite reflection and spore coloration index. These two plots illustrate that source rocks reach the maturation zone at approximately 2,000-2,100 meters. A north-south seismic section through Sopa Field is shown where we can see that some part of GUF in the Sopa field has reached the mature zone based on the depth line or top of oil window at 2,000 meters (which is converted to time domain at 1,740 milliseconds)

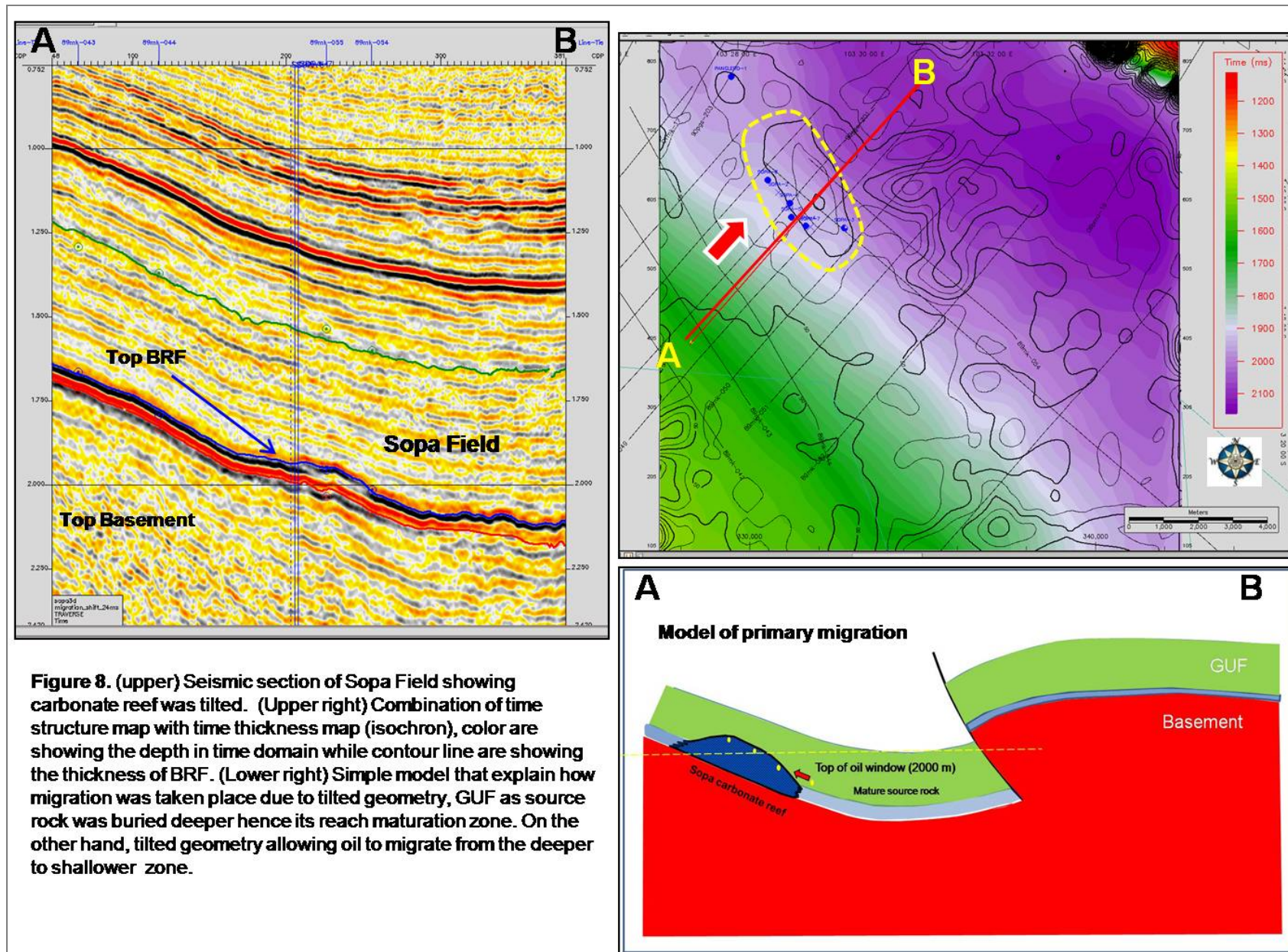


Figure 8. Seismic section of Sopa Field showing tilted carbonate reef (upper left). Combination of time structure map with time thickness map (isochron), colors show the depth in time domain while contour lines show BRF thickness (upper right). Simple model that explains migration due to tilted geometry, GUF as source rock was buried deeper, reaching the maturation zone. On the other hand, tilted geometry allows oil to migrate from the deeper to shallower zone (lower right).