New Viewpoint on the Geology and Hydrocarbon Prospectivity of the Seychelles Plateau*

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Abstract

We have reprocessed, re-imaged, and interpreted 10000+ km of legacy 2D seismic data in the Seychelles, particularly in the western part of the Plateau. Seychelles data have been difficult to image, particularly for the Mesozoic section: volcanics are a major attenuator of low frequency signal, and a hard water bottom contributes to signal problems. Enhanced low frequency techniques were applied to improve the signal fidelity in the 4 to 20 Hz range, and to remove spectral notches of shallow geologic origin. These efforts have allowed a reasonable view of the structure of the Plateau to a depth equivalent to about 3.5 sec TWT, and permit a comparison of areas atop the Plateau to the south coast where the three 1980's Amoco wells were drilled. It is clear that the main Plateau area of the Seychelles (excluding the outlying territories) is comprised of several separate basins, each with similar Karoo, Cretaceous, and Cenozoic sections that relate to the East African and West Indian conjugate margins, but the basins each have nuanced tectono-stratigraphic histories. The previously recognized Correira Basin in the SE and the East and West South Coast Basins face the African conjugate margin; other unimaged ones complete the periphery of the Plateau. The interior of the Plateau is dominated by the Silhouette Basin to the west of the main islands and the Mahé Basin to the east. The coastal basins have harsh tectono-thermal histories comparable to other continental margins around the world; they are typically characterized by stretching, subsidence, and breakaway from their respective conjugate margins. In contrast the interior basins are comparable to 'failed' rift systems such as the North Sea or the Gulf of Suez. The South Coastal Basins, for example, tend to be more extended which complicated interpretation of the Amoco wells, but they have significant upside, as exemplified by the Beau Vallon structure. The interior basins, on the other hand, have typically simpler structure: The Silhouette Basin contains a system of NW-trending linked normal faults that could easily harbor North Sea-sized hydrocarbon traps with a variety of rift-related reservoir possibilities. Bright, reflective, hard volcanic horizons are less common than usually presumed, but most of the basins may contain considerable pyroclastic material in parts of the section. All the basins appear to be predominantly oil prone, with considerable upside prospectivity.

The Seychelles Islands sit atop one of several intra-oceanic plateaus scattered across the Indian Ocean that owe their origin to the breakup of Gondwanaland during the Cretaceous. Some are Deccan and similarly timed volcanic additions to oceanic crust, large igneous provinces erupted during the breakup and during sea floor spreading (Coffin and Eldholm, 1994), but the main Seychelles Islands are a microcontinent underlain by Precambrian granites (e.g. Tucker et al., 2001; and many others). The islands themselves are exposures of that basement, and of Cenozoic acidic volcanic rocks. The Seychelles Plateau broke away from Africa and drifted with India during the initial breakup of the Gondwana continents (the separation of East and West Gondwana) in mid-Cretaceous time, and shortly thereafter were stranded during the breakup of the east Gondwana continents (Collier et al., 2008) in the late Cretaceous.

The sedimentary cover of the Seychelles Plateau (Figure 1) consists of a section that might generally be divided into three phases: (1) mixed siliciclastic rocks mostly of continental character inherited from the united Gondwana, similar to those of Madagascar, East Africa, and India (essentially equivalent to the Karoo Supergroup), that accumulated prior to the breakup (2) a Jurassic-Cretaceous marine section dominated by siliciclastics and some carbonates developed during breakup, and (3) a post-isolation open marine section dominated by carbonates accumulated on top of the Plateau after separation from India. The section contains a variety of volcanic rocks, including possibly Karoo-aged basalts, but clearly contain a range of flood basalts and associated acidic rocks of late Cretaceous and Paleogene. Post-isolation syenites and microgranites outcrop in a Paleogene ring complex on Silhouette and North Islands (Stephens, 1996). None of the sedimentary section occurs onshore. Judging from the seismic data, i.e. from the distribution of the bright reflective horizons tied to basalts in the wells, hard volcanic horizons are less common than usually presumed, but most of the basins may contain considerable pyroclastic material in parts of the section.

What is known of the stratigraphy is known from four exploration wells and the influence they have on seismic data across the Plateau (Figure 3). Reith Bank-1, Owen Bank-1, and Seagull Shoals-1 were drilled by Amoco in the early1980's in a cluster in the southwest of the Plateau. Constant Bank-1 was drilled by Enterprise in 1995 on the southern tip of a southeastern promontory from the main Plateau. There were various reasons why these wells were unsuccessful (absence of seal, no closure, abandoned on way to target), but they did establish that a thick oil prone section overlies the basement and that much of that section is in the oil window. Oil shows in sidewall cores and streaming fluorescence from the Reith Bank-1 well were downplayed in the well report, but subsequently used to support subsequent leasing (Franks et al., 2006). Tar balls have washed up on beaches of several islands, which have been typed to source intervals in the wells.

Exploration operations in the Seychelles began in the 1970's with seismic acquisition by the Burmah Oil Company, followed by Amoco's wells and others. Currently, only the far western edge of the Plateau is under lease, much of it in deep water. The outlines of the traditional exploration blocks are shown in Figure 2.

