Gravity Anomalies over the Marda Fault Zone, Ethiopia.

P. G. Purcell *

INTRODUCTION

The Marda Fault Zone, a major fault zone trending NW-SE across the Ogaden Basin, was first recognized for its association with the linear volcanic outcrop of the Marda Range and was named the "Marda Line" (Gouin and Mohr, 1964). Recently, Black et al. (1974) recognized the extension of the fault beyond the Marda Range to Belet Uen in Somalia and referred to Jijigga-Belet Uen faulting. Mohr (1975) has recently used the term "Marda Fault" in noting extension of the floor of the Afar Depression and its possible relation to sinistral shear faults in the Aisha region. A major fault zone extending SE from Belet Uen area to the Somali coast (Geol. Surv. Som. Rep., 1973) is an obvious extension of the Marda Fault Zone which, from these indications, has a length in excess of 1400 km and must be considered a significant structural element across the Horn of Africa.

The nature of the fault is not understood. It was first considered a normal down-to-the-east fault (Gouin and Mohr, 1964) and this interpretation is well supported by the abrupt linear contact of the Mesozoic and Tertiary outcrops (Kazmin, 1972). More recently, significant shear zones have been identified near Jijigga (Black et al., 1974). Purcell (1975) has reviewed the geology and geophysics along the zone and proposed that the zone is a Pre-Cambrian lineament that has had a significant influence on the geologic history of the region, perhaps even to present times.

This interpretation is well supported by gravity data on the zone. These data, from surveys by the Upper Mantle Project group and several oil exploration companies, are reviewed in this discussion. Results of seismic surveys across several of the gravity anomalies are discussed.

AVAILABLE DATA

Gravity surveys by Gewerkschaft Elwerath in the early 1960's provided a significant amount of the data on the fault zone between Shilavo and the Ethiopian border (Gewerkschaft Elwerath, 1967). Considerable seismic data were recorded on these gravity anomalies and permit detailed comparison of Bouguer gravity and subsurface structure.

Gravity control near Daghabur was obtained by the Whitestone Ethiopia Petroleum Company and Louisiana Land and Exploration programme of the northern Ogaden Basin.

* Whitestone Ethiopia Petroleum Company, Addis Ababa.

Reconnaissance control in the Jijigga area has been obtained by the Upper Mantle Project group (Makris et al., 1972). These data and the Whitestone data are both on the international gravity datum. No accurate tie of the Elwerath surveys to the international datum is available but the different datums are not significant for the discussion.

DISCUSSION OF DATA

The data are discussed separately for four areas (Figure 1).

