PSIntegrated Exploration of the Owambo Basin, Onshore Namibia: Hydrocarbon Exploration and Implications for a Modern Frontier Basin*

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Abstract

The hydrocarbon potential of onshore Namibian basins has long been overlooked during the rush to explore offshore concessions. Recent analysis of the Owambo Basin in northern Namibia has identified significant onshore hydrocarbon potential. However, subsurface data limitations due to extremely limited drilling activity (one reservoir test in a basin area the size of New Mexico) have made reliance on potential field geophysics, vintage 2D seismic interpretation, and outcrop studies of the basin periphery critical to predictive models of hydrocarbon occurrence and basin potential.

Interpretation of approximately 2000 line-kilometers of vintage 2D seismic was integrated and used to calibrate results from a recent high-spatial-resolution magnetic and gravity survey, satellite imagery interpretation, and older regional potential field data. From this analysis, we have identified the structural style of the basin and its implications for trap development.

This integrated effort identified three primary phases of deformation and hydrocarbon trap formation in the region.

- **Rift phase (~900 Ma):** Rifting of the Rodinia continent and the development of north-northwest-trending horsts and grabens in the metamorphic Precambrian basement. Some deep grabens in the Owambo Basin may be structural traps.

- **Collision phase (~580-500 Ma):** Contractional tectonics of the Damara Orogeny which resulted in complex crustal shortening and collision between the Kalahari and Congo cratons. East-west directed-shortening (580-550 Ma) led to north-south-trending Kaoko Belt structures followed by north-south directed-shortening leading to east-west-trending structures in the Damara Belt (550-500 Ma). Northeast-trending (right lateral) and northwest-trending (left lateral) wrench zones developed in the basement rocks during this phase

and some older trends were reactivated. There is some evidence of these contractional faults and folds in the basin acting as structural traps.

- **Rift Phase (~132 Ma-present):** Initiation of rifting along north-northwest-trending extensional faults resulted in the opening of the South Atlantic. This extension caused left lateral wrench motion along prominent north-northeast-trending basement zones in the Owambo Basin, forming local wrench-related structural traps. These late folds are prominent structural features in the basin. Their prominence and local significance as structural traps was not recognized until this study.

These three structural trap styles have been further documented by basin margin outcrop studies of source rocks, reservoir facies, and structural features including fractures, faulting, and mesoscale folding.

From these field studies and basin analysis, further constrained by apatite fission track thermal maturity studies, we have attempted to minimize exploration risk in a modern frontier basin. Acquisition of planned modern 2D and 3D seismic should further minimize exploration risk in an unexplored modern frontier basin with tremendous potential for world-class reserves.

Introduction

Namibia contains two large onshore basins, the Nama Basin in the south and the Owambo Basin in the north. The hydrocarbon potential and significance of these two basins has been largely overshadowed by recent exploration interest in the offshore region. Figure 1 shows the location of the major onshore and offshore basins in Namibia.

The entire Owambo Basin encompasses approximately 268,000-350,000 square kilometers, an area slightly larger than the state of New Mexico. Namibia shares the Owambo Basin with Angola, whose southern border roughly divides the basin in half. The basin has little surface expression, less than 100 meters relief, with its lowest point lying on the Etosha Pan at 1084 meters above sea level. The Owambo is presently considered a modern frontier hydrocarbon basin with only one test of potential reservoir horizons. Hydrocarb Energy has a concession area approximately the size of New Jersey. No wells have been drilled in the concession and only 15% of the area has been investigated by a 1970's vintage 2D seismic data grid.

Regional Geology

The geology of the Owambo Basin is shown in the geologic map in Figure 2. The Owambo Basin is covered by the sands of the Kalahari Formation. A DEM (digital elevation model) image of the same area is shown in Figure 3. On this image the outcrops along the basin margins can be delineated.

Along the basin margins, the outcrops of the Late Proterozoic carbonate and clastic sediments lie unconformably on lower to mid-Proterozoic poly-deformed metamorphic and granitic basement (Miller, 1997). Geophysical data indicate that the western portion of the basin is deeper than the eastern portion and may contain up to 8,000 meters of sediments (Miller, 1997). No wells drilled within the basin have sampled crystalline basement.

The goal of the regional integrated analysis was to establish the regional geologic context in which to place the airborne geophysical survey data collected over the Hydrocarb concession.

This objective was accomplished by:

- Providing a regional integrated context for the newly-acquired aerogravity and aeromagnetic survey,
- Integration of previous potential field surveys into a coherent template,
- Delineation of outcrop structural styles traceable into the basin for assessment and verification during fieldwork, and
- Developing a framework to extrapolate the seismic mapping into areas where seismic control is currently lacking.

Field Studies

Figure 3 is a digital elevation model (DEM) of the basin with an overlay of the current hydrocarbon concessions in the basin, and the location of the 1970’s vintage 2D seismic grid. This graphic also shows the outline of the most recent survey boundaries for the Hydrocarb, Preview and Carson potential field airborne surveys. To ameliorate the problem of minimal seismic data in the basin and the high cost of collecting new data over such extensive areas, most recent exploration companies have flown potential field surveys (aeromagnetics and aerogravity) to identify prospective lead areas.

In 1962, Owambo Basin hydrocarbon exploration commenced with a regional airborne magnetics survey conducted by Hunting Surveys Ltd. It was a large regional reconnaissance survey encompassing most of the basin that was collected at a relatively high altitude for Etosha Petroleum.

Commencing in 1996, very high spatial resolution aeromagnetic data collected with sensitive cesium vapor detectors have been flown over most of the country for the Geological Survey of Namibia. Survey specifications for the government collections included tight 200 meter line spacing with orthogonal tie lines at 2,500 meter intervals. Flight altitudes were low, generally at 80 meters Above Ground Level (AGL). Magnetometer sample rates were 10 samples per second with detection sensitivities of better than .01 nanotesla (nT). These government data are low-cost and of very high quality.

Airborne gravity surveys have also been flown in the Owambo Basin. The first survey was done by Carson Services in 1990 over the eastern half of the basin for Overseas Petroleum and Investment Corporation. Aerogravity coverage within the country is not extensive but it has been acquired for most of the Owambo Basin. A few limited ground-based gravity surveys were also conducted, the first being done by Ray Geophysical in 1963.

Table A provides collection details and areal extents of key airborne potential field data acquisitions in the western Owambo Basin. Traditionally, aerogravity surveys have always included magnetic instrumentation because both data sets can be acquired simultaneously at little additional cost. Typical sample rates for recent aerogravity surveys have been 1-2 samples per second with an accuracy of less than 1 milligal at a 6 kilometer wavelength for 1 sigma Root Mean Square Errors (RMSE).

Exploration History

The Owambo Basin has had minimal historical exploration activity involving short bursts of activity followed by long periods of inactivity. This sporadic activity largely reflects the complex and variable effects of politics in southern Africa. Figure 4 shows the exploration history timeline for the basin. Figure 5 summarizes the four petroleum test wells that have been drilled in the basin since 1959, only one of which actually tested the uppermost section of the potential reservoir.

In 1959, Texas Eastern purchased the first exploration rights to the Etosha (now Owambo) Basin. During their ownership of nearly the entire Namibian half of the Etosha Basin, the company flew a regional aeromagnetics survey in 1962. A ground-based gravity survey was also performed by Ray Geophysical in 1963. In 1964, Texas Eastern created a subsidiary operation designated Etosha Petroleum which also served as the operating company. In 1964, the Etosha Petroleum Stratigraphic Test #1 well was drilled.

In 1966, Brilund Mines acquired Etosha Petroleum. The merged company completed a photogeology and outcrop study of the basin in 1966, that led to a 2D Vibroseis seismic program from 1968-1970. The initial seismic survey was conducted by Seismograph Service Limited (SSL) in 1968, followed by Teledyne who took over the project in 1969. Etosha Petroleum also had a regional surface geochemistry study conducted in 1967 over 19,220 square kilometers of the basin. In 1970, Etosha Petroleum also drilled two shallow wells (Etosha 1-1 and 2-1 wellbores) into the Owambo Formation, and one deeper test (Etosha 5-1A) into the uppermost Otavi Group carbonate reservoir. No additional effort was conducted in the basin from approximately 1970 through 1990.

During this time period (1960-1990) when the basin was being explored by Brilund-Etosha, significant military and political activity occurred in the region. Finally, in December 1988, after over twenty years of dispute and armed conflict, South Africa signed an agreement linking its withdrawal from the disputed territory to an end of Soviet and Cuban involvement in the long civil war in neighboring Angola. Namibian independence from South African administration occurred on March 21, 1990 after the UN negotiated cessation of warfare. Since independence, Namibia has had stable governments and a commitment to improved social welfare for its population.

Following these ongoing political maneuvers, Brilund formed a partnership with OPIC (Overseas Petroleum Investment Corporation) of Taiwan in 1988. This partnership led to the drilling of the shallow OPIC OPO-1 well in 1991 after the acquisition of an additional 800 kilometers of 2D seismic, and the collection of aerogravity data using Carson Services. OPIC left the basin in 1991.

OPIC was replaced by Occidental International in 1992 as Brilund's partner. Occidental funded a surface soil gas study, some Total Organic Carbon (TOC) analyses, a limited apatite fission track analysis, and fluid inclusion work based on outcrop sampling of over 200 samples. Occidental did not drill any wells and left the basin in 1993.

Following Occidental's departure, there was little outside exploration interest in the basin for approximately ten years. During that time, Etosha relinquished the license they had held in the basin since 1964. Commencing in 1991, the Namibian Government, using German-coordinated subcontractors, collected high-resolution magnetic data over the majority of the country, including the Owambo Basin.

From 2003-2009, First African Oil held exploration blocks 1714, 1814, 1715, 1815, 1716, 1816, 1717, 1817, 1718, and 1818. They contracted a regional airborne magnetics and gravity survey of 7,627 square kilometers. First African became a subsidiary of Circle Oil during this time. No wells were drilled.

In 2011, Preview Energy was awarded a concession area for blocks 1716 and 1816A and flew a limited aerogravity survey over that area. They also submitted samples for AFTA (apatite fission track analysis) from the Etosha Strat Test #1 and 5-1A wells.

In 2011, Hydrocarb Energy signed an exploration agreement for blocks 1715, 1815A, 1714A, and 1814A. Hydrocarb Energy flew an aeromagnetics and aerogravity survey in 2013 to identify prospective areas for a 2D seismic survey. Additional field work in 2012 and 2013 has been done to sample outcrops for source and reservoir rocks.

In 2012, Frontier Resources, a UK corporation, was awarded a concession for blocks 1717 and 1817 and to date has completed a limited soil gas survey which was reported to show the presence of anomalous levels of methane, ethane, propane, and butane (Frontier Resources, 2014).

The Owambo Basin has had a long but very limited exploration history. The basin has been recognized since approximately 1964 when the Etosha Stratigraphic Test Well #1 confirmed the presence of a deep basin hidden beneath the Kalahari sands.

At this point, the entire Namibian portion of the Owambo Basin has been assessed using aeromagnetics, and a majority of the western basin has been examined using aerogravity methods. The limited subsurface database of wells and seismic is currently restricted to the southern and central basin. This restricted data occurrence represents a significant limitation to our understanding of the potential petroleum system that should be present in the basin.

Stratigraphy

In the Owambo Basin, the oldest sedimentary rocks in the basin belong to the late Proterozoic-age Nosib Group which lies unconformably on Precambrian-age poly-deformed basement rocks and granitic intrusives. Figure 6 shows the generalized stratigraphic column for the basin. Additional discussion and summary of regional stratigraphic relationships can be found in Hugo (1969), Hedberg (1979), Hoffmann and Prave (1996), Miller (1997, 1999, 2008), and Bechstadt et al. (2009).

Potential reservoir and source rock horizons include the Proterozoic Nosib, Otavi and Mulden groups. The Otavi Group is believed to be a self-sourcing carbonate system. There are also interbedded shale zones and shaly carbonates in the lower section (Miller, 1999, 2008; Bechstadt et al., 2009).

The Nosib Group includes interbedded marine and continental clastics with minor carbonates. Nosib rocks were deposited during intracontinental rifting during the break-up of the Rodinia supercontinent (Miller, 2008). From observed outcrop relationships along the southern and western basin margins, Hedberg (1979) interpreted that the Nosib was deposited into syntectonic grabens during early rifting.

Above the Nosib Group lies the Proterozoic-age Otavi Group. The Otavi Group is primarily dominated by shallow marine carbonates, with lesser amounts of interbedded sandstones and shales. Stromatolites and oolitic shoals are common at the top of the Otavi (Miller, 2008). The Otavi Group consists of the basal Abenab Formation and the overlying Tsumeb Formation.

Between the Tsumeb and Abenab formations lies an interstratified glacial tillite, the Chuos Formation (Hoffmann and Prave, 1996). The thin Chuos Formation glacial tillite (Hedberg, 1979; Hoffmann and Prave, 1996; Bechstadt et al., 2009) is widespread across the basin. Clast compositions and interpreted provenance suggest a distal source for much of the material (Hedberg, 1979).

Total organic carbon content (TOC) of the Otavi Group can range up to nearly 9% as observed in outcrop, although most samples typically show less than one percent TOC (Bechstadt et al., 2009). Outcrop sampling by Hydrocarb Energy has confirmed similar TOC contents and is believed to reflect fluid flow through the carbonate section. The presence of dolomite in many of the shales makes accurate rapid TOC calculations more difficult depending on the analytical method used and may lead to a lower TOC than would be assessed using alternative methods. Work in progress is attempting to understand and resolve this problem.

Otavi Group porosity ranges up to 15% in logs and 21-37% in outcrop samples (Dommer, 2012). Permeability in the uppermost Otavi Group stratigraphic interval is believed to be high due to anecdotal driller reports of numerous lost circulation zones encountered while drilling the Etosha 5-1A wellbore that have been interpreted to represent fractured zones.

Following the plate collisions which formed Gondwana, the Owambo Basin again subsided and was filled with continental clastics. These sediments were shed toward the foreland during the Proterozoic-age Damara Orogeny (580-530 Ma), forming the late Proterozoic-age Mulden Group (Prave, 1997; Miller, 2008). Marine conditions returned during the later Mulden deposition, depositing carbonates, sandstones, and shales. The Owambo Black Shale Member (~100 meters thick, Hedberg, 1979; Miller, 1997, 2008) lies at the base of the Owambo Formation, part of the upper Mulden Group.

Following a period of uplift and erosion spanning the lower Paleozoic, the Permian-age Karoo Supergroup was deposited unconformably over the Proterozoic-age Mulden Group (Miller, 2008). The Lower Permian-age Dwyka Formation, at the base of the Karoo Group, consists predominantly of tillites, with thin interbedded shales, dolomitic siltstones, limestones and sandstones. The Dwyka is overlain by strata that consist predominantly of black carbonaceous shales in the lower section as well as alternating dark shales and light to greenish grey finegrained silty and argillaceous sandstones. Limited occurrences of Karoo coal have been reported, however they are not sufficiently thermally mature to produce oil or gas (Hugo, 1969; Miller, 2008).

The upper part of the sequence consisting of flood basalts (Etendeka Formation) and aeolian sandstones (Etjo Formation) are believed to not be present or are of limited extent in the central part of the Owambo Basin (Hugo, 1969). However, limited borehole subsurface data at this time makes this interpretation subject to future revision. Aeromagnetic signatures indicative of near-surface basalts are present adjacent to the Gam Lineament, a major structure which trends northwest-southeast across the western Owambo Basin. These basalts are believed to be interstratified with or directly underlie the Karoo (Klawitter, 2012) but appear too deep to have been sampled by the DDH coring program (Hugo, 1969).

Overlying the entire sequence are the poorly consolidated sands of the Cretaceous-Recent-age Kalahari Formation. These sands blanket the basin and completely obscure the complex subsurface structure (Miller, 2008).

Structural Geology

An idealized structure section across the basin is shown in Figure 7 using the available subsurface control. Because of the limited control, the deep interpretation of the basin is equivocal. However, the structural style of the deepest structures should reflect the 900 Ma rifting and subsequent deposition of the Nosib Group. In the Late Proterozoic, commencing approximately 580 Ma (Gray et al.,2008), the structural style of the basin shifted to a convergent plate boundary and the development of fold-and-thrust contractional features seen on seismic sections (not shown in idealized graphic section, however, see Figure 16 discussed later).

Due to the high obliquity of the contractional deformation trends to pre-existing features (especially the Gam, Opuwo , Omaru linear disturbance zones, Figure 8), there should be a preponderance of wrench deformation along these deep pre-existing structural anisotropies in the basin.

Additional wrench deformation has been documented at an even younger time. The Oponono Anticline shows Karoo sediments folded and then overlain by onlapping sediments of the Karoo Group (also see Figures 17 and 18). The exact timing of this late-phase deformation is being investigated and confirmed by examining the Karoo and Kalahari sediments age in the shallow DDH water well boreholes (Hugo, 1969) which appear to correlate in the seismic data to these very shallow deformed horizons.

The regional structural fabric within the western Owambo Basin is consistent with trends introduced during the Damara Orogeny and deformation within the Kaoko Belt. The Damara Belt is 300 kilometers south of the Hydrocarb concession and was the site of rifting 900 Ma followed by continental collision 650 Ma. The Damara Belt trends N60E. The Kaoko Belt is the northwest extension of the Damara Belt. It is less than 200 kilometers west of the Hydrocarb concession. The Kaoko Belt trends N25W and is characterized as a classic example of a Neoproterozoic transpressional orogen (Goscombe et al., 2005).

As a result, the western outcrop belt of the basin is dominated by N25W trending linear features related to initial emplacement of the Kaoko Belt from 580-550 Ma (Gray et al., 2008) followed by the development of N60E linear features and structures related to the north-south collision of the Damara Belt from 550-530 Ma (Gray et al., 2008).

Figure 9 shows the rose diagrams of interpreted linear features from the geologic map in Figure 8. The linear features were interpreted from LANDSAT Thematic Mapper (TM) imagery, DEM (digital elevation model) imagery data combined with surface geologic maps from the Namibian Geologic Survey. The rose diagrams show that the majority of features and the dominant structural orientations in the basin can be readily identified from imagery analysis.

From the rose diagrams and the interpreted linear features, the controlling influence of the Gam, Opuwo and Omaru lineaments zones is apparent. Visual inspection of the linear feature trends within the larger fault blocks defined by these mega-lineaments clearly underscores the importance of these zones in controlling the orientation of basin structures that form within them. This also has profound implications for hydrocarbon migration and the charge potential for various structural traps over time.