Seychelles seismic data have been difficult to process into clear imaging, particularly for the Mesozoic section: volcanics are a major attenuator of low frequency signal, and the thick Cenozoic carbonate section plus a hard water bottom contribute to signal problems. We have reprocessed, re-imaged, and interpreted 10,000+ km of legacy 2D seismic data in the Seychelles, particularly in the western part of the Plateau (Figure 2). Enhanced low frequency techniques were applied to improve the signal fidelity in the 4 to 20 Hz range, and to remove spectral notches of shallow geologic origin. These efforts have allowed a reasonable view of the structure of the Plateau to a depth equivalent to about 3.5 sec TWT, and permit a comparison of areas atop the Plateau to the south coast where the three 1980's Amoco wells were drilled (Figure.3). We have mapped the Silhouette Basin in some detail as illustrated below, and are in the process of progressively integrating more information into the project. The area currently in hand is shown in a pink overlay on Figure 2.

It is clear that the main Plateau area of the Seychelles (excluding the outlying territories) is comprised of several separate basins (Figure 3), each with similar Karoo, Cretaceous, and Cenozoic sections that relate to the East African and West Indian conjugate margins, but the basins each have nuanced tectono-stratigraphic histories. The previously recognized Correira Basin in the SE (by WHL), and the East and West South Coast Basins face the African conjugate margin; other unimaged ones complete the periphery of the Plateau. We have generically named them the NW Offshore, NE Offshore, and North Basins. The interior of the Plateau is dominated by the Silhouette Basin to the west of the main islands and the Mahé Basin to the east. The central, core area of the Plateau around the main islands have been excluded from exploration licensure (Figure 2), whereas other areas have been designated for licenses.

There is a diversity of the extensional environments represented in the Seychelles. The coastal basins presumably have tectono-thermal histories comparable with other continental margins around the world, characterized by stretching, subsidence and breakaway from their respective conjugate margins. Effectively, within each of these basins the crust thins from that under the Plateau itself, something like 30-33 km (Hammond et al., 2013), through a continent-ocean transition (COT) to typical oceanic crustal thicknesses, ca 7 km. In contrast the interior basins are comparable to 'failed' rift systems such as the North Sea or the Gulf of Suez with smaller extensions and the accordingly simpler history. In all cases, the geometry of the Karoo-aged structure is poorly constrained in that it has been overprinted by the Gondwana breakup deformation. This adds additional risk to the geometry of pre-Jurassic unconformity traps. Our interpretation attempts where appropriate to define a near-top Triassic horizon, but this is not universally picked and has less confidence than younger picks (Figure 1). Inversions are possible anywhere in the system, and there are several places where inversions are suspected.

To accommodate post-Karoo stretching, and the influence of the plate margin setting, structure around the periphery of the Plateau seems in general to be more complicated than it is in the interior, as we show below. From the plate tectonic setting, and our data do not refine the plate tectonic picture, the South Coastal and Correira Basins represent the conjugate margin to Africa and are dominated mostly by extension. We have no direct seismic data to work with in the NW Offshore Basin, but its position and configuration suggest that it is occupied by a transform system, strike-slip components (along with any restraining or releasing structures) sympathetic with the drift history of the Plateau. The North and NE Offshore Basins are the conjugate margin to India; again, we have no data from that area.

Our data bear mostly on the South Coastal and interior Silhouette Basins (Figure 3). The South Coastal Basins tends to be more extended than the Silhouette, which coupled with poor seismic imaging complicated interpretation of the geology at the Amoco wells. They nevertheless have significant upside, as exemplified by the Beau Vallon structure (Figure 4), and by hydrocarbon indicators in the Amoco wells. The Silhouette Basin contains a system of NW-trending linked normal faults that could easily harbor North Sea-sized hydrocarbon traps with a variety of rift-related reservoir possibilities. From what little we have seen of the Mahé Basin, it is comparable to the Silhouette, but may not be influenced by the Tertiary-aged volcanism at Silhouette Island.

Samples of the seismic interpretation are given in Figure 4, Figure 5, and Figure 6. Figure 5 gives the tie from the Amoco wells toward the edge of the West South Coastal Basin (WSCB) and toward the Silhouette Basin. The fault blocks at the right appear to be truncated by the Cretaceous unconformity and are above the oil window even at the Jurassic level. Figure 6 is a typical line across the Silhouette Basin and comes close to tying Figure 5 at the south end. It shows a series of simple fault blocks within the Cretaceous with locally thickened section in the Cretaceous and Tertiary above the more structured Mesozoic.

The structure of the Silhouette Basin is shown in Figure 7, using the near top Triassic horizon as a sample. The line spacing is too narrow to qualify a solid prospect of economic proportions, or even as giant oilfield stature. In Figure 8, we show a sketch map of all the faults (the colored faults are the master- or through-going faults), with the areas of some large North Sea Fields for comparison. The point here is that the line spacing is too wide to guarantee even a single-line profiles across potential prospects. Further imaging is required to delineate prospects. Some 3D surveys have been acquired in a few areas, particularly in the South Coast Basins.

The heating history of various locations on and around the Plateau has been studied by Waples and Hegarty (1999) who conclude it has been complicated by reason of numerous heating events that have affected various places differently. We expect that in general the coastal basins have had histories comparable to typical continental passive margins, probably higher than the interior basins, and significantly complicated enough to be variable from place to place. Waples and Hegarty (1999) indeed show significant variability but there is not enough data to say whether the interior basins have had a universally significantly milder thermal history. They show various hydrocarbon generation profiles for source rocks in some of our basins, ranging from Jurassic in age to present day. The most delayed is in our Mahé Basin, with maturity beginning in the Permo-Triassic but not reaching significant transformation until well into the Cretaceous, and even today only at something like a 0.7 transformation ratio.