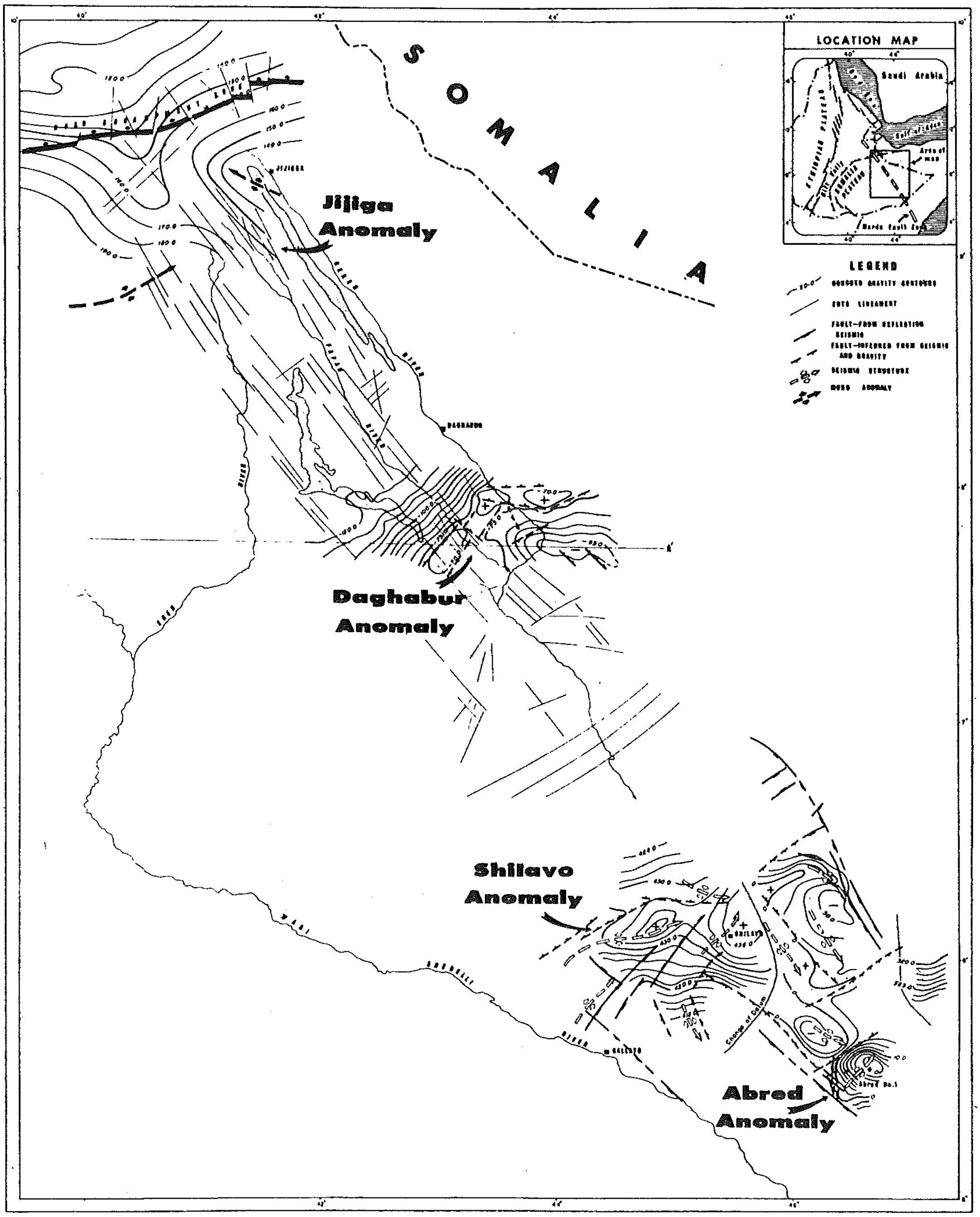

Figure 1. Bouguer gravity anomaly on the Marda Fault Zone.

a) The Jijigga Anomaly

The form of the Jijigga anomaly is taken from the Bouguer gravity map of the Upper Mantle Project in Ethiopia (Makris et al., 1972). The ENE trending gravity gradient zone along the southern margin of the Afar Depression is interrupted east of Dire Dawa by positive and negative NW-SE trending anomalies. A negative anomaly trending NW occurs on the Afar floor on trend with these anomalies. A negative axis trends ENE north of Jijigga and is flanked on the south by a positive anomaly centred on Jijigga. This anomaly has previously been correlated with the Marda Fault (Gouin and Mohr, 1964). Regional control in the northern Ogaden Basin (Purcell, 1975a) defines a major negative anomaly coincident with the crest of the Somalia Plateau and indicates, in more detail, the interruption of the smooth Bouguer anomaly pattern in this area.

The limited control precludes any interpretation of the Jijigga gravity anomaly acros the Marda Fault Zone. However, it can appropriately be noted, that the fault zone is coincident with a complex of Bouguer gravity anomalies that interrupt the relatively simple ENE trending Bouguer field which is related to thickening of the crust at the Afar Margin. The depth of the Moho discontinuty is interpreted from the data to have at least local anomalies coincident with, and across, the fault zone (Makris et al., 1975).

It is anticipated that additional gravity control will be obtained on the anomaly in the coming year. This data should connect the Jijigga and Daghabur anomalies and provide a more detailed view of the gravity anomaly on this section of the fault zone.

2. The Daghabur Anomaly

The Daghabur anomaly is characterized by steep Bouguer gravity gradients of approximately 2.0 mgls per km. The abruptness of the anomaly is readily apparent on an E-W Bouguer gravity profile across the northern Ogaden Basin (Figure 2). The steep NE trending Bouguer gravity gradient zone culminates in a positive axis, which changes in trend from NE-SW to E-W across the surface trace of the zone. A negative anomaly, also trending E-W, is located south of the E-W positive anomaly.

Significantly, there is virtually no indication of any NW-SE trending anomaly. In detail, residual anomalies on the flank of the main positive area seem to trend NW-SE but these features are relatively small. The basic cause of the anomaly is believed to be crustal and/or intrabasement. A major change of basement type probably occurs across a NE-SW trending fault coincident with the main NE trending gradient zone.