One regional lineament, a zone of aligned and concentrated linear features, was interpreted. It is a conspicuous structure on both satellite imagery and the DEM and emerges from outcrop in the northwestern portion of the Owambo Basin and trends directly into Hydrocarb concession block 1714A. The lineament proceeds through block 1715 and enters Angola near 16° east longitude and has been previously described in literature as the Opuwo Lineament (Corner, 2002).

The Opuwo Lineament occupies a broad zone at least 60 kilometers wide and is characterized by terminations of topography, abrupt changes in lithologies and geologic trends. Additionally, it re-folds older northwest-trending folds. Corner (2002) described the Opuwo Lineament as the onshore extension of the Rio Grande Fracture Zone, a broad zone of mappable basement structures (Gamboa and Rabinowitz, 1981). Southwest of the basin margin, near the Otuziru base metal prospect, the Opuwo Lineament is host to hydrothermal activity and intense folding (Bannon Ltd, 2013).

Integration of Magnetic/Gravity and Seismic Data

One of the main objectives of the airborne potential field survey was to identify potential prospective areas to further investigate using seismic data. In addition, we wanted to extrapolate the seismically-calibrated potential field interpretation into those areas where seismic control was lacking. The location map for the seismic lines and gravity/magnetic profiles used in this presentation is shown in Figure 10.

A key part of the integration process, especially given the ability to map surface features using various imagery sets as shown in Figure 8 and Figure 9, was to interpret linear features on the magnetics and gravity maps. Figure 11 shows the interpreted linear features superimposed on the free air gravity data. The majority of interpreted features appear to lie on structures, rather than faults. Figure 12 shows the interpreted linear features superimposed on the International Geomagnetic Reference Field (IGRF) removed total field RTP (reduced-to-pole) magnetic data. These interpreted features mainly lie on interpreted faults rather than structures.

These two maps of the potential field data show the dominant subsurface trends interpreted from a range of gravity and magnetic mapping techniques. These techniques included: second derivative maps, use of azimuthal hill-shading, density-slicing, use of tilt derivatives, horizontal gradients, slope absolute value of slope maps, and residual mapping.

One of the outcomes of the potential field survey was the creation of a depth-to-basement map created using modeled magnetic and gravity profiles. Example profiles are shown in Figure 13. There is a close correspondence between matched and observed profiles for both gravity and magnetics. It was determined that the basement composition (density and magnetic susceptibility) has the greatest influence on the observed gravity and magnetic values. The modeled intrasedimentary properties are much less significant.

Seismic Interpretation and Calibration of Potential Field Data

As mentioned earlier, one of our primary objectives was to extrapolate the results of the potential field survey, calibrated using seismic interpretation, into those areas where seismic control was non-existent. We have chosen four seismic lines to illustrate the structural style in the basin. Figure 14 is the OND-6 interpreted seismic line from the northernmost part of the seismic grid, close to the basin center. This line has been interpreted to show Nosib Group sedimentation related to the earliest rift deformation. The Nosib is shown in that graphic as a tan wedge of sediment adjacent to a deep normal fault.

The WET 28 line (Figure 15) located in the southwest corner of the basin shows wrench deformation. In this area, due to the high obliquity between the pre-existing structural fabrics and the subsequent deformation phases, most of the older fabrics would be reactivated during later deformation. There appears to be an uplifted basement section in this area. There is some evidence of extensional faulting in the deeper section. A dike was interpreted on the magnetic data set and is added to the line. There is very little seismic discontinuity associated with the dike.

The regional contractional deformation resulting in a fold-and-thrust geometry is shown in OKA-2 line (Figure 16). The OKA-2 line extends northward into the basin from just north of the southern basin margin. This line shows the characteristic asymmetric long back limb, short forelimb structural style of most fold-and-thrust belts. Again, the obliquity of deformation phases indicates that there should also be considerable wrench motion in this section.

The final deformation phase is shown in OPO-12 line, uninterpreted (Figure 17) and interpreted (Figure 18). These lines show the Opono Anticline located in the southern basin center. This line shows the complex interplay between symmetric upright folding and interpreted wrench zones in the basement. From the uppermost stratigraphy, the timing of deformation can be shown to be Karoo in age given that the intra-Karoo stratigraphy is both folded, and onlaps and drapes the structure. It should be emphasized that the observed structure is inconsistent with drape folding over basement due to thickening in the upper shale section.

Additional support for a wrench interpretation in the Opono locality is shown by time structure maps of the Top Mulden and Top Otavi surfaces. Both surfaces (Figure 19) show en echelon folds oriented obliquely to the adjacent Gam Mega-Lineament (zone of disturbance). Independent resource assessments for the Opono Structure show the potential for nearly a billion barrels of oil (Netherland and Sewell, 2013).

Thermal Maturity and Burial History

To better understand the thermal evolution of the basin and calculate the maximum burial depth, apatite fission track analysis (AFTA) was used (Preview Energy, 2010). Figure 20 shows the sample location map used for the AFTA analysis. There is a mix of outcrop samples from the southern basin margin, along with a few samples from wells within the basin. AFTA data were provided to us by Preview Energy.

The map in Figure 21 shows the time of maximum burial depth and commencement of uplift during the Carboniferous. Maximum burial occurred at approximately 325 Ma. Approximately at that time, active hydrocarbon generation ceased and the Mulden Group entered into the Early-Mature oil window. There was a period of secondary burial and uplift at 180 Ma, during the Late Jurassic, likely corresponding to the beginning of regional uplift and the commencement of South Atlantic rifting.

The AFTA Burial history plot (Figure 22) for the Etosha Stratigraphic Test #1 wellbore, located in the basin center, is located off structure on a deep syncline. This burial history shows maximum burial around 350-320 Ma and a final second phase of burial and uplift at around 180 Ma. During initial uplift, the section was uplifted approximately 3000 meters. During the second phase of uplift, the section was uplifted around 1000 meters. Note that by increasing the geothermal gradient from the assumed heating rate of 1 degree Celsius per My and the cooling rate of 10 degrees Celsius per My, the amount of calculated uplift can be made considerably smaller. Values chosen were based on current gradients and were likely higher in the past due to rifting and other tectonic events. Additional samples should be collected to further constrain the thermal history of the basin and more accurately calculate the amount of erosion and uplift that may have occurred in the basin.

Hydrocarbon Indications

In the early 1990’s Occidental International commissioned a soil gas survey in the basin. The results are shown in Figure 23. This map, from the southwest margin of the basin, shows a single oil occurrence in the Okatjangee Gorge. Additional oil and gas indicators in the Okonjota Anticline and some additional oil and gas indicators were observed in samples collected along the 1970’s vintage seismic grid.

To further assess the presence of hydrocarbons in the basin, a sample was collected in 2012 of the soil from the Etosha 5-1A wellsite that was drilled in 1970. Figure 24 is a gas chromatogram showing that the sample is biodegraded (lacking the aromatics and light hydrocarbons) but has a prominent C 29 Hopane peak interpreted to indicate oil generated by a carbonate source rock.

Based on the interpreted presence of oil and gas indicators in the southwest part of the basin from geochemical soil gas analysis, combined with a gas chromatograph showing persistent hydrocarbon soil contamination from the 5-1A drillsite, it appears that an active hydrocarbon system is present in the Owambo Basin. Additional sample collection would help to refine the migration and maturation model.

Prospective Areas for Future Seismic Program

The primary goal of the integration between the potential field surveys and the seismic interpretation was to identify the characteristics of structural features in the potential field surveys and what the corresponding structures look like in the seismic data. From this integration, prospective areas for further seismic surveying were outlined. Figure 25 shows the prospective areas and their ranking criteria. Highest ranking was given to those prospects that had seismic, magnetics, and gravity data. Intermediate ranking was done for those prospects which had gravity and magnetics data. The lowest rank was reserved for prospects with either magnetic or gravity data. From these calibrated prospects, analog prospects can be likely identified in those areas where seismic data is lacking.

Hydrocarbon Kitchen

Closely related to the identification of prospects and the thermal maturity of the basin is the location of the hydrocarbon source or kitchen. The gravity-derived depth-to-basement map was made by integrating the profile data, regridding it and making a contour map. From this contour map, the deepest part of the basin was identified for the present-day basin configuration. Figure 26 shows the outline of the hydrocarbon kitchens in the deepest areas of the basin. Figure 27 shows the same kitchens on a hill-shaded, RTP total field magnetics base map. From this map, areas of magnetic structures can be seen. Presumably these structures would fill from the center of the basin outward. This map gives a general sequence of progressive filling of structures in the basin and gives some insight into the likelihood that a structure contains hydrocarbons. It should be noted that some of the structures approaching the basin margin, where the structures become shallower, show breaching of some of the shallower shale intervals which have been interpreted as seals. Figure 28 shows the same kitchen areas on a regional free air gravity base map.

Finally, Figure 29 uses the free air gravity map projected in three-dimensions to more graphically illustrate the location of various basin structures relative to the deeper kitchens. The vertical exaggeration of this diagram allows the relationships between various structural elements to be more easily recognized.

In all of these maps and diagrams, the importance of the Gam and Opuwo lineament zones is critical. From the seismic data, we have seen that these zones exert a profound control on the structural features encompassed within the larger fault blocks flanked by these lineaments. As a result, these lineament zones also likely control the migration pathway of hydrocarbons in the basin.

As additional seismic data becomes available to infill the structural geometry of the basin interior, this data, integrated with the hydrocarbon kitchen map, will help refine hydrocarbon migration models for the basin. Work in progress is attempting to refine the significance of the major lineament zones and their control on migration based on the existing potential field data sets.

Basin Evolution

As shown in the previous graphics the Opuwo, Gam, Omaruru and Onimwandi/Owambo lineament zones exert a profound control on the development of structures in the basin. By examining how these fault zones moved during stress regimes oriented obliquely to them, we can determine the potential orientation of structural traps within each block. Figure 30 illustrates the geodynamics of the Owambo Basin from the contractional Kaoko event, through the subsequent Damara event, concluding with the relatively late wrench tectonics that has created many of the shallow fold structures believed to contain hydrocarbons. By thoroughly understanding the controls on these structures, especially the late wrench system, we are better able to predict their geometry in areas where only potential field data is currently available. In addition, by understanding their kinematic evolution and complex history, we can better develop accurate geologic models for folding and fracturing. From this, we will be able to predict and assess the plausibility of various migration and trapping scenarios in the basin subsurface.

Conclusions

The deep Owambo Basin configuration is now thought to be different from previous assessments, with the deepest part located to the south and east of previous interpretations. Maximum calculated depth-to-basement is 7000 meters (20,000 feet). Analysis of LANDSAT TM imagery and DEM data identified and corroborated dominant regional trends and local structural features determined by older field mapping. There is a close relationship between results obtained from surface structural mapping and imagery analysis.

Seismic data integrated with potential field data show examples of Early Katangan rifting and deposition of Nosib sediments, Damaran fold-and-thrust deformation from the west to east, then south to north, followed by younger (Late Karoo-?) wrench motion. It is important to recognize the control of potential field line spacing on interpreted features. Magnetic data used in the project have 10X the line density compared to gravity, significantly enhancing its ability to resolve smaller features. Seismic and gravity data sets do not image the Onimwandi dikes due to their narrow widths.

Magnetic data reveal fault zones (probably due to enhanced magnetization and alteration in fault zones), whereas gravity data shows structures. Seismic data confirms the presence of structures related to both sets of the interpreted features.

The Opuwo Lineament zone is a wide zone (>50 km) that involves basement, appears significantly shallower than previous interpretations, and shows a structural complex composed of smaller blocks and wrench related basins. The Gam Lineament involves basement and shows a complex history of wrench motion, and appears to control the extent of rift-related dikes and shallow lava flows in the basin. Adjacent structures (e.g. the Oponono Anticline) appear to have formed by wrench fault motion.

Approximately eighteen prospective conventional targets were identified for additional 2D seismic surveying in this frontier basin. An active hydrocarbon system in the basin is suggested by geochemical indicators and soil samples from the Etosha 5-1A wellsite. This system is further enhanced by the high likelihood of numerous seals for abundant structures due to abundant thick shale intervals.

Each data set integrated in the study provides significant additional information to facilitate the maximum level of understanding of the Owambo Basin petroleum system. The study clearly underscores the critical importance of acquiring and integrating multiple data sets.

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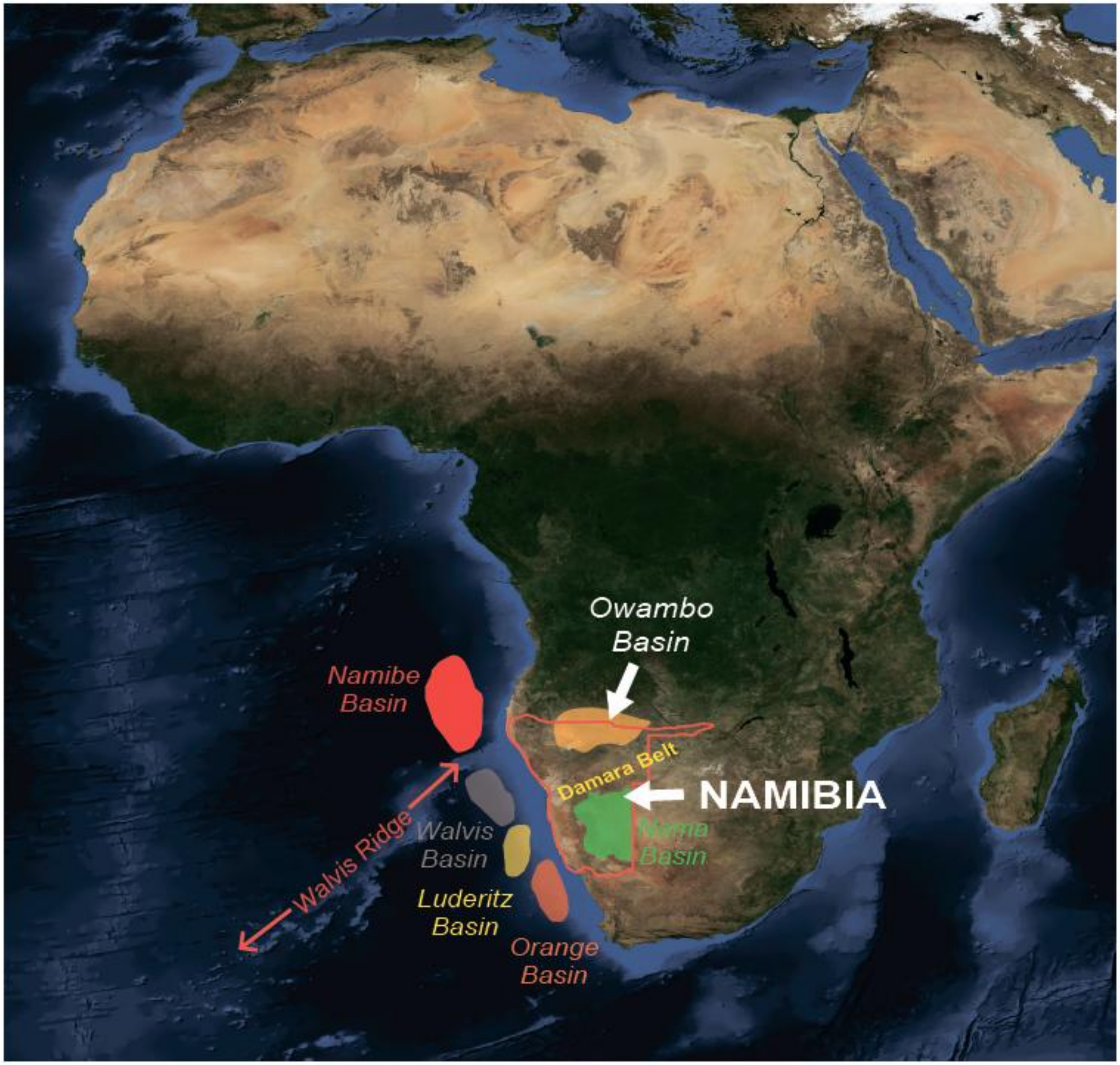
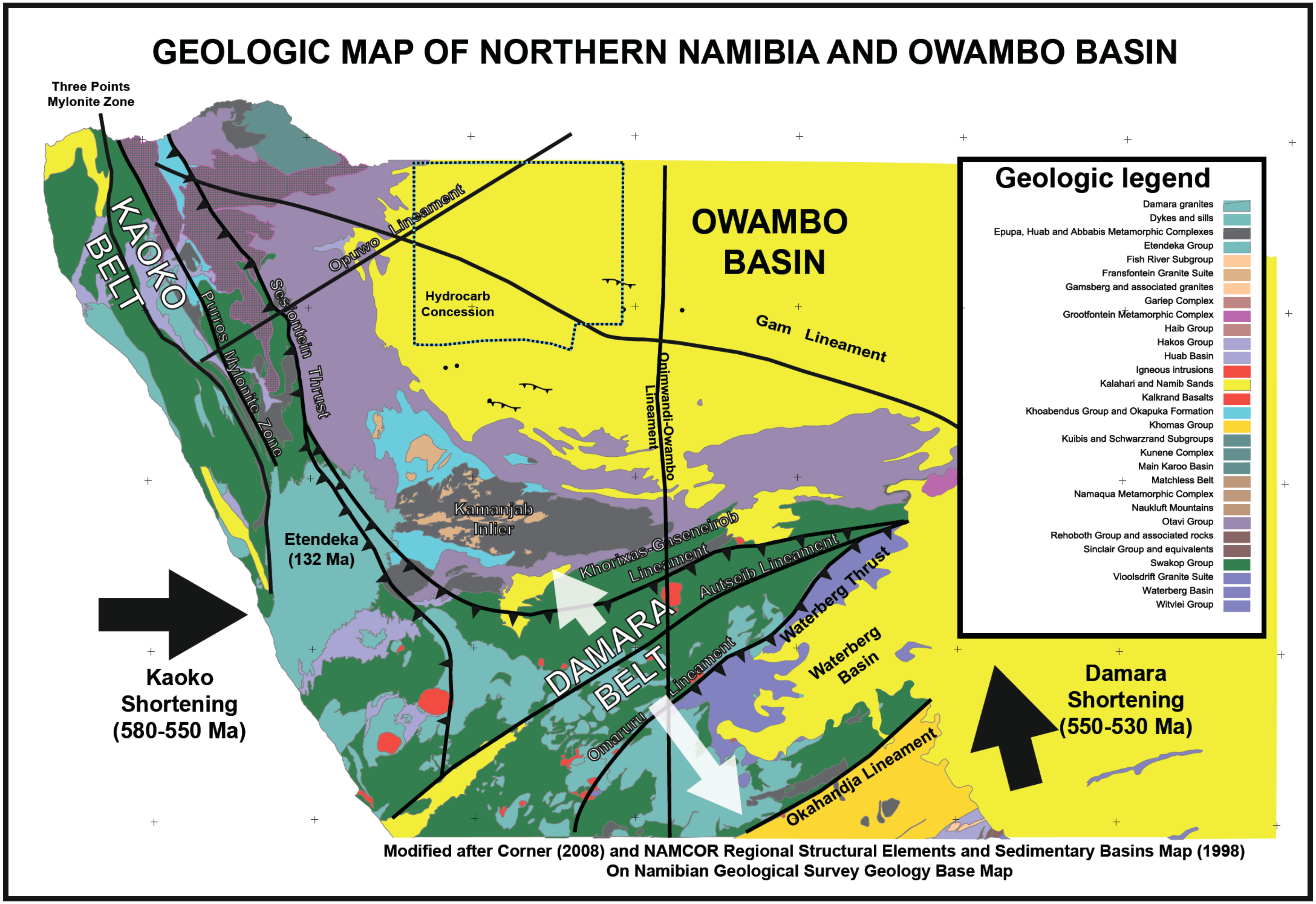


Figure 1. Onshore and offshore petroleum basins of Namibia.