In conclusion we can say that active oil-prone petroleum systems are present in the basins, as evidenced by well shows and tar ball occurrences, supported by petroleum systems and seal modeling. The heating history is complicated and may lead to differences between the basins: several source rocks are possible. Structure timing and severity is variable across the Plateau, reflecting several tectonic events and several settings (e.g. interior basin, continental margin). Well density is low, and infill seismic is necessary in many cases to prove-up closures. Almost no work has been done on the northern edge of the Plateau, the conjugate margin to India. The Seychelles still represent a very viable frontier province with several basins and much open acreage.

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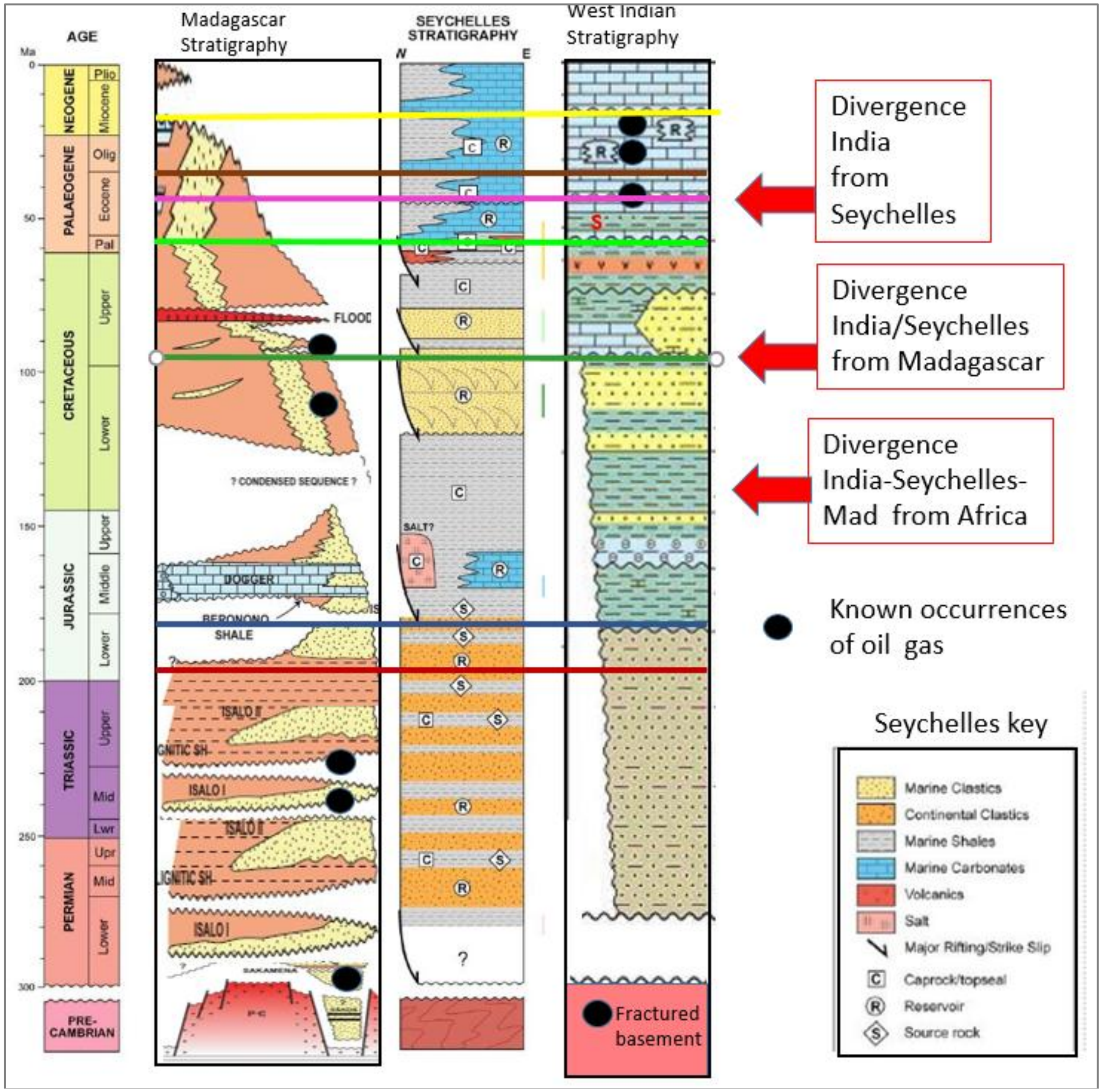

Figure 1. Generalized stratigraphic chart of the Seychelles Plateau with correlations to Madagascar and to India, basic tectonic events and known occurrences of oil and gas. This portrayal downplays the important of volcanic components, limiting the occurrence to the late Cretaceous, and especially the contribution of volcaniclastic units to the column. Basalts may also occur in the Karoo section below the lower Jurassic unconformity. Indicated on the column are also the units picked in the seismic interpretation: yellow mid-Miocene, brown late Eocene unconformity, magenta mid-Eocene unconformity, bright green top Cretaceous, dark green mid-Cretaceous unconformity, blue lower Jurassic unconformity, and maroon near top Triassic. Left column after Tari et al., 2004, central figure after PDF seal report for Petroquest/EAX (2007), right after Roberts et al., 2010.