Modified after Corner (2008) and NAMCOR Regional Structural Elements and Sedimentary Basins Map (1998)
On Namibian Geological Survey Geology Base Map

Figure 2. Geologic map of northern Namibia and Owambo Basin.

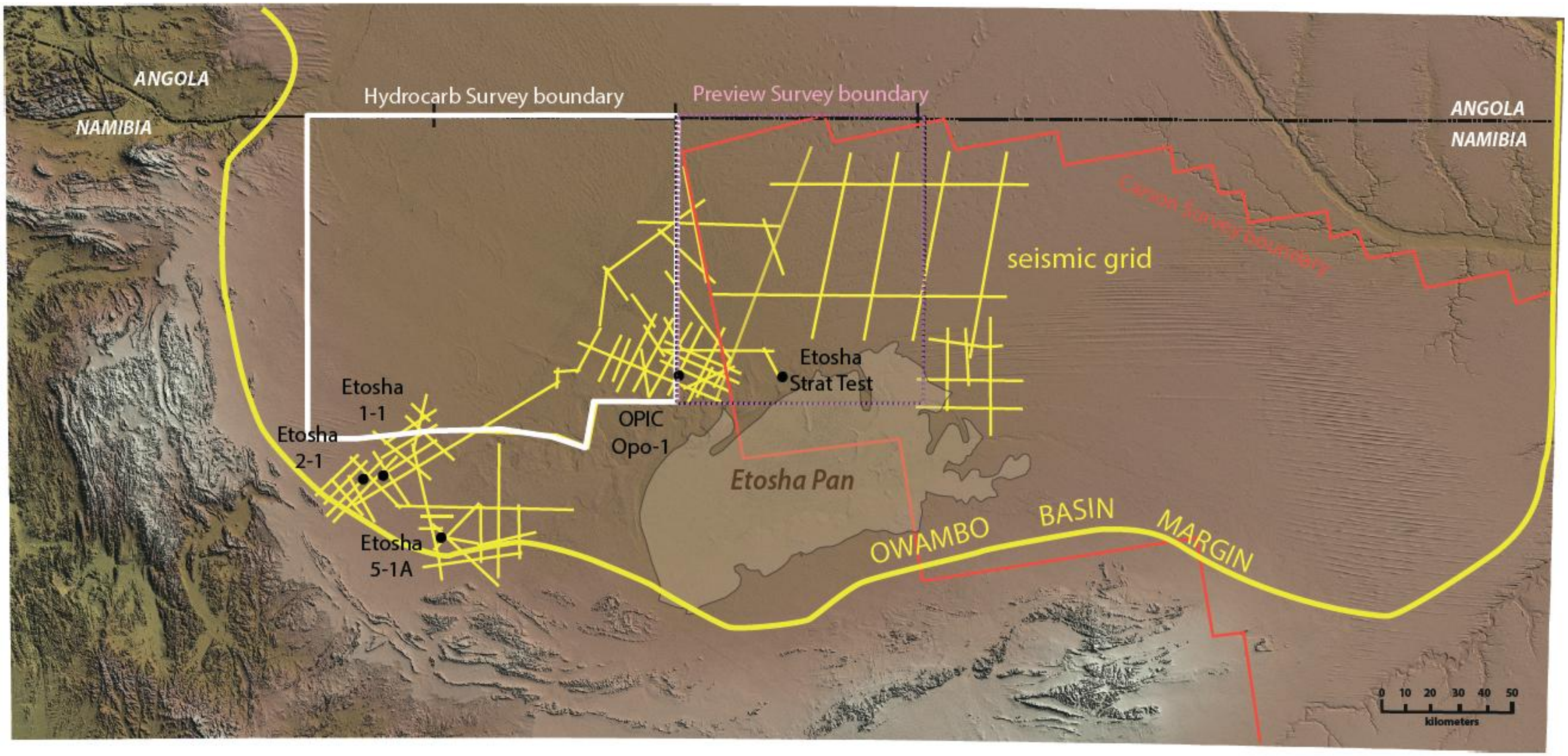


Figure 3. Digital elevation model of Owambo Basin with magnetic/gravity survey boundaries, seismic grid, and well locations.

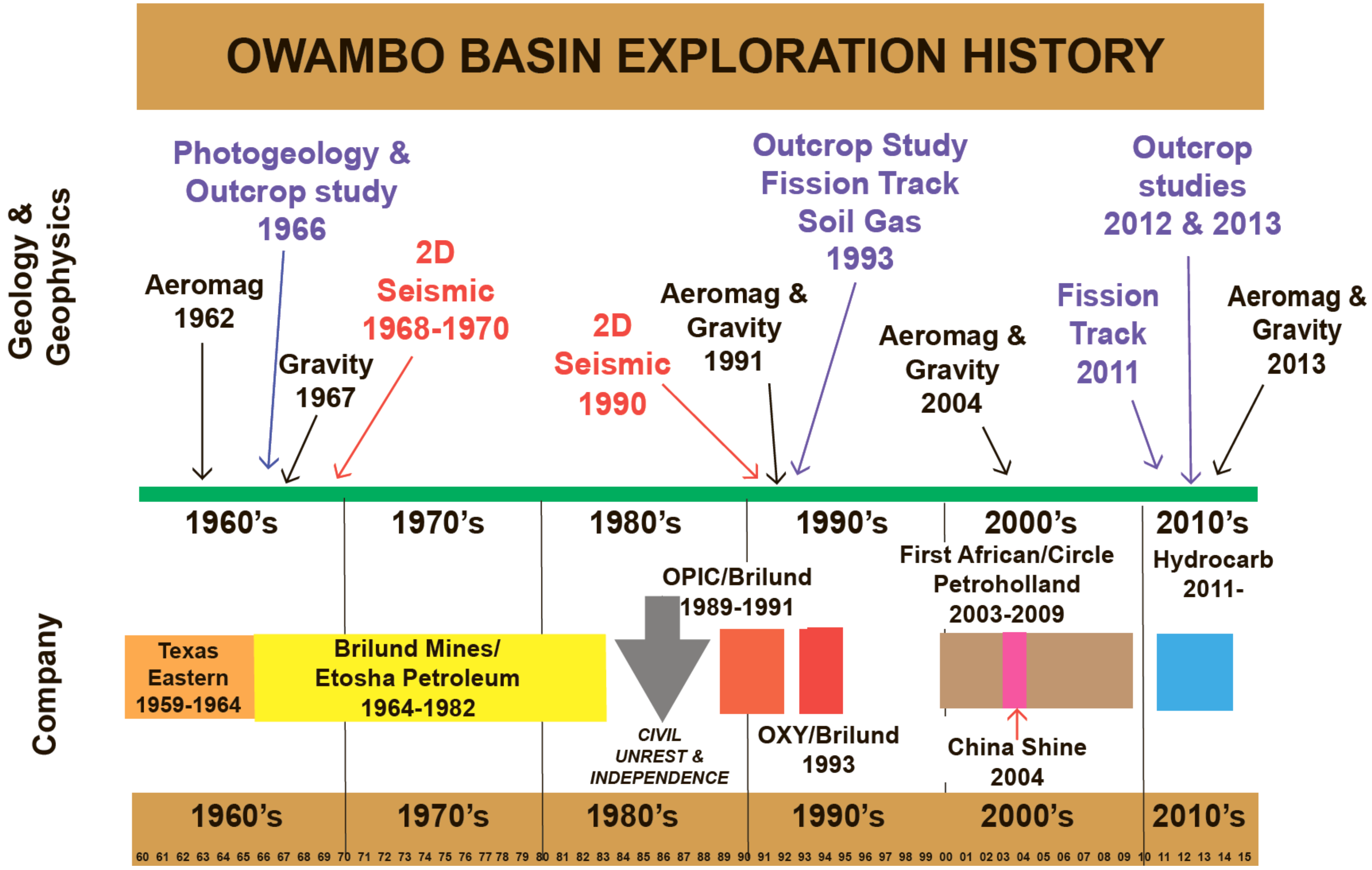
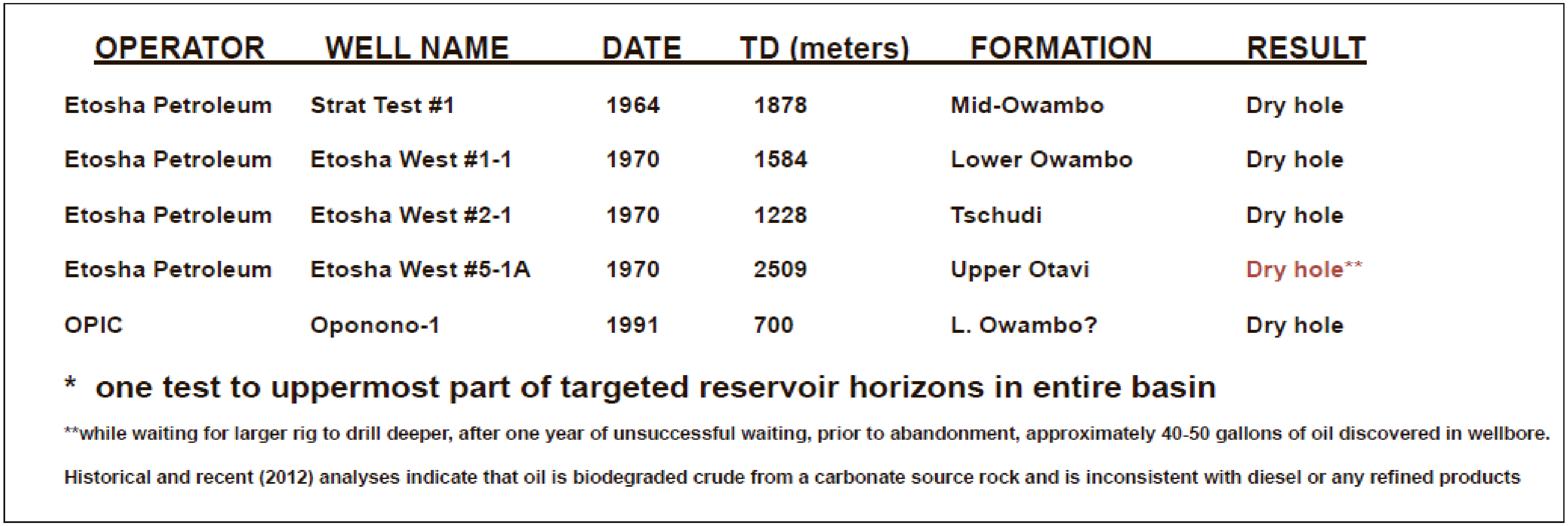


Figure 4. Exploration history of Owambo Basin.



OPERATOR	WELL NAME	DATE	TD (meters)	FORMATION	RESULT
Etosha Petroleum	Strat Test #1	1964	1878	Mid-Owambo	Dry hole
Etosha Petroleum	Etosha West #1-1	1970	1584	Lower Owambo	Dry hole
Etosha Petroleum	Etosha West #2-1	1970	1228	Tschudi	Dry hole
Etosha Petroleum	Etosha West #5-1A	1970	2509	Upper Otavi	Dry hole**
OPIC	Oponono-1	1991	700	L. Owambo?	Dry hole

* one test to uppermost part of targeted reservoir horizons in entire basin

**while waiting for larger rig to drill deeper, after one year of unsuccessful waiting, prior to abandonment, approximately 40-50 gallons of oil discovered in wellbore.

Historical and recent (2012) analyses indicate that oil is biodegraded crude from a carbonate source rock and is inconsistent with diesel or any refined products

Figure 5. Table of 5 exploration wells drilled in Owambo Basin.

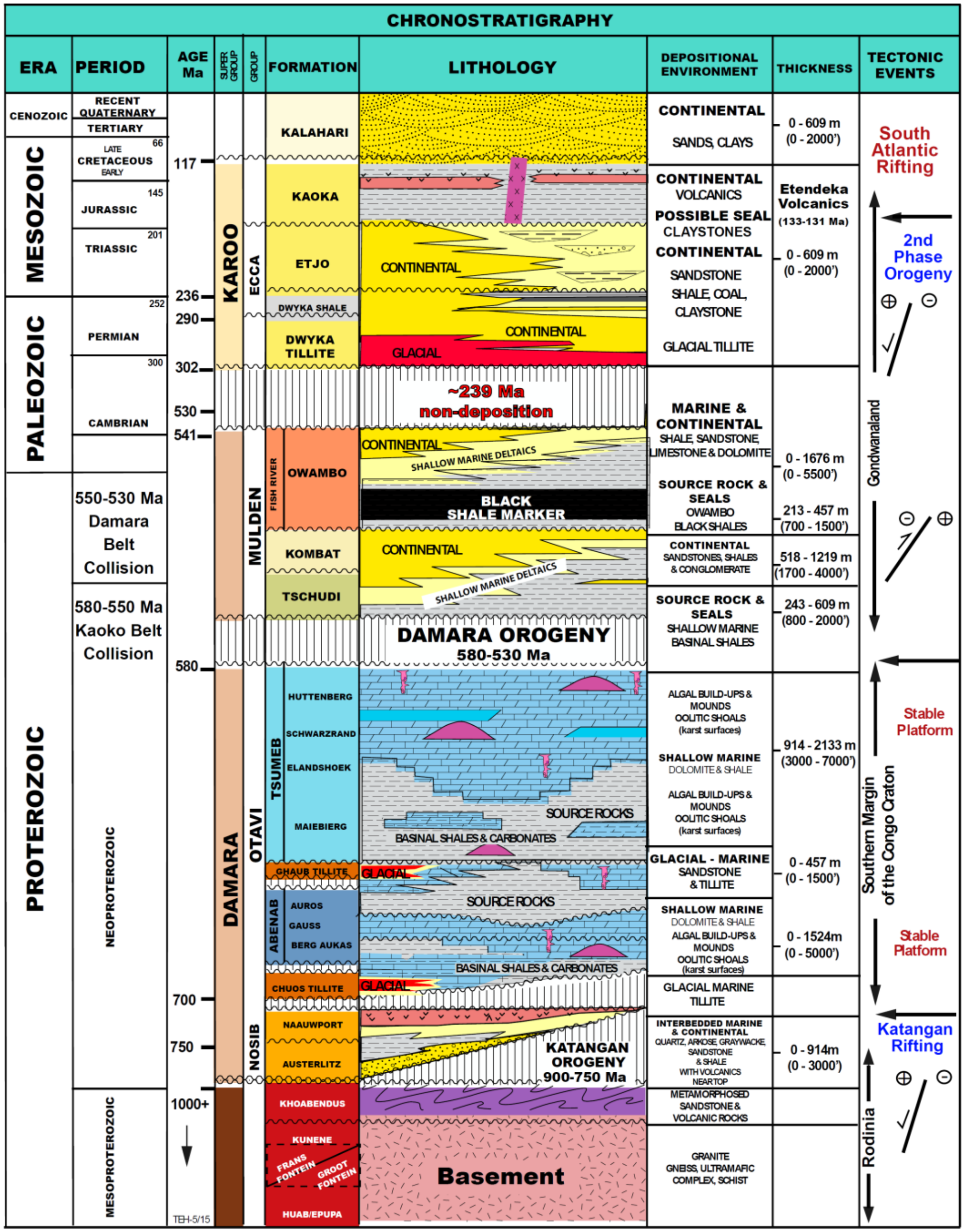


Figure 6. Generalized stratigraphic chart of Owambo Basin.

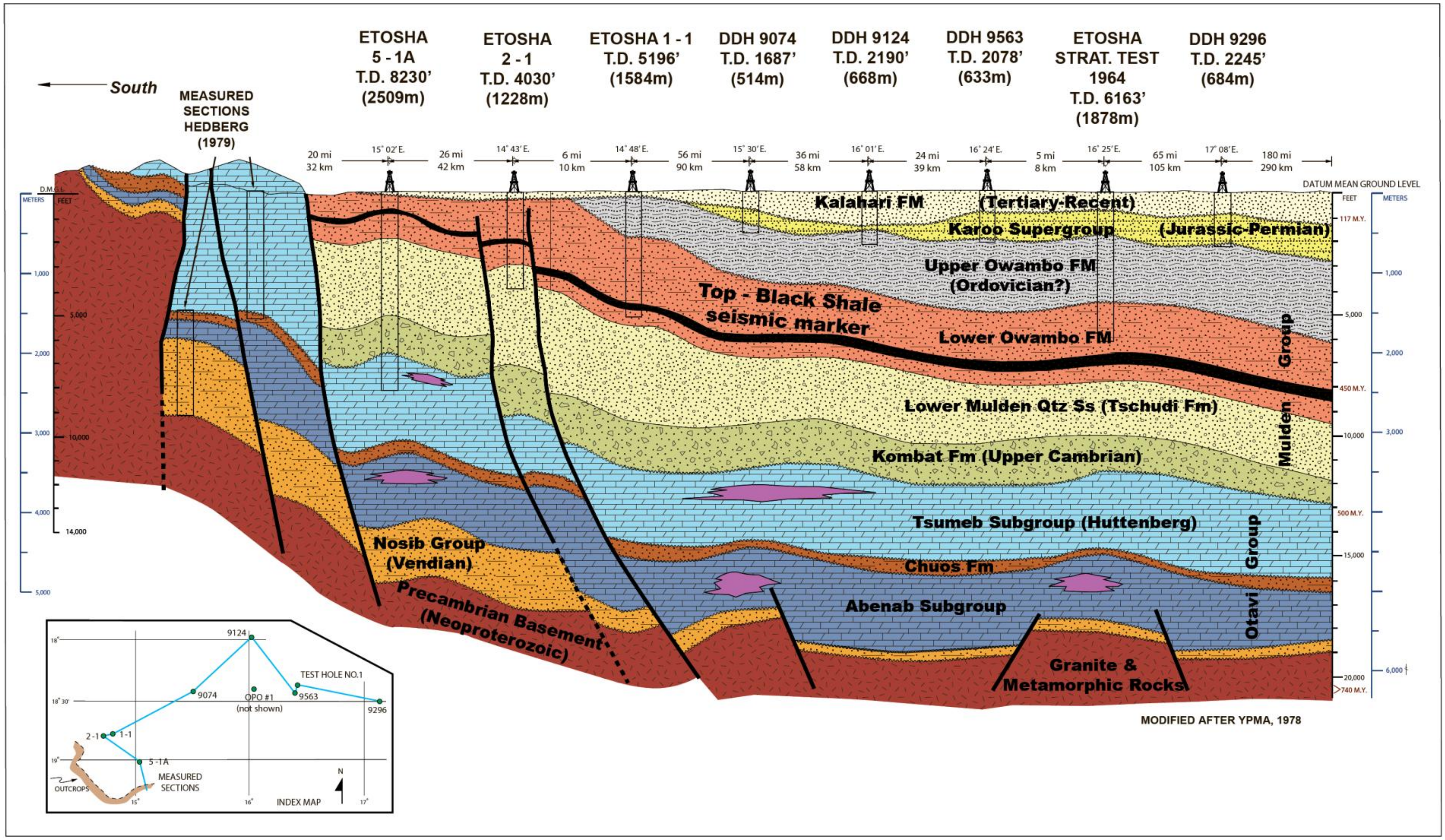


Figure 7. Schematic structural cross section of Owambo Basin.

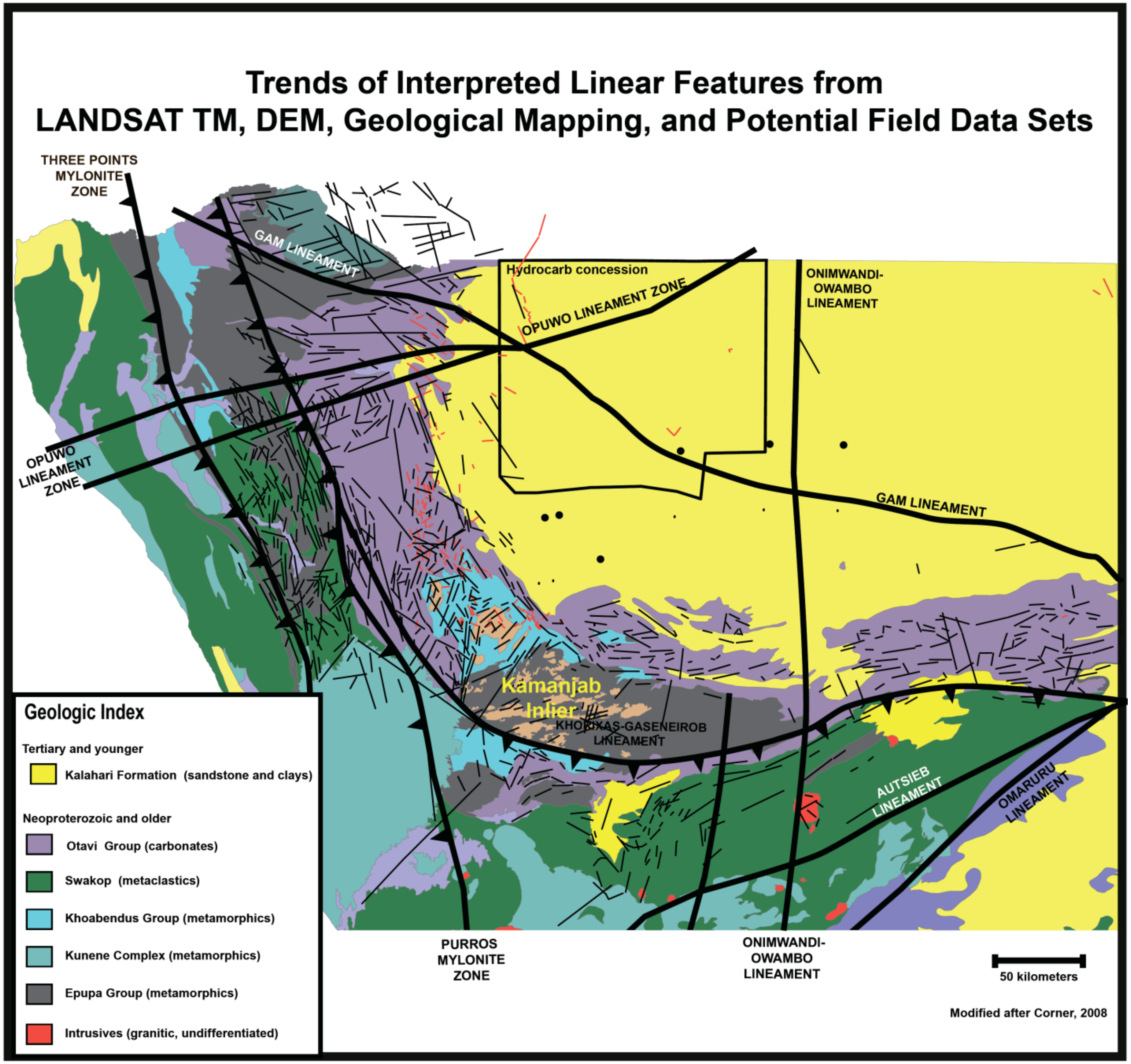
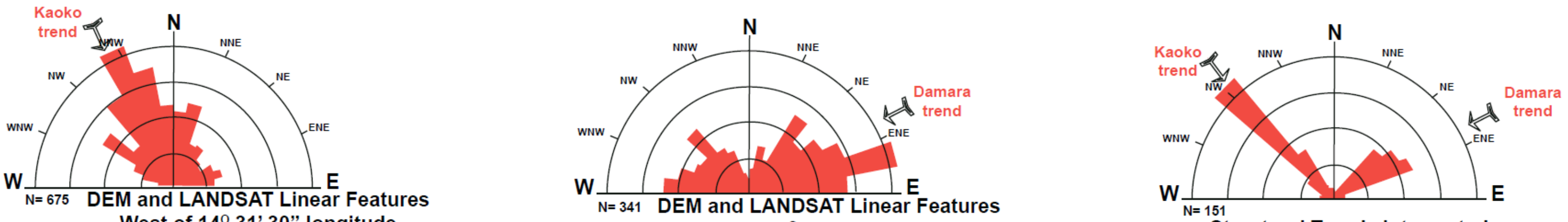


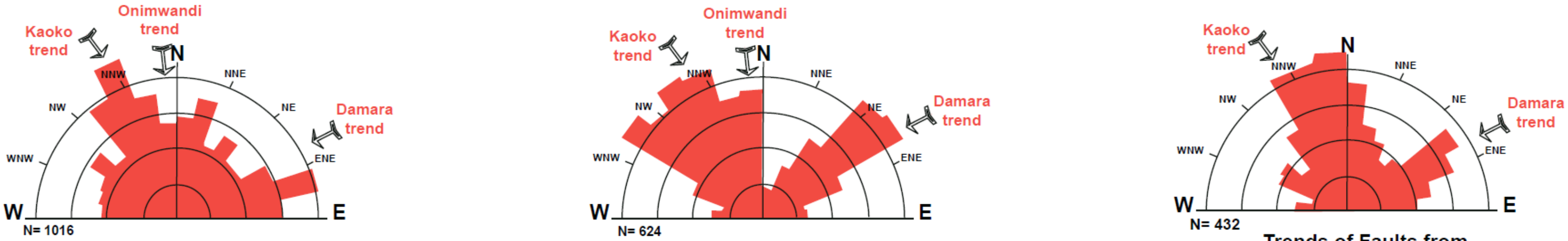
Figure 8. Trends of interpreted linear features from LANDSAT TM, DEM, geologic mapping, and potential field data sets.



DEM and LANDSAT Linear Features
West of 14° 31' 30" longitude
West of 450 000 meters UTM

DEM and LANDSAT Linear Features
East of 14° 31' 30" longitude
East of 450 000 meters UTM

Structural Trends interpreted
from Regional Gravity Data



All DEM and LANDSAT Linear Features
in and adjacent to Owambo Basin

Trends of Owambo Basin structures
interpreted from Magnetic Data

Trends of Faults from
Namibian Geological Survey Data

Figure 9. Rose diagrams of interpreted linear features from LANDSAT, DEM and geologic mapping.

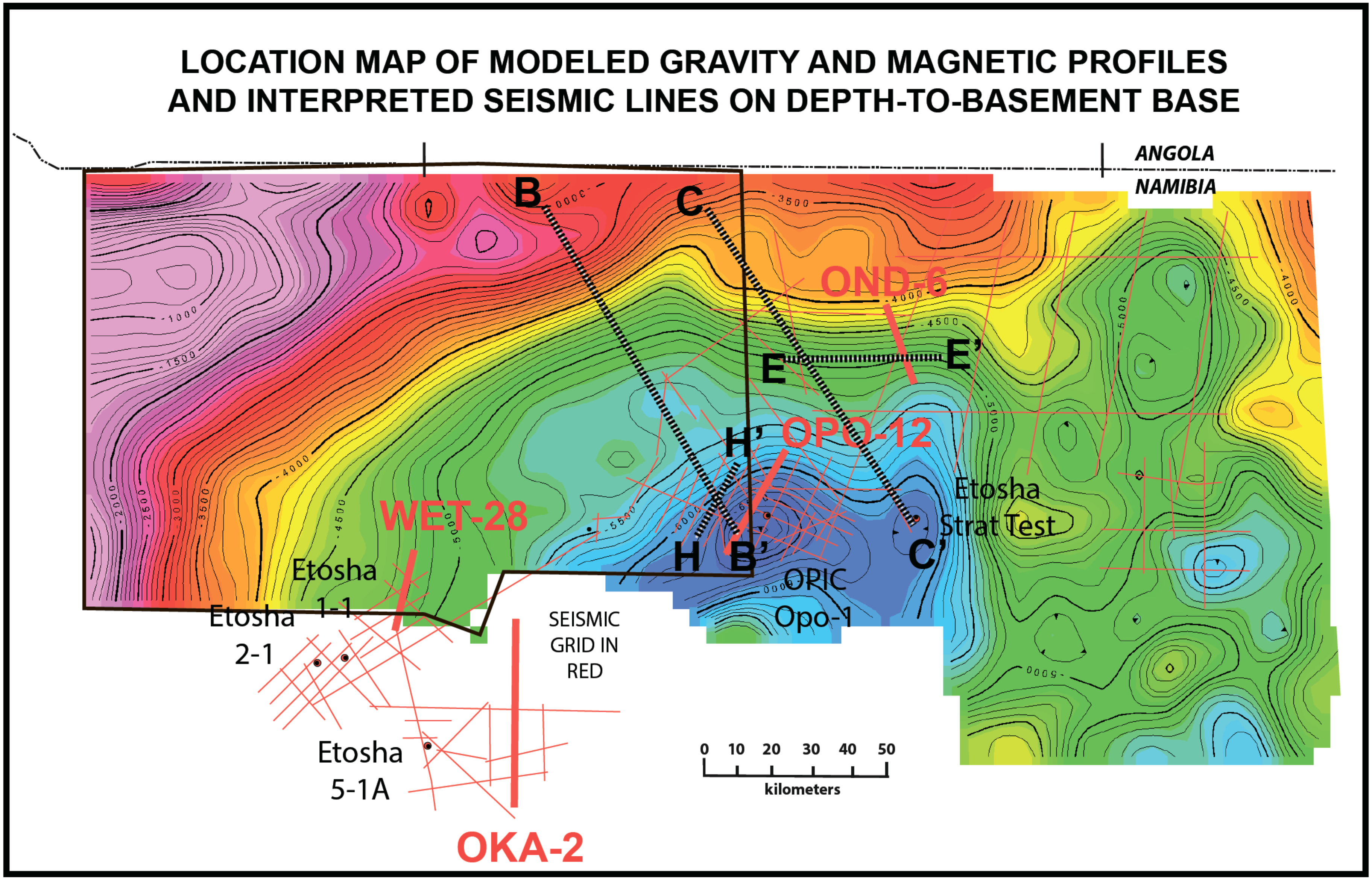


Figure 10. Location map of modeled gravity and magnetic profiles and interpreted seismic lines on depth-to-basement base.

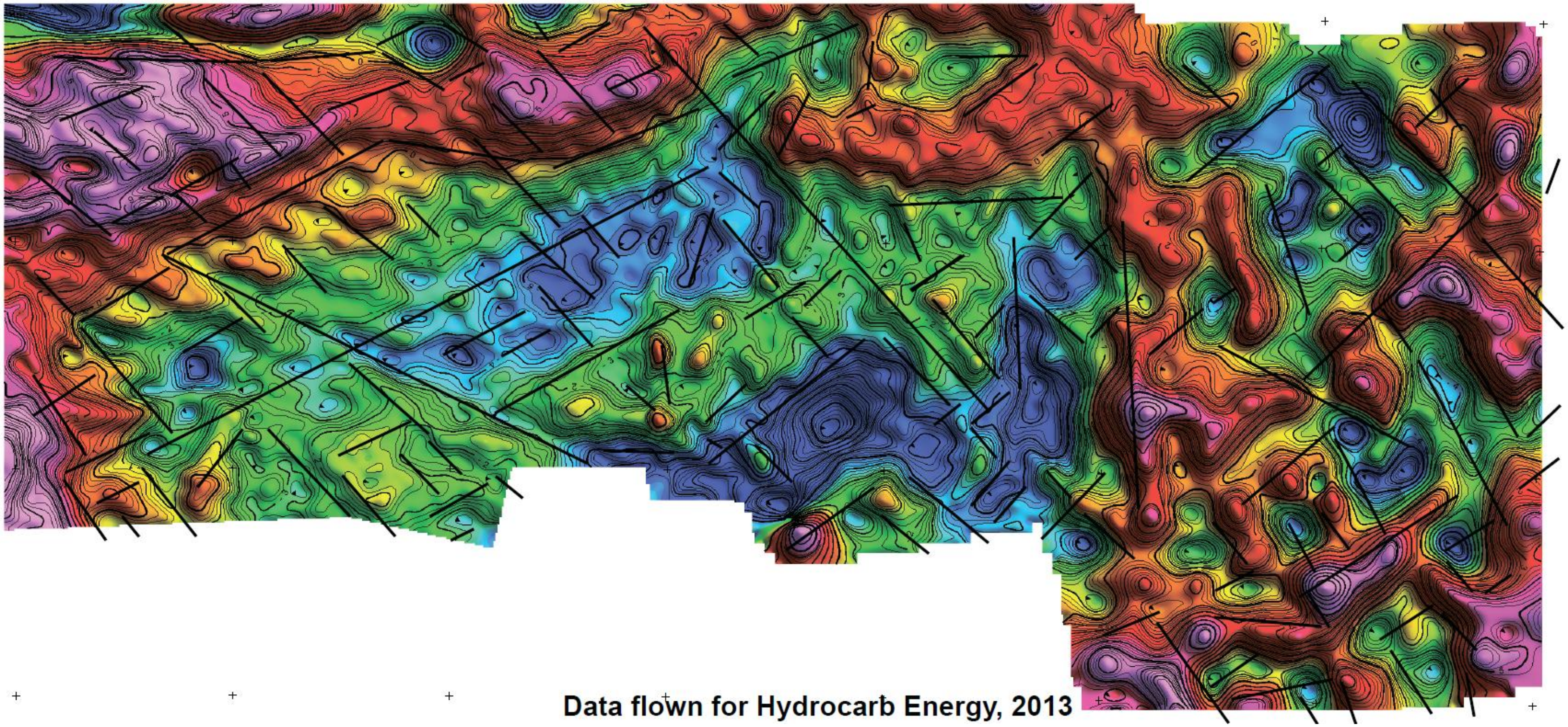


Figure 11. Free air gravity residuals, northeast hill-shaded and interpreted linear features.