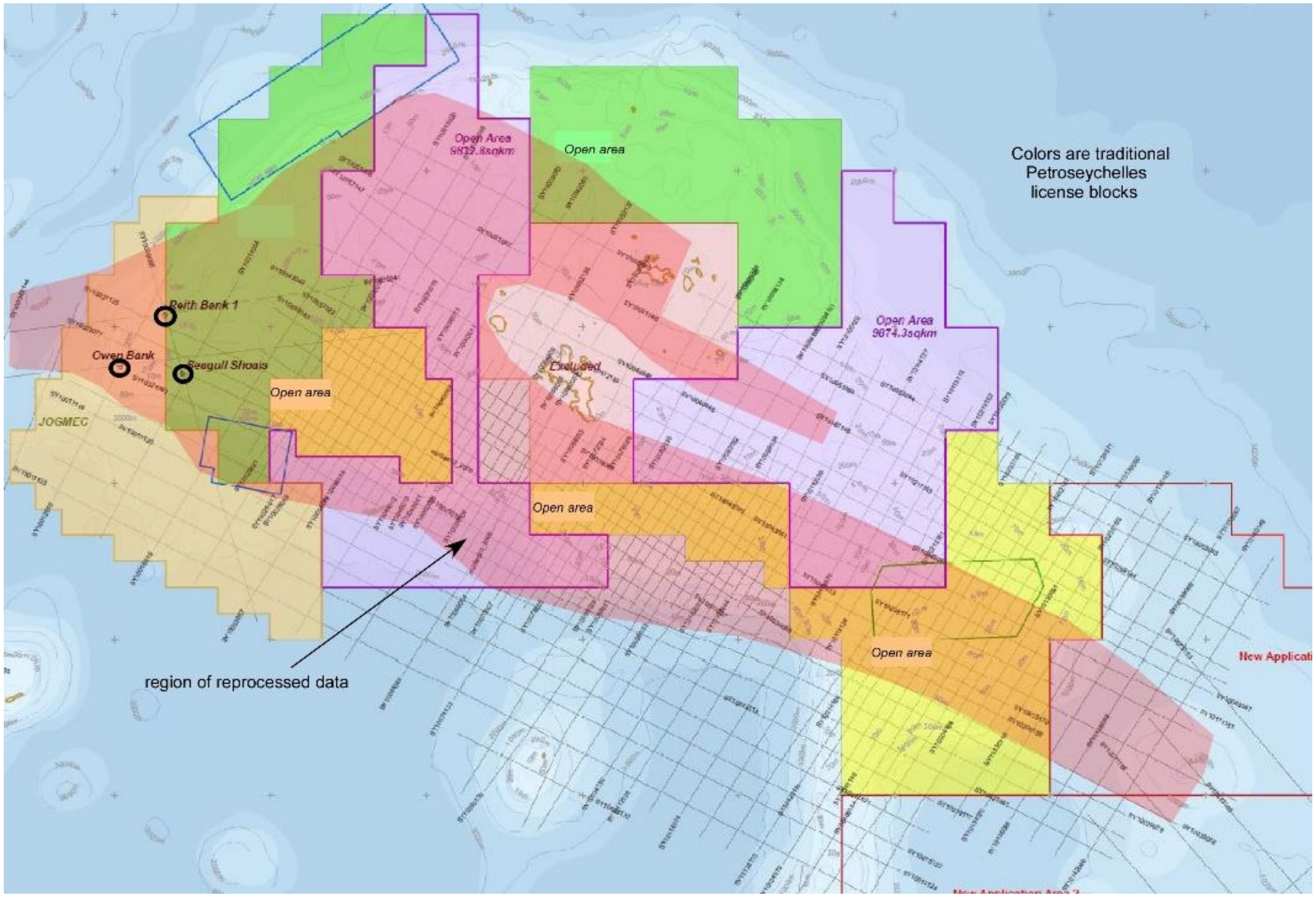

Figure 2. Seismic and license base of the Seychelles Islands. Three of the wells discussed in the text are shown in black circles, 4th is just off the south edge of the map (see Figure 3). Only the far western block is licensed at present. Reprocessed data in this study are highlighted with the irregularly shaped pink overlay.