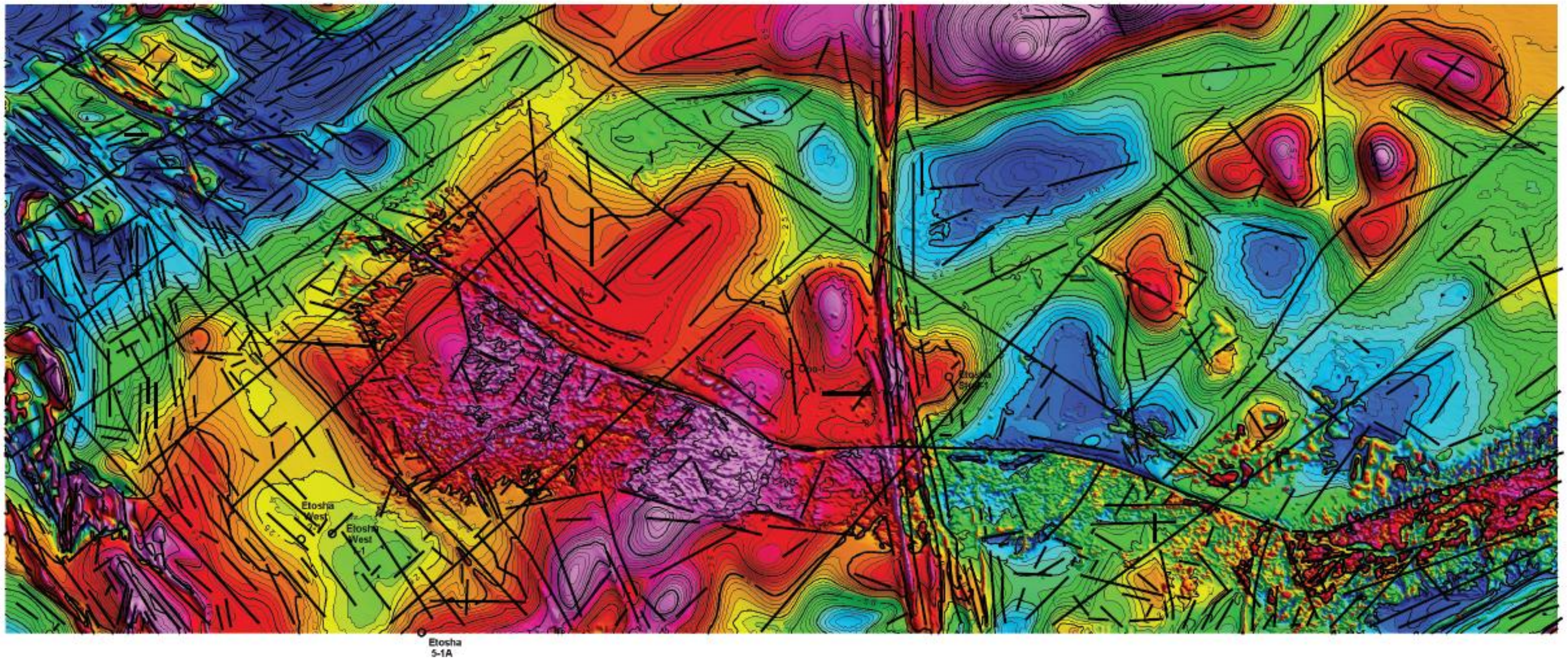


Figure 12. Total intensity, IGRF-removed, reduced-to-pole magnetics, and interpreted linear features. From public data from Namibian Geological Survey. GSN survey 1996-2010, 200 meter north-south flight lines with 2500 meter east-west ties.

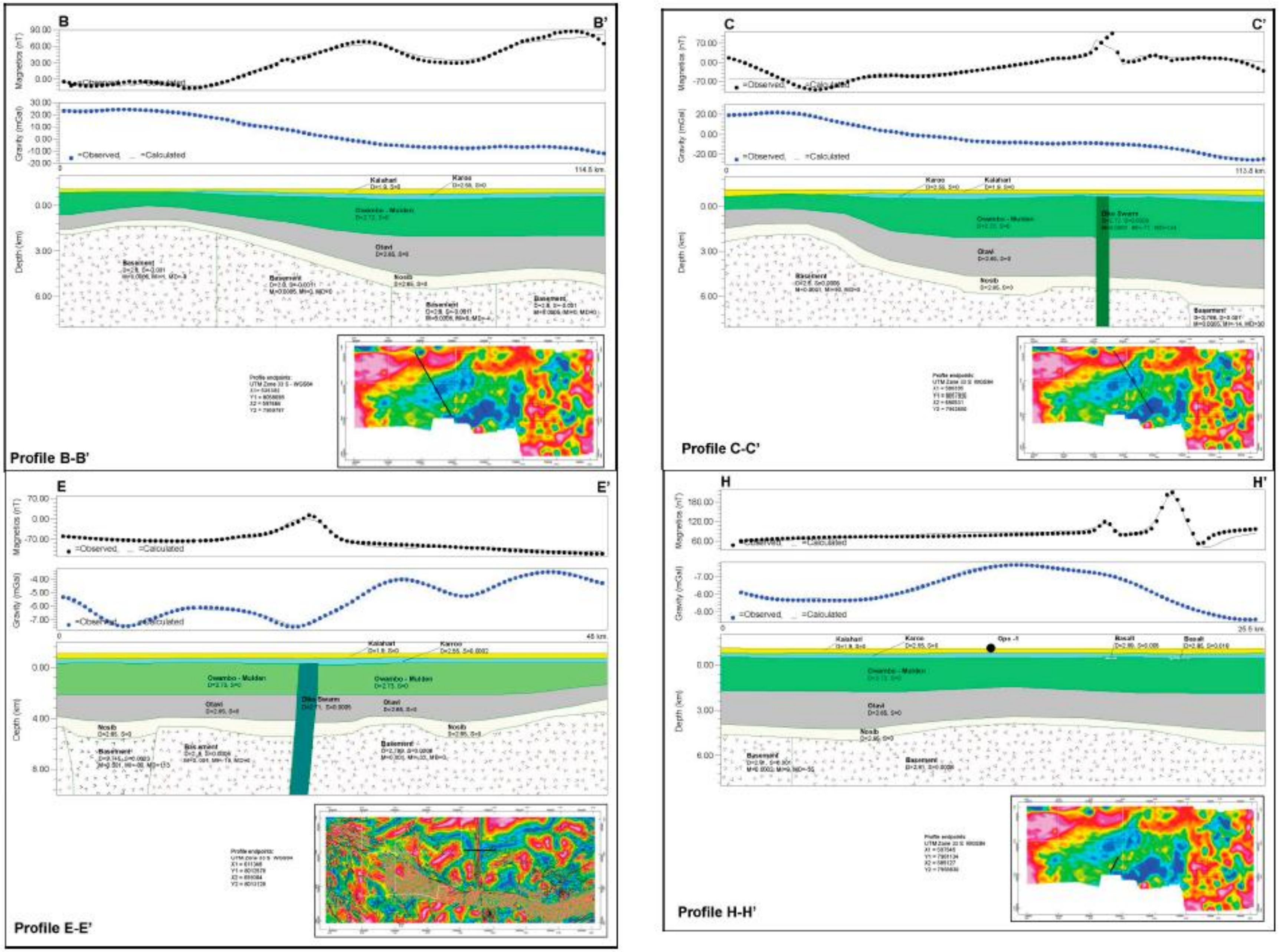


Figure 13. Modeled gravity and magnetic example seismic profiles.

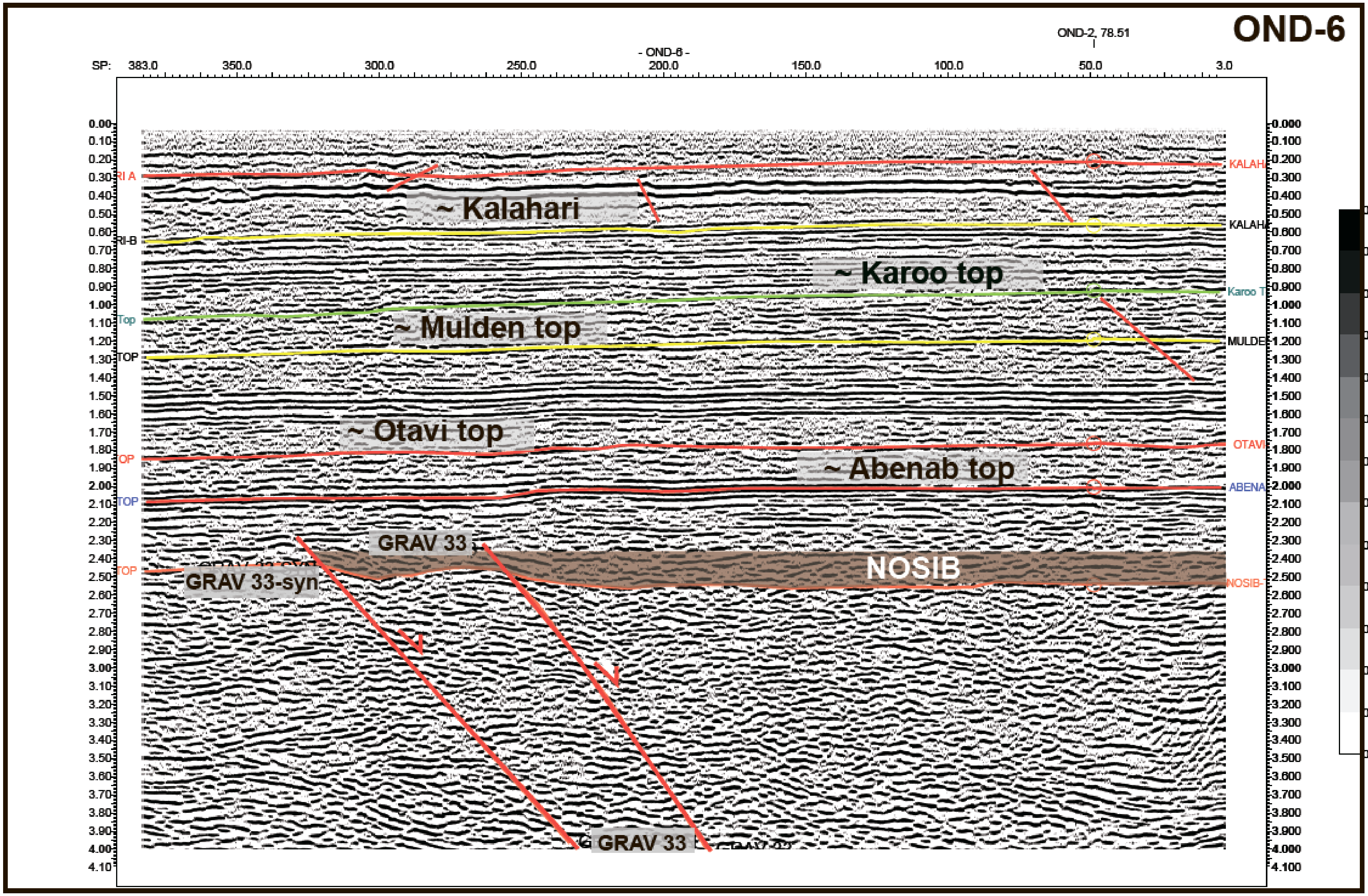


Figure 14. OND-6 interpreted seismic line from the northernmost part of the seismic grid, close to the basin center. This line has been interpreted to show Nosib Group sedimentation related to the earliest rift deformation. The Nosib is shown in that graphic as a tan wedge of sediment adjacent to a deep normal fault.

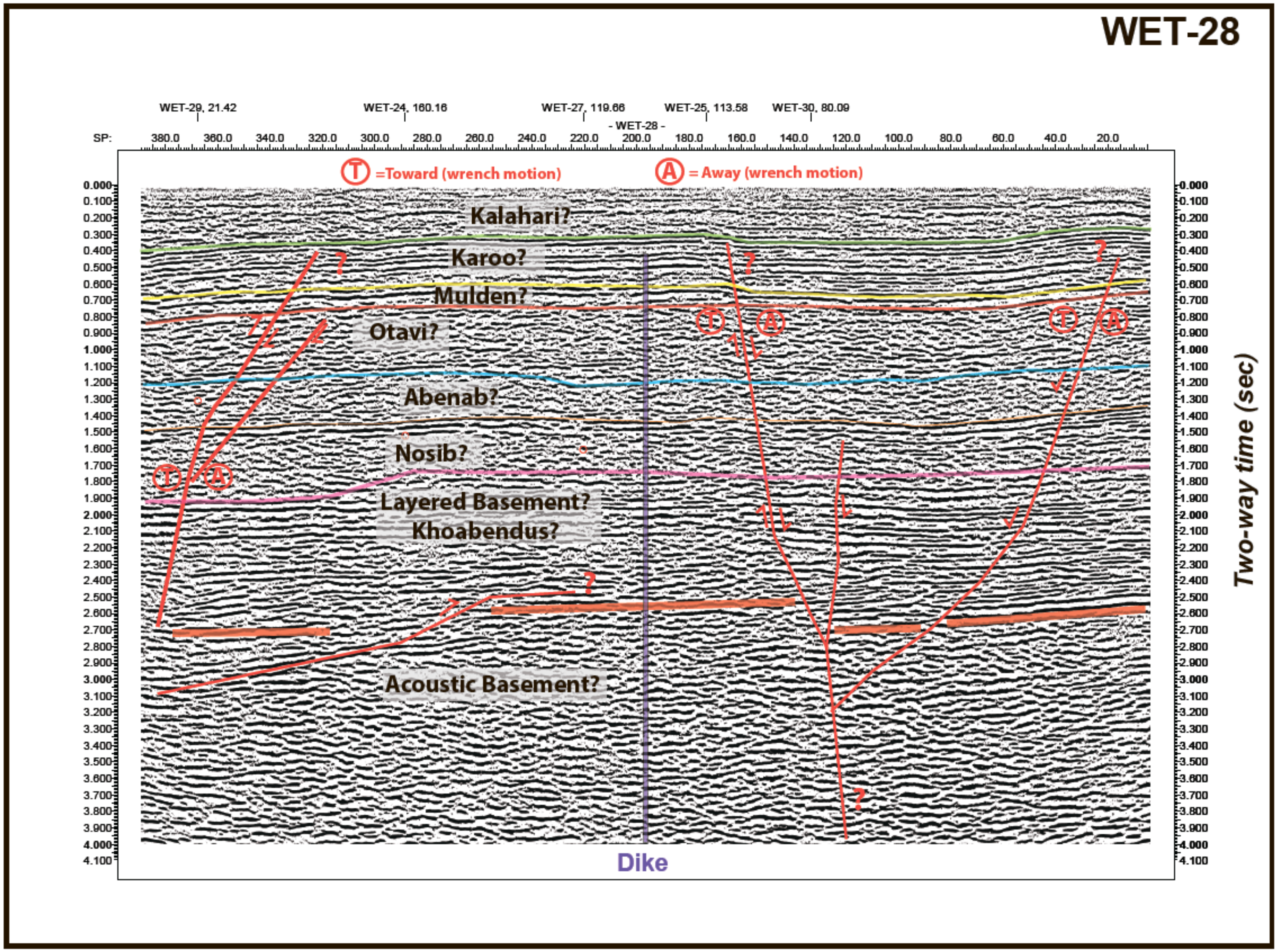
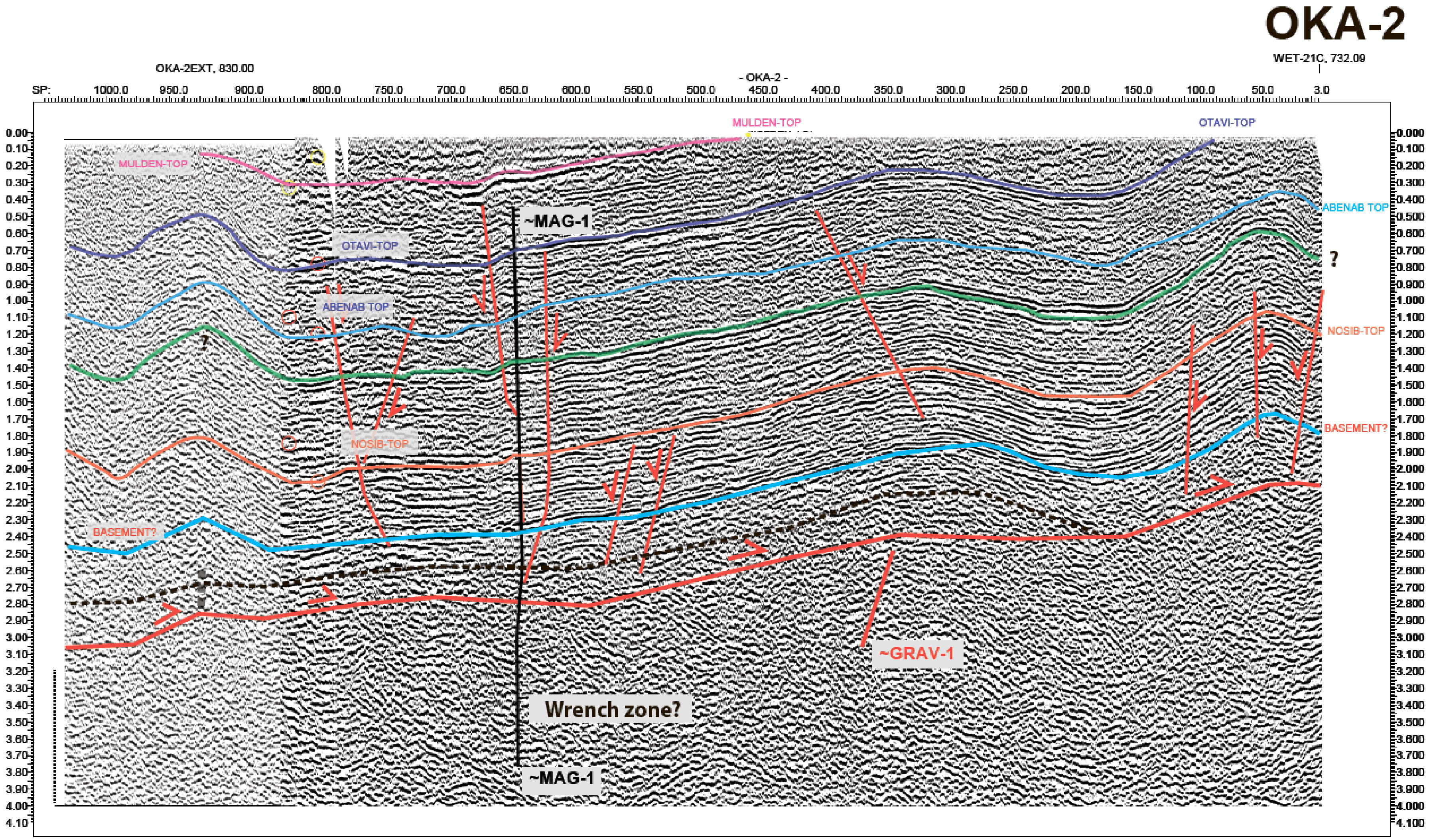


Figure 15. The WET 28 seismic line located in the southwest corner of the basin shows wrench deformation. In this area, due to the high obliquity between the pre-existing structural fabrics and the subsequent deformation phases, most of the older fabrics would be reactivated during later deformation. There appears to be an uplifted basement section in this area. There is some evidence of extensional faulting in the deeper section. A dike was interpreted on the magnetic data set and is added to the line. There is very little seismic discontinuity associated with the dike.



Section balances, mag/grav linears correspond to basal thrust ramps

Figure 16. The regional contractional deformation resulting in a fold-and-thrust geometry is shown in OKA-2 line. The OKA-2 line extends northward into the basin from just north of the southern basin margin. This line shows the characteristic asymmetric long back limb, short forelimb structural style of most fold-and-thrust belts. Again, the obliquity of deformation phases indicates that there should also be considerable wrench motion in this section.

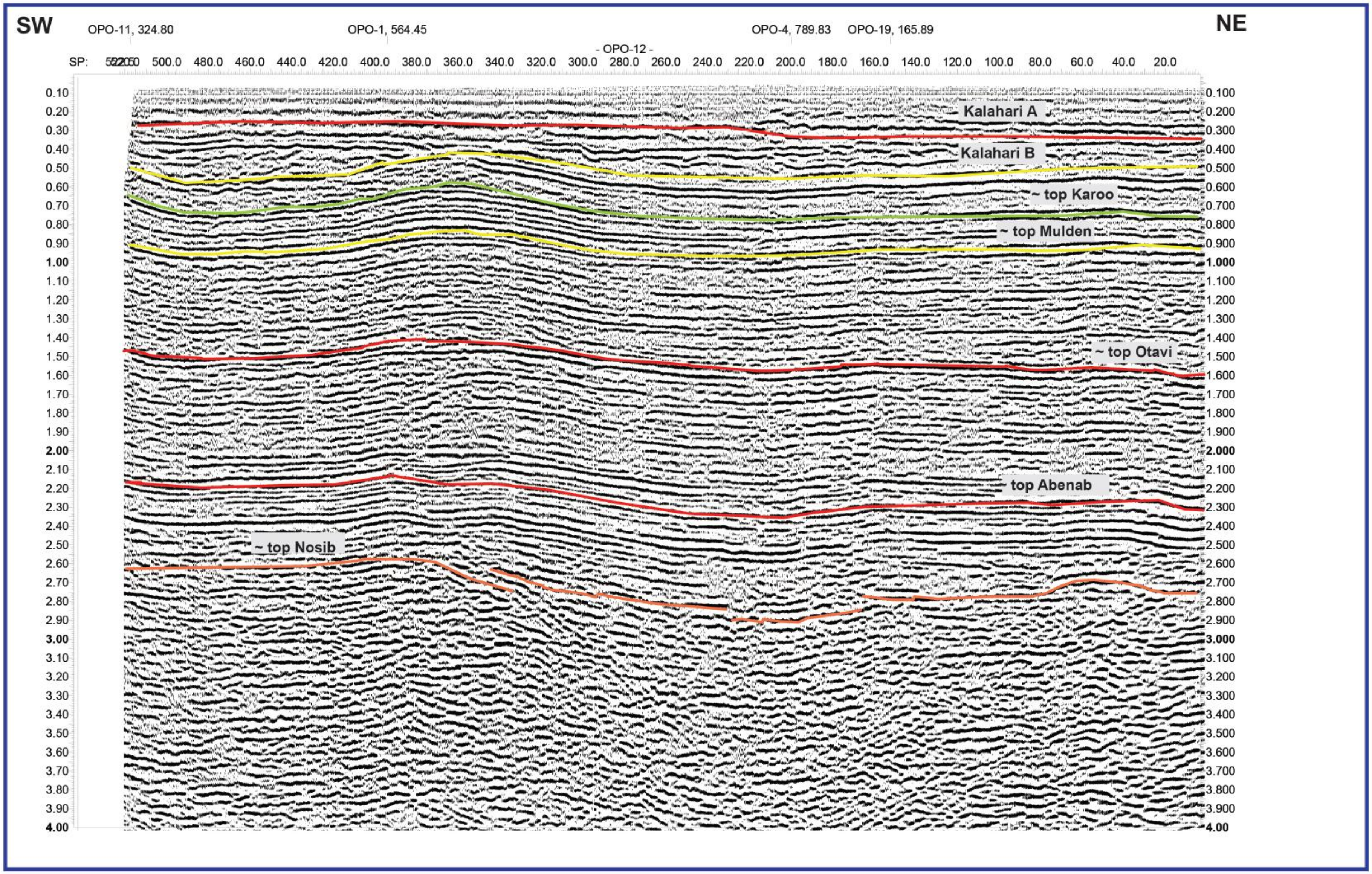


Figure 17. The final deformation phase is shown in OPO-12 line, uninterpreted and interpreted (Figure 18). These lines show the Oponono Anticline located in the southern basin center.

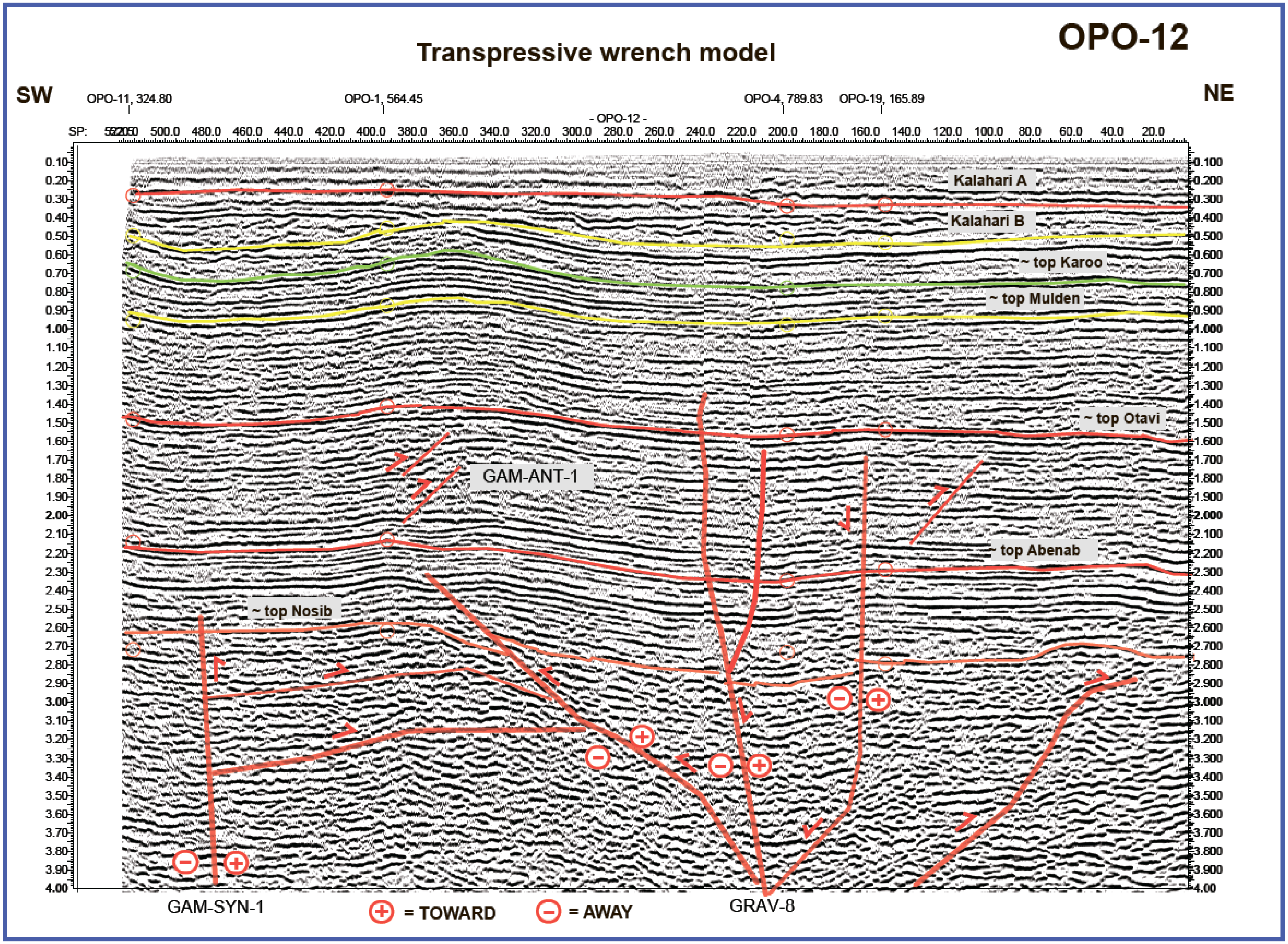
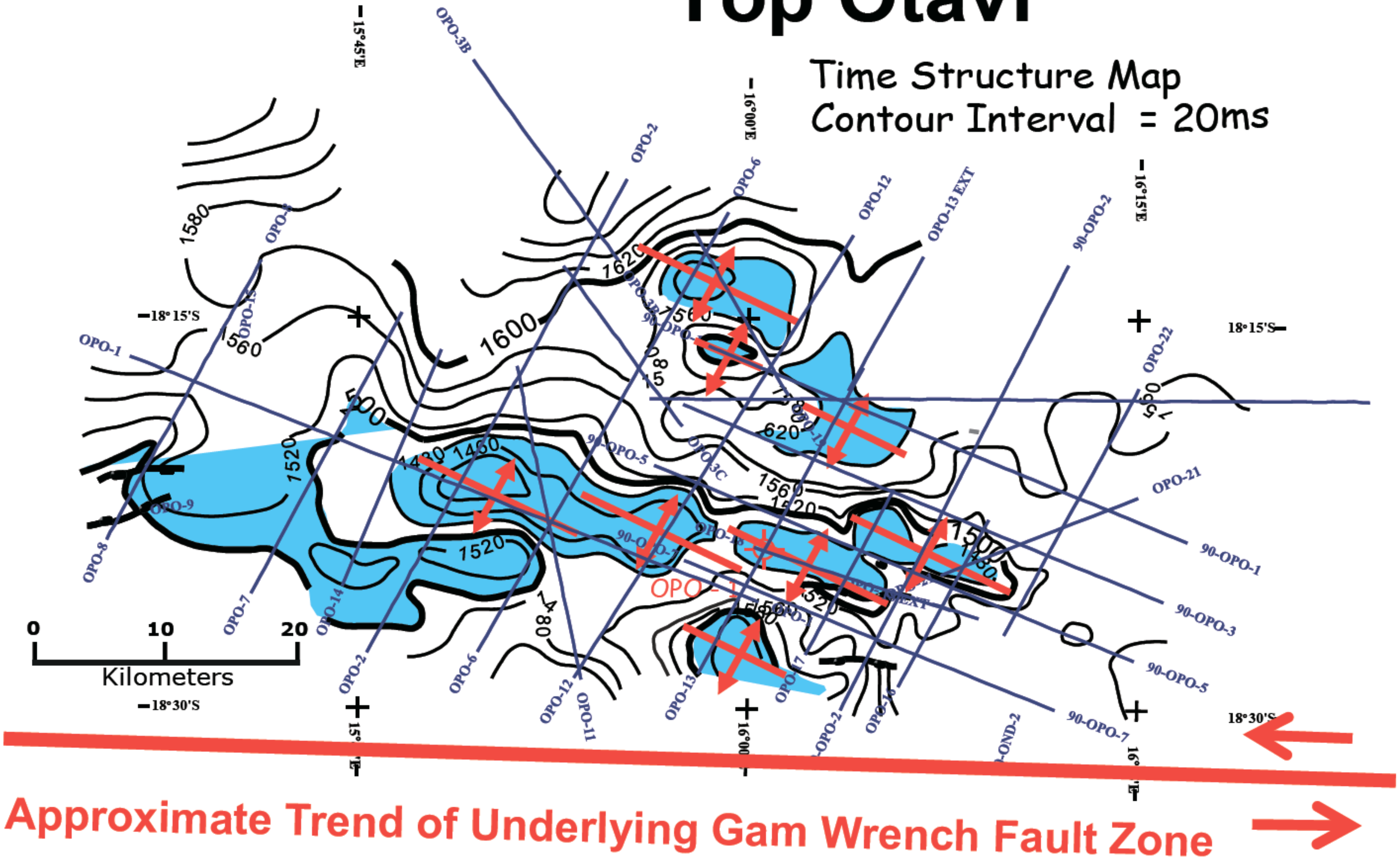


Figure 18. Interpreted seismic line OPO-12. This line shows the complex interplay between symmetric upright folding and interpreted wrench zones in the basement.

Oponono Region: En Echelon Fold Axes
Top Otavi

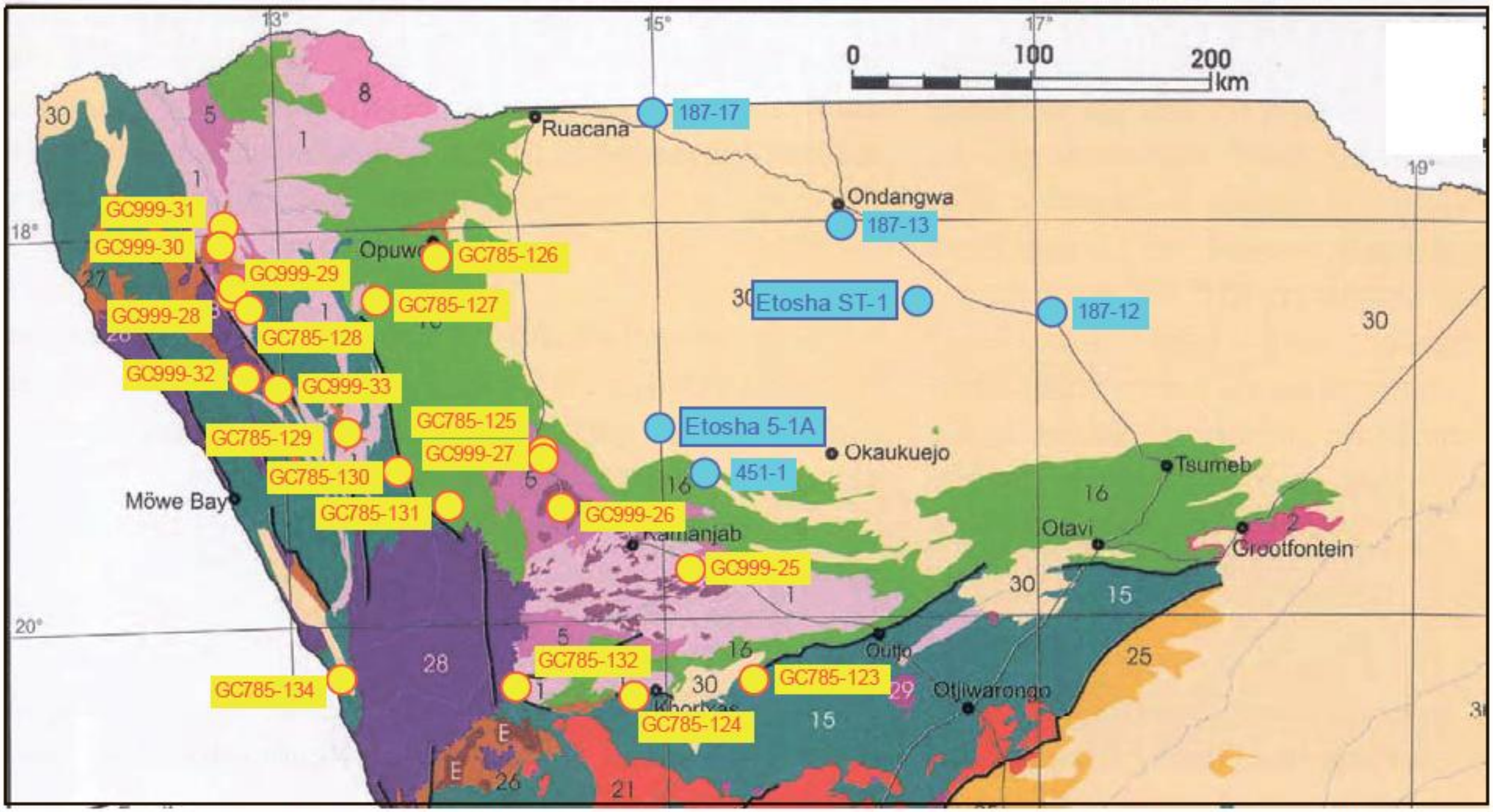


Time Structure Map

Contour Interval = 20ms

Approximate Trend of Underlying Gam Wrench Fault Zone

Figure 19. (top) Structure map showing en echelon fold axes at the top of Mulden in the Oponono region. (bottom) Structure map showing en echelon fold axes at the top of Otavio in the Oponono region.



Blue samples are from subsurface and shallow boreholes in Owambo Basin. **Data from Preview Energy Report with permission.**

Figure 20. Apatite Fission Track Analysis (AFTA) sample locations.

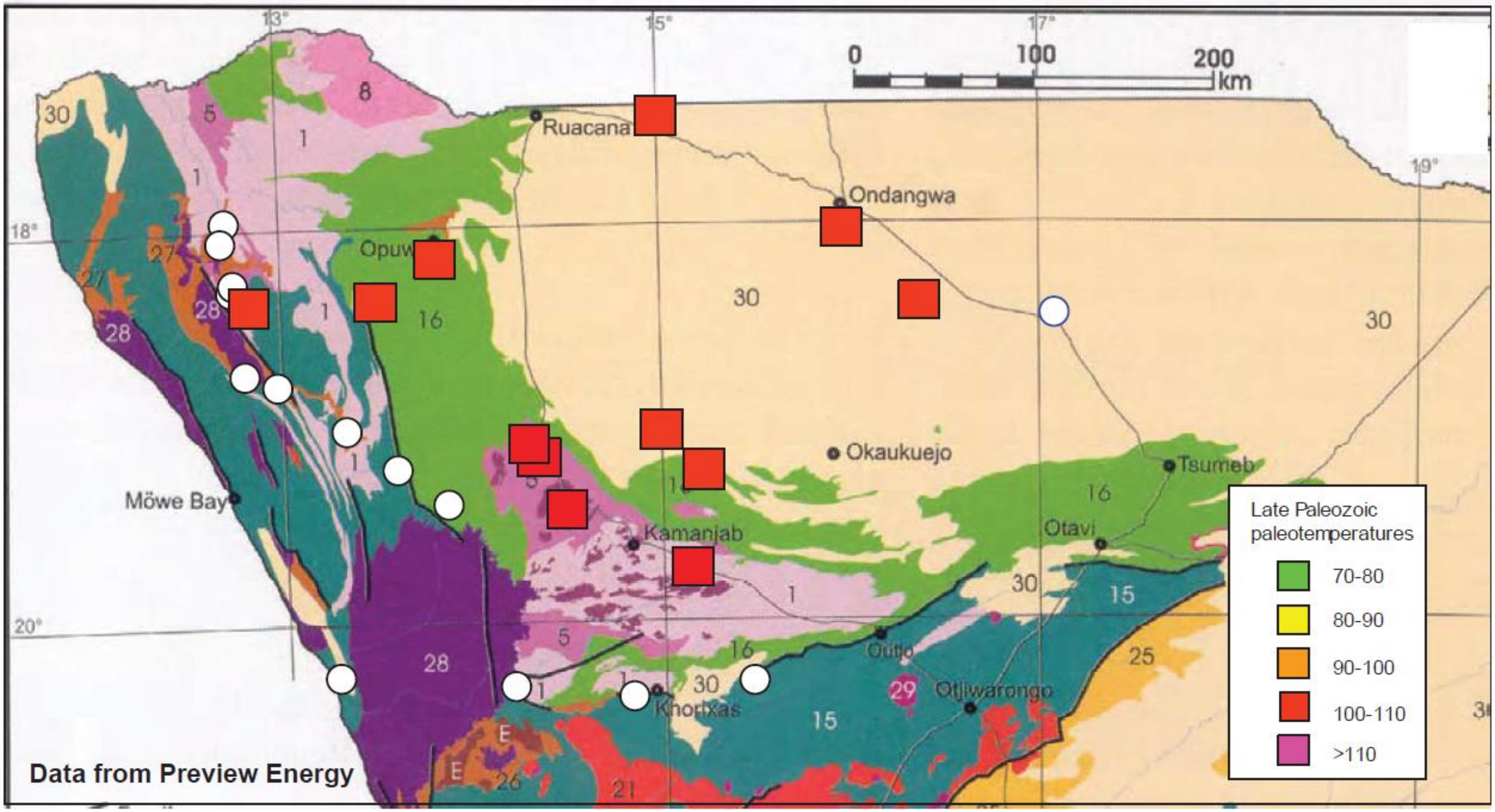


Figure 21. Carboniferous (350-300 Ms) paleotemperatures derived from AFTA data.