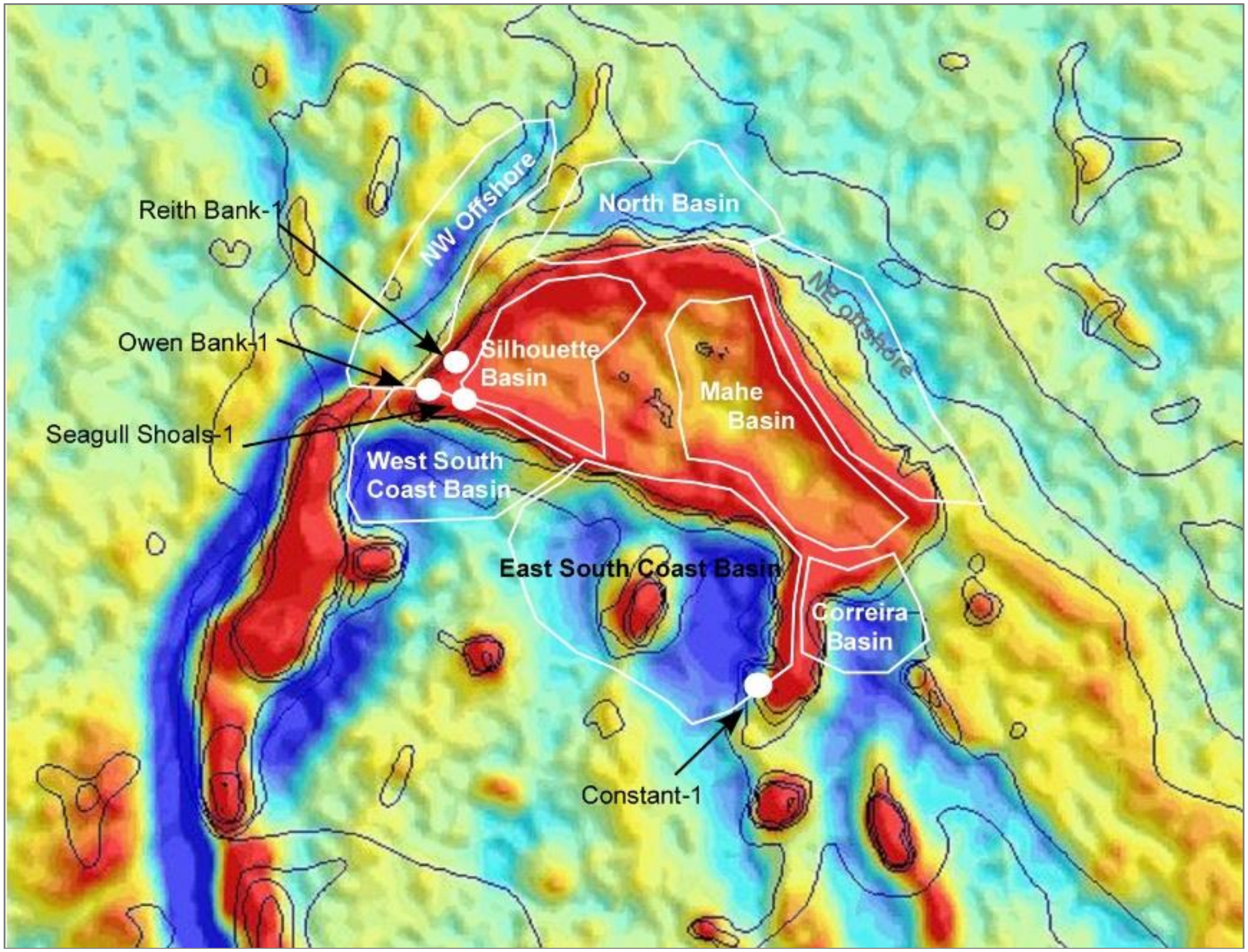

Figure 3. A Sandwell-Smith free-air gravity rendition of the Seychelles Plateau with the four exploration wells located in white circles and the outlines of the various basins we have recognized in this study.

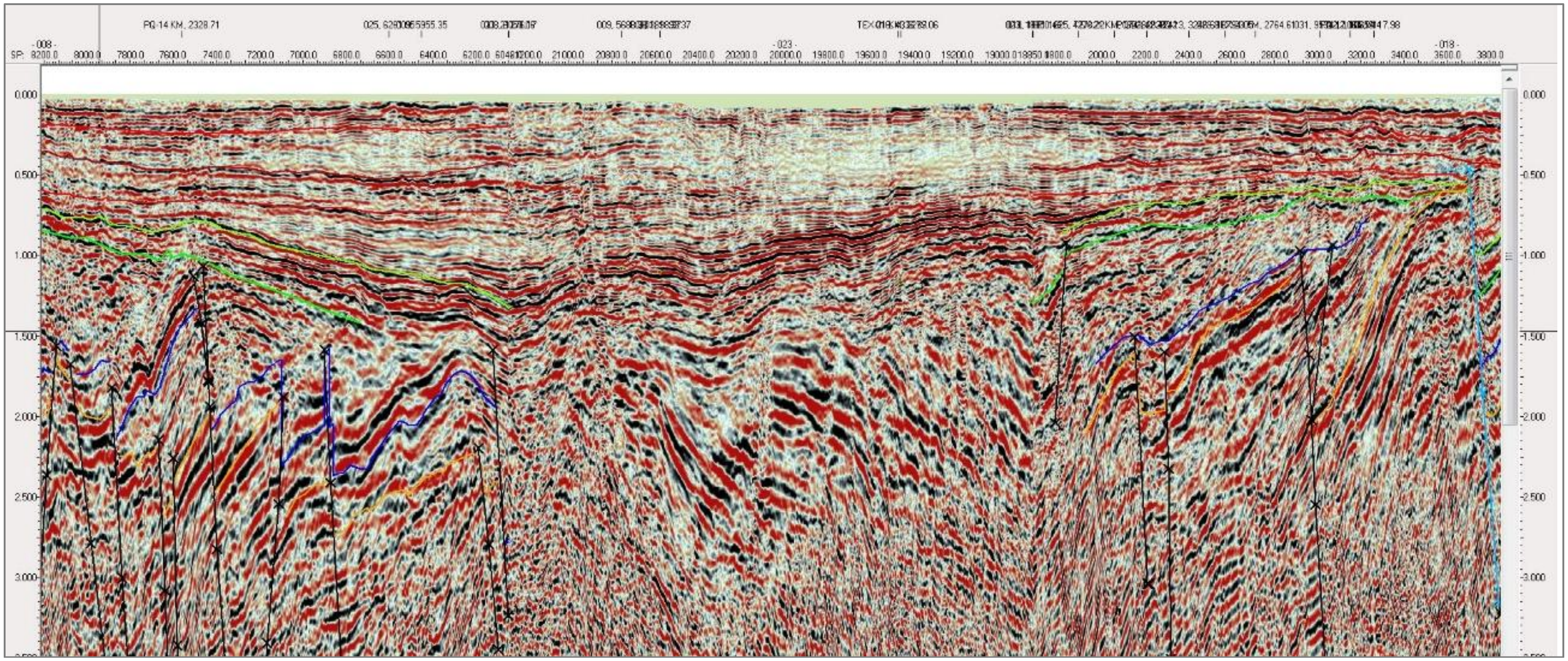

Figure 4. Typical seismic line in the West South Coast Basin, showing the Beau Vallon structure (at the arrow). Blue horizon is the lower Jurassic unconformity near the top of the Karoo section so that this structure is developed in the pre-breakup structure and the applicable section.

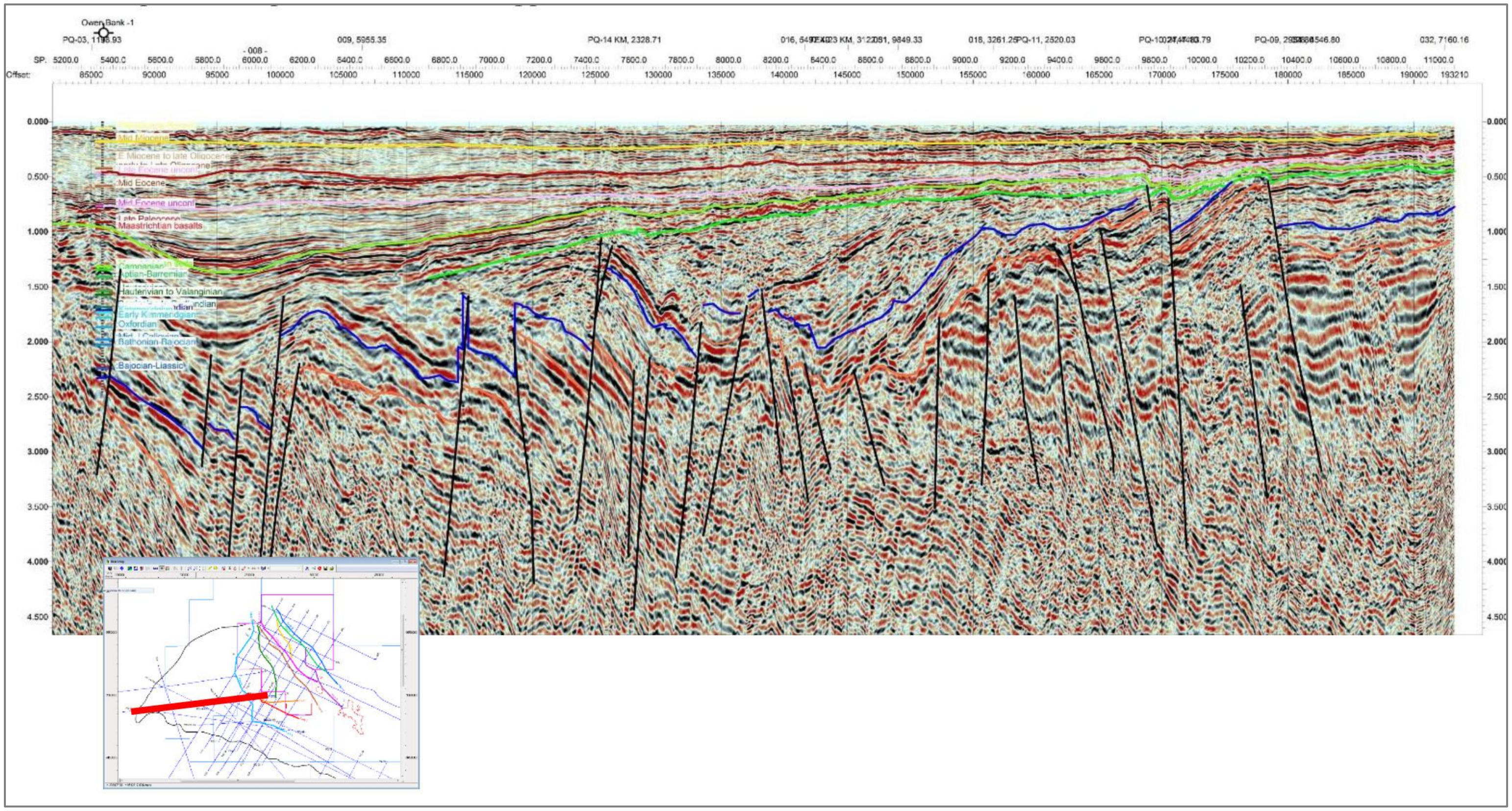

Figure 5. Seismic line Spectrum-008 from the Amoco wells eastward in the West South Coast Basin. Horizons as detailed in Figure 1. This line runs up to the divide between the WSCB and the Silhouette, which is illustrated in the next figure.