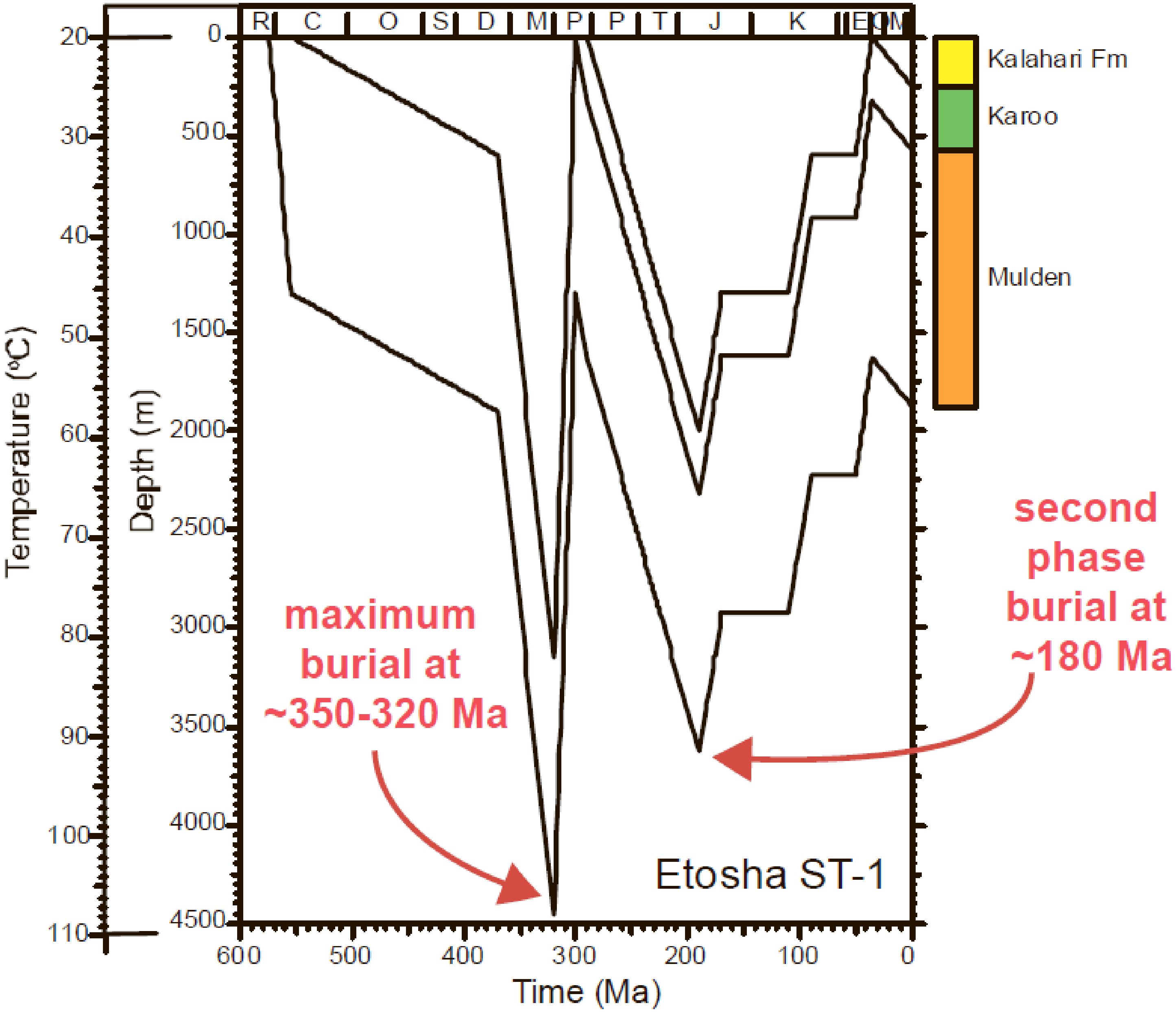


Figure 22. Burial and uplift history for Etosha Strat Test #1 well, derived from AFTA data. Assumed paleo-geothermal gradient of 18.8 degrees C based on BHT measurement. Assumed heating rate of 1 degree C/Mry and cooling rate of 10 degrees C/Myr.

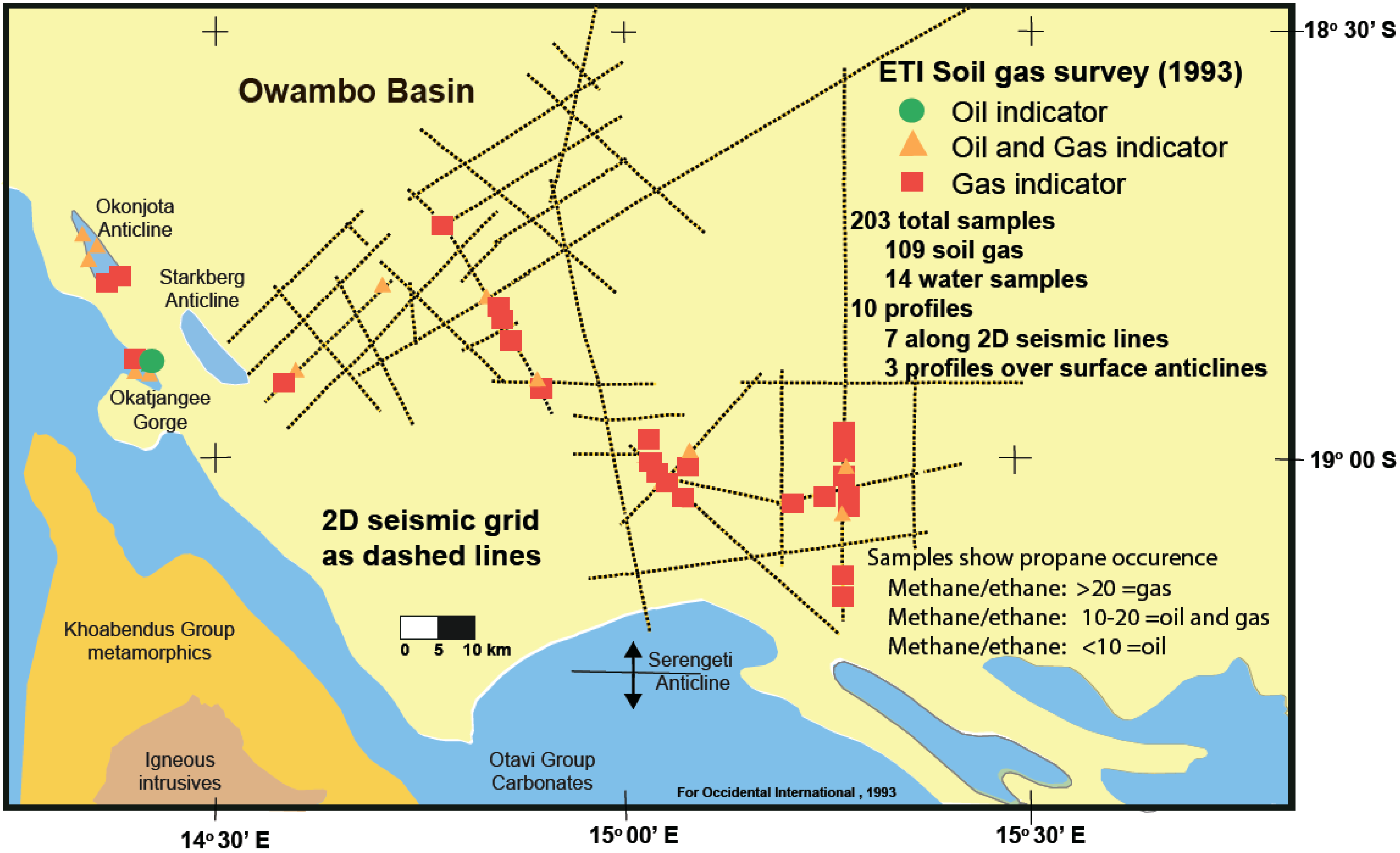


Figure 23. ETI soil gas survey map.

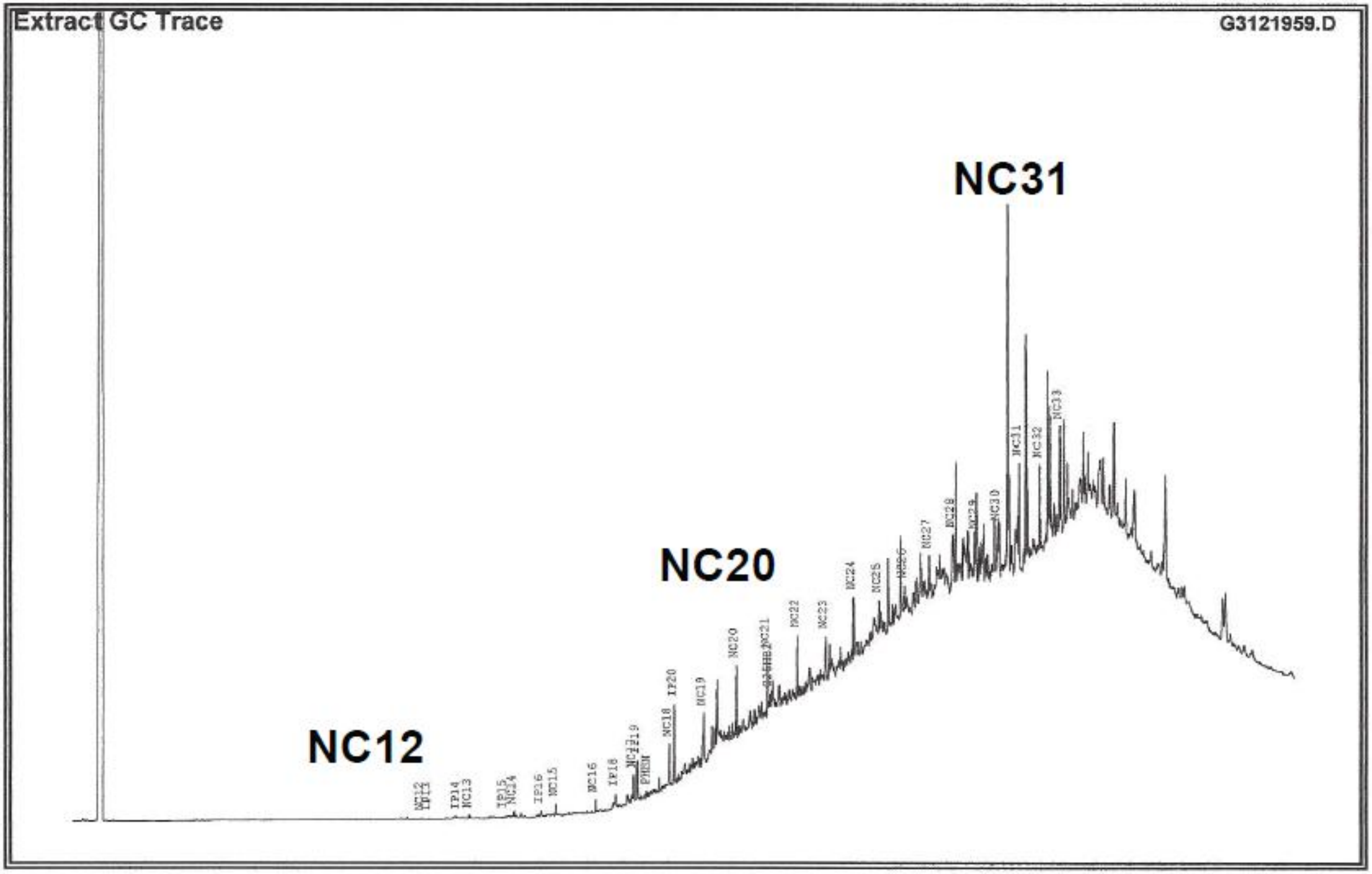


Figure 24. Soil sample gas chromatograph from Etosha 5-1A well.

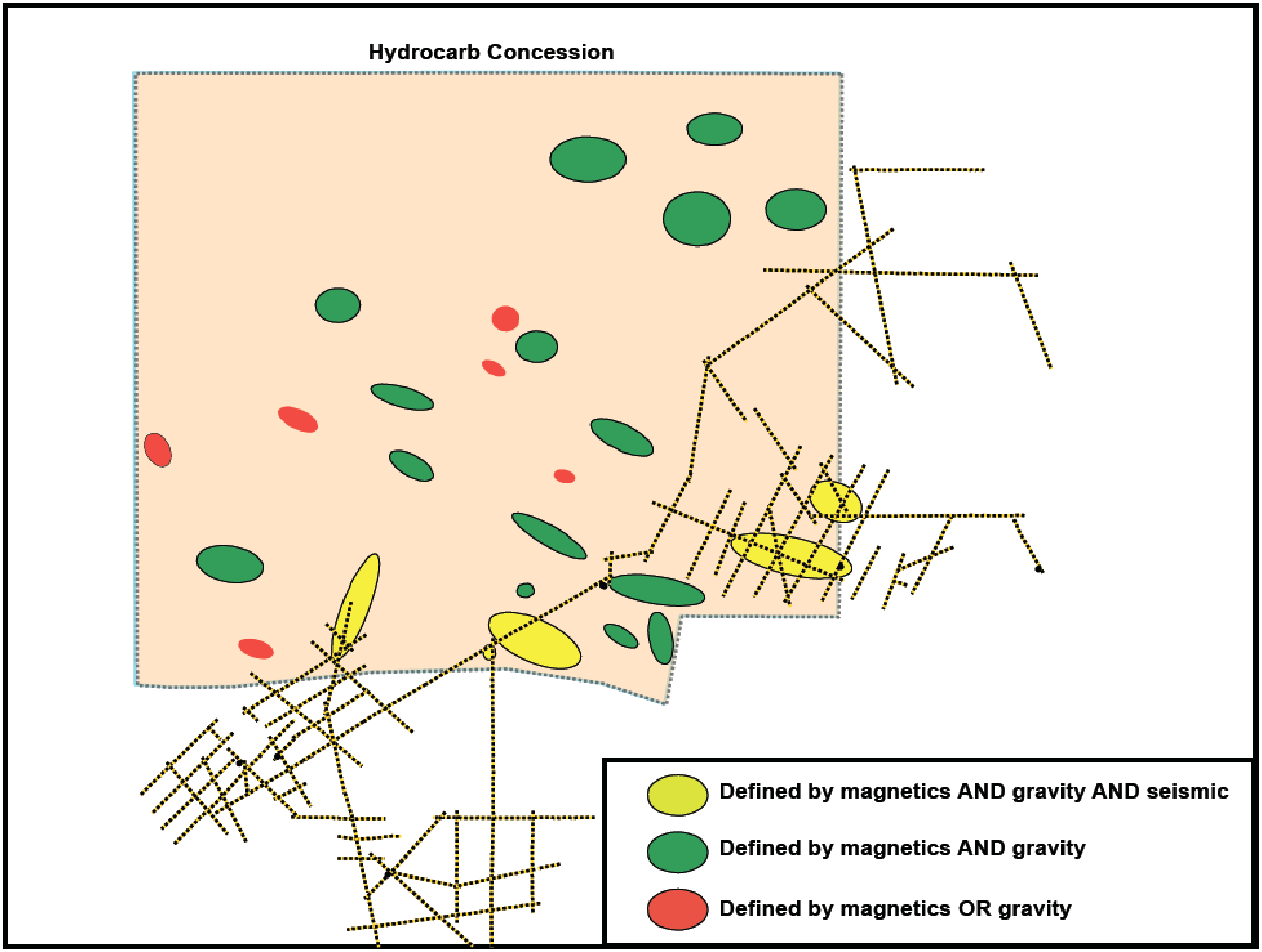
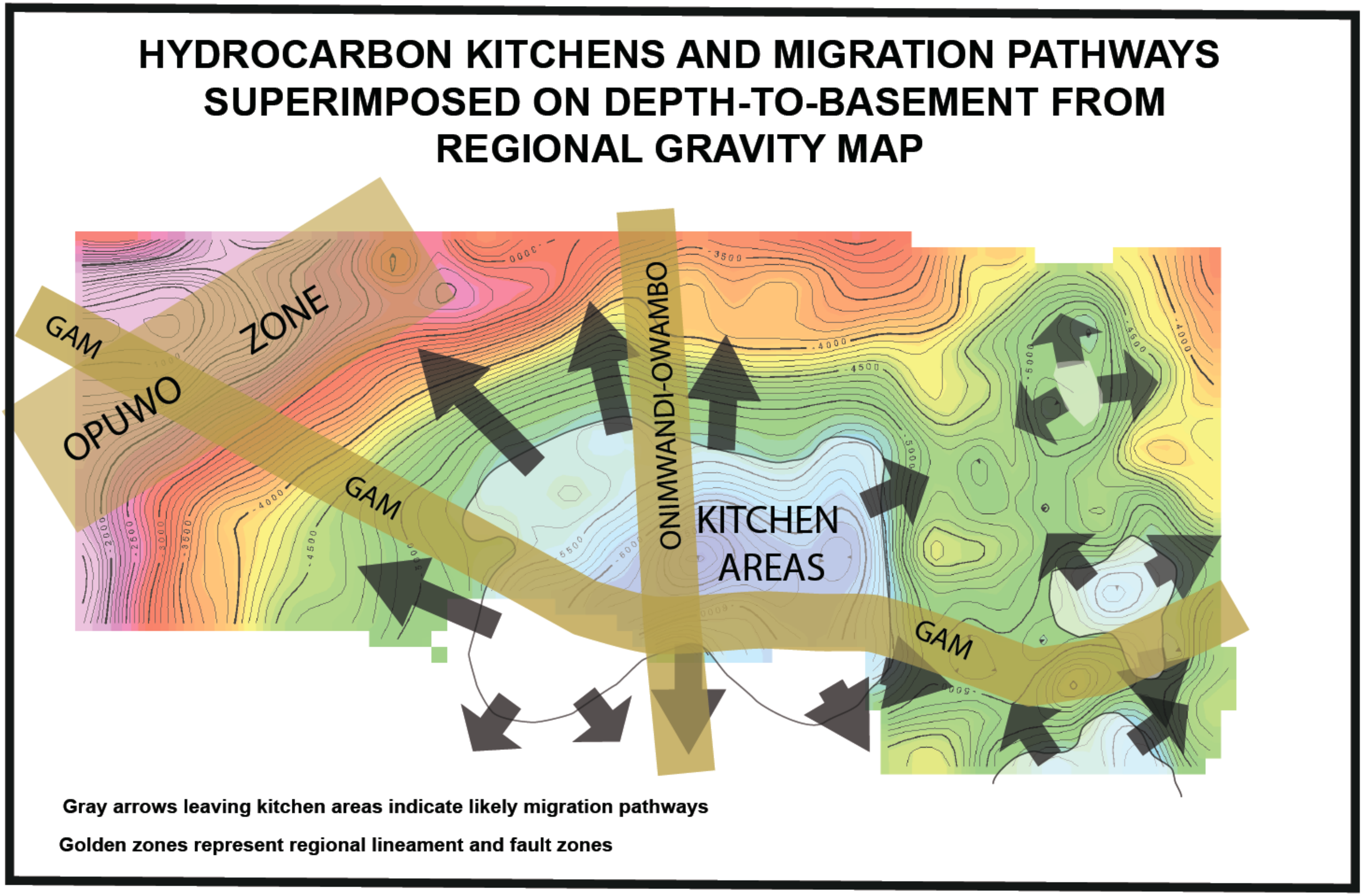