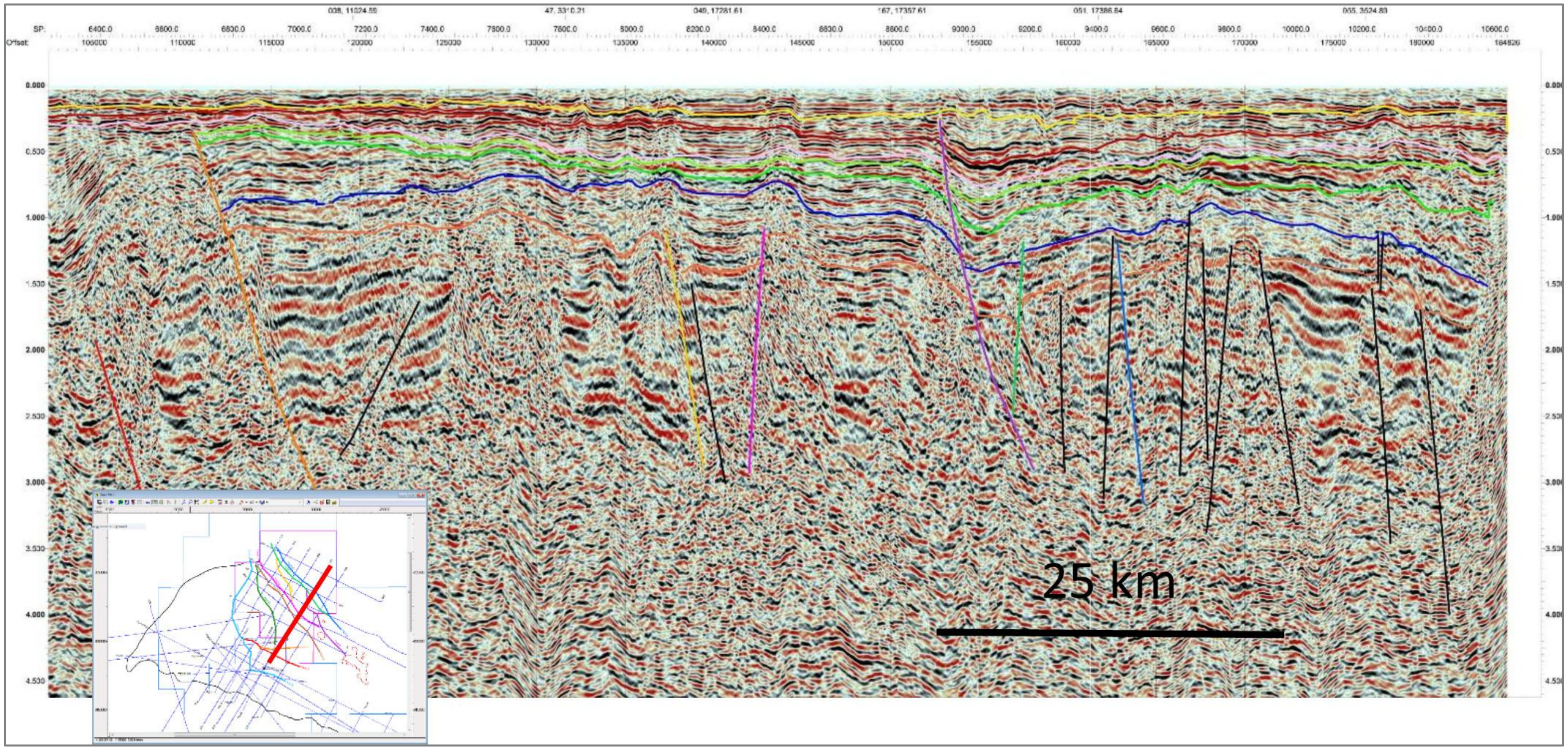

Figure 6. Line Spectrum-032 across the Silhouette Basin. South end of this line nearly ties that of Figure 5 on the divide between the Silhouette Basin shown here, and the WSCB in Figure 5.