Figure 25. Prospective areas for future seismic exploration program in the Owambo Basin.

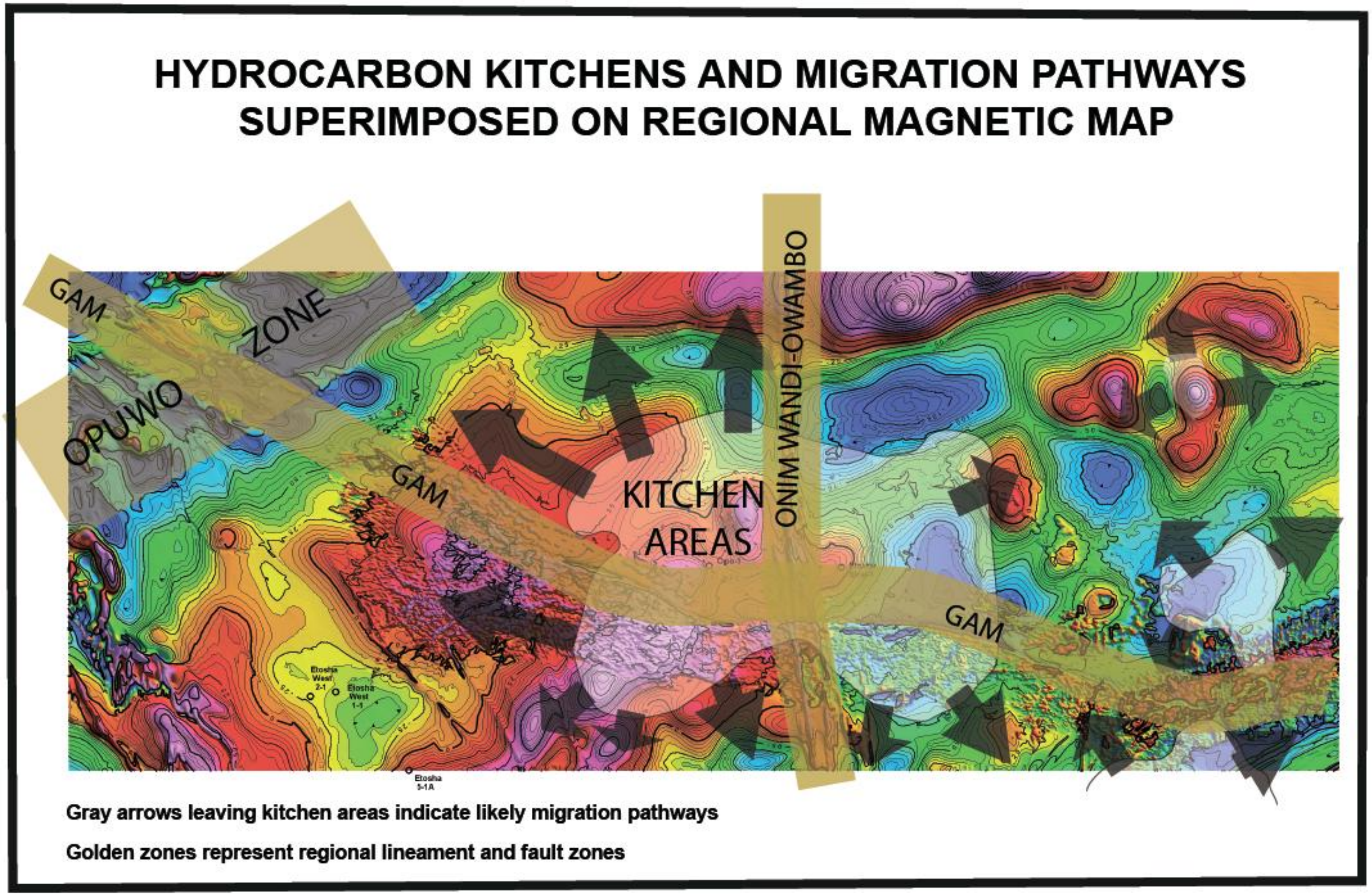


HYDROCARBON KITCHENS AND MIGRATION PATHWAYS SUPERIMPOSED ON DEPTH-TO-BASEMENT FROM REGIONAL GRAVITY MAP

Gray arrows leaving kitchen areas indicate likely migration pathways

Golden zones represent regional lineament and fault zones

Figure 26. Hydrocarbon kitchens and migration pathways superimposed on depth-to-basement from regional gravity map.

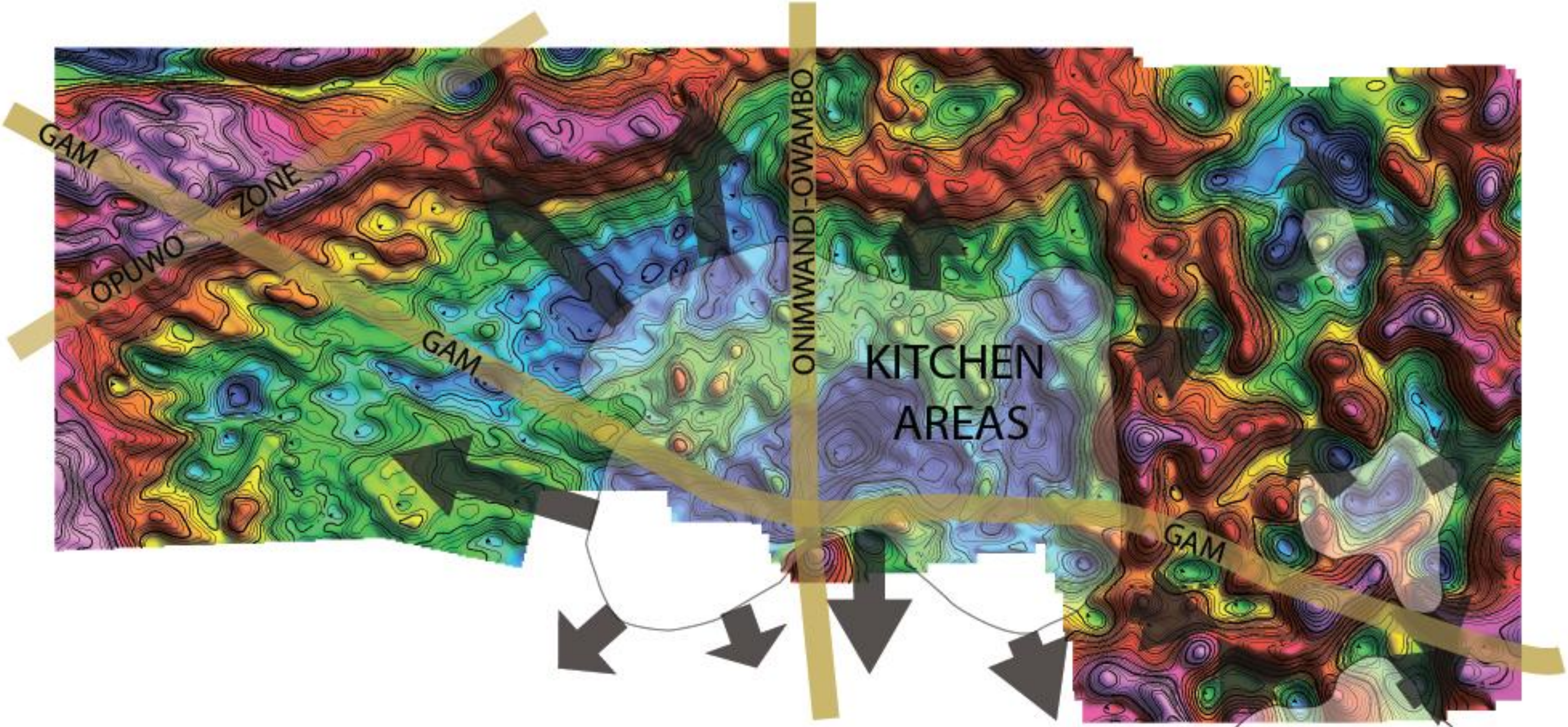


HYDROCARBON KITCHENS AND MIGRATION PATHWAYS SUPERIMPOSED ON REGIONAL MAGNETIC MAP

Gray arrows leaving kitchen areas indicate likely migration pathways

Golden zones represent regional lineament and fault zones

Figure 27. Hydrocarbon kitchens and migration pathways superimposed on regional magnetic map.



Gray arrows leaving kitchen areas indicate likely migration pathways **Golden zones represent regional lineament and fault zones**

Figure 28. Hydrocarbon kitchens and migration pathways superimposed on regional gravity map.

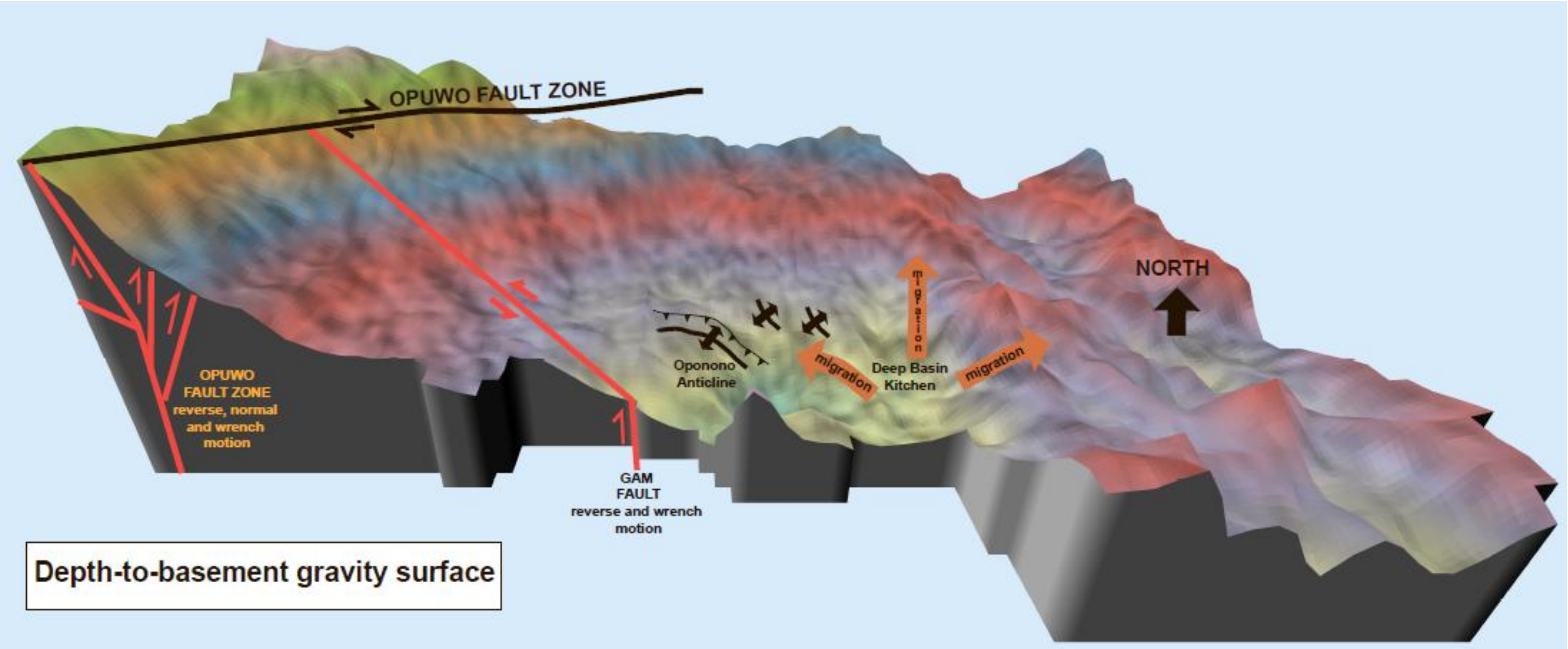


Figure 29. Regional structures, hydrocarbon kitchens, and migration pathways superimposed on regional gravity surface block diagram.

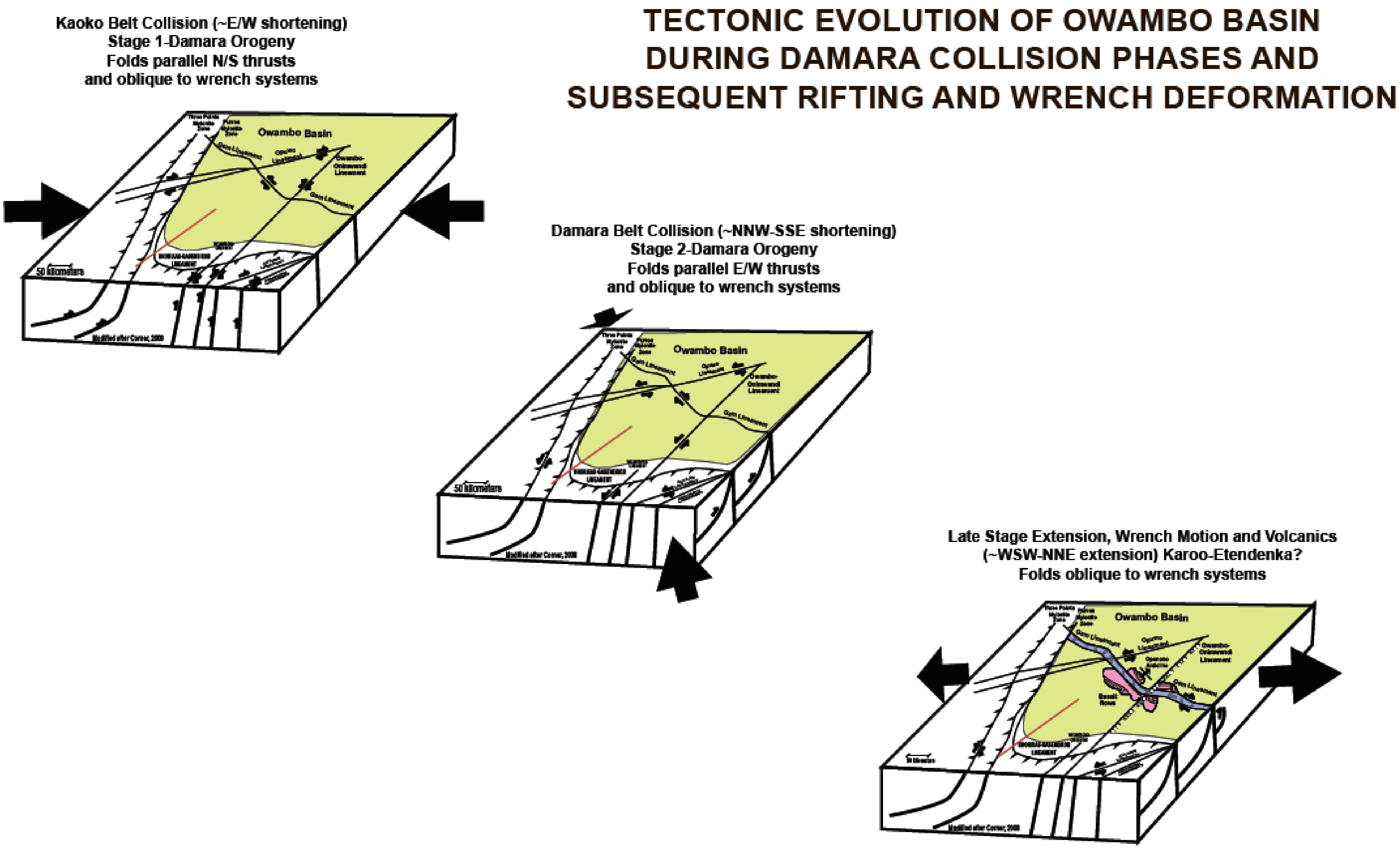


Figure 30. Tectonic evolution of Owambo Basin during Damara collision phases and subsequent rifting and wrench deformation.