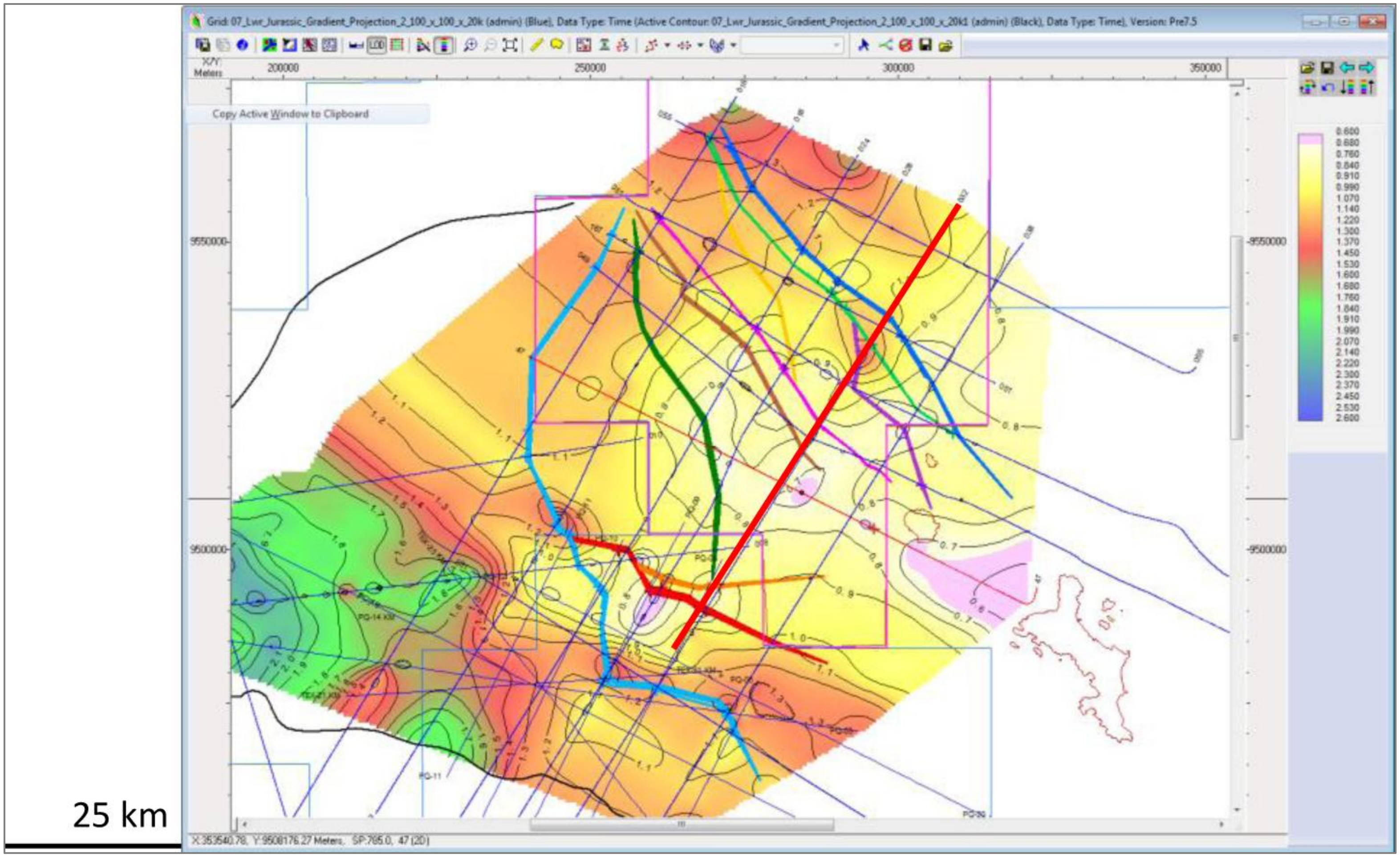

Figure 7. Sample structure map on the near top Triassic horizon for the Silhouette Basin. Silhouette Island is outlined in red in the SE corner of the map. Colored lines are the major faults mapped in the interpretation and link this map to the sketch map of the full fault network in Figure 8.

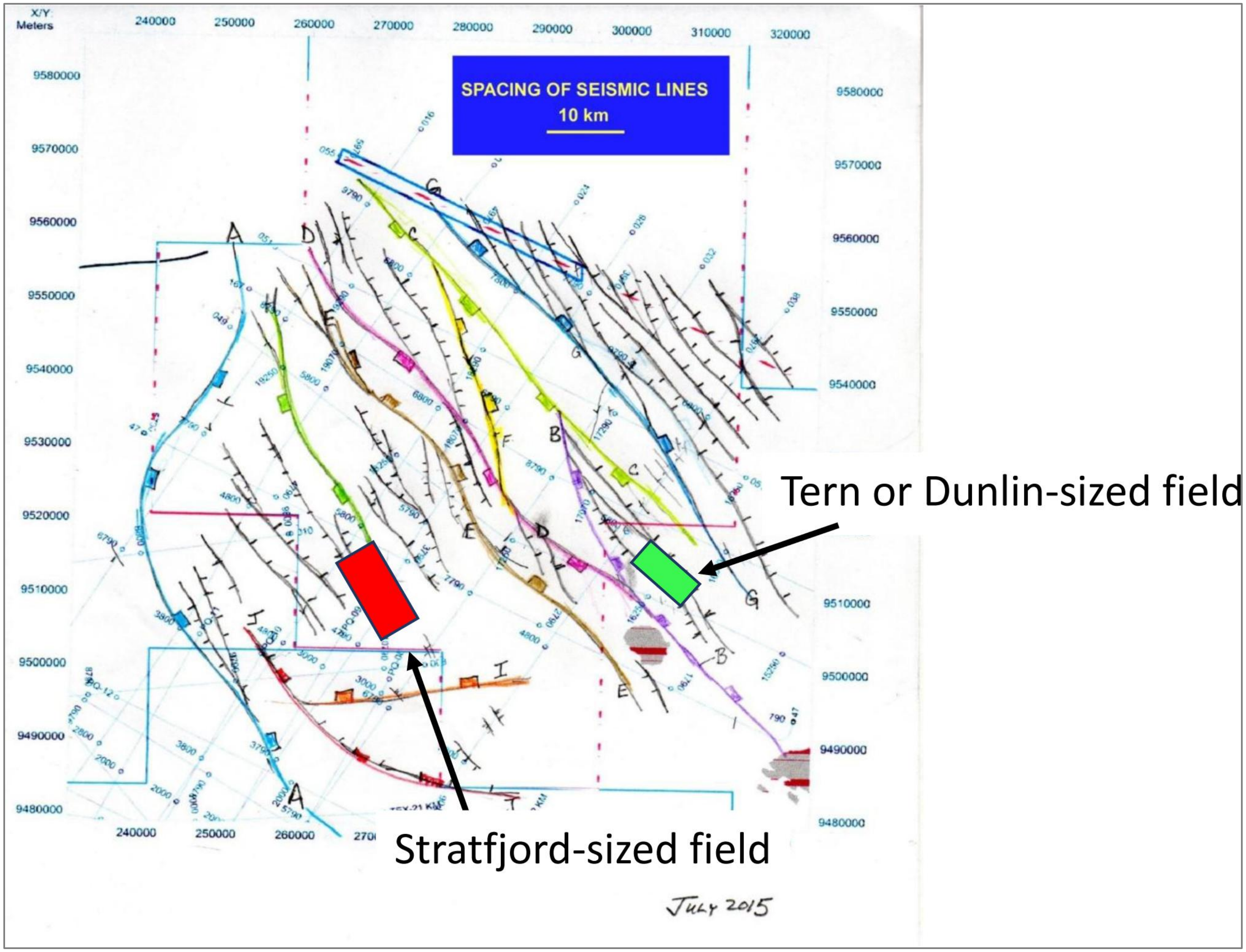

Figure 8. Sketch map of the full fault network in the Silhouette Basin showing size of some typical North Sea fields. Stratfjord Field is a 2 Bbl field, Tern or Dunlin are 300-500 MMbl fields. Line is approximate location of Figure 7.