Detailed profile analysis of the anomaly consistently indicates a residual positive anomaly of approximately 6 milligals superimposed on the main anomaly (Figure 2). Depth analysis (Skeels, 1962) of the residual anomaly suggests a maximum depth of the causative density contrast at approximately 2000 m. This density contrast may relate to structural relief on the basement. Measured sections in the Fafan and Gerer River valleys, projected basinward, indicate a minimum 1000-1500 m of sediments in the area of the Daghabur anomaly. However, control of the basinward expansion of the Mesozoic sediments is very limited and it is felt that 2000 m is an acceptable estimate for the basement depth.

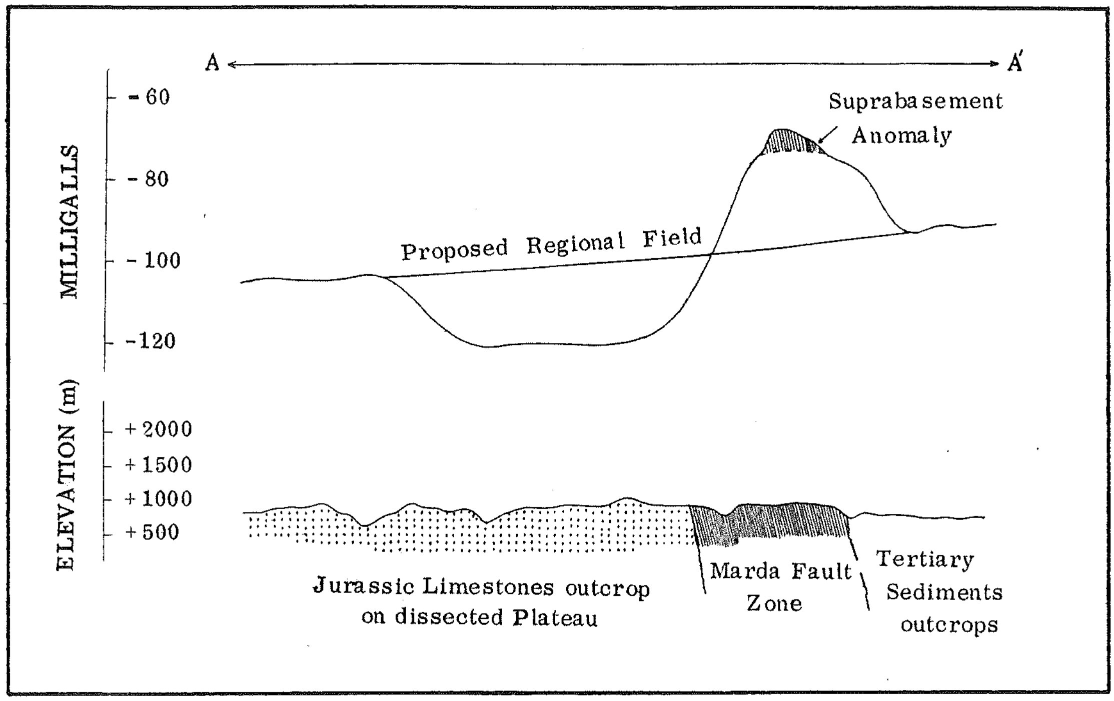

Figure 2. Elevation (bottom) and Bouguer gravity (top) profiles across the Dabhabur anomaly. Location of the profile is shown on Figure 1.

Magnetic surveying of the Daghabur anomaly indicates an excellent correlation of low amplitude negative magnetic anomalies with the residual gravity anomaly. Depth estimates are questionable because of the limited control (stations are 2 - 3 km apart) but suggest a magnetic basement depth of approximately 2300 m. This is considered in good agreement with the gravity basement depth estimates. A broad positive magnetic anomaly is coincident with E-W negative gravity anomaly. The steep flanks and flat crest of this magnetic anomaly are suggestive of a basement relief anomaly, and gradient zones on the flanks of this anomaly indicate a magnetic basement depth of 3300 m.

The absence of regional Bouguer gravity control to the east does not permit detailed analysis of the main anomaly. However, depth analyses, assuming simple projection of the regional field, yield maximum depth solutions in the range of 4000 - 5000 m. This interpretation does not preclude the possibility that the intrabasement contrast may occur at the basement surface.

It is possible therefore to view the Daghabur anomaly as a superposition of intrabasement and suprabasement anomalies. The residual gravity anomalies correlate with the magnetic data and suggest the presence of a fault-controlled, basement horst block trending NE-SW, and then E-W across the Marda Fault. The large intrabasement anomaly might indicate juxtaposition of different basement types by Pre-Cambrian faulting.

The Marda Fault has recently been discussed in the context of wrench faulting (Morton, 1974). The Daghabur horst may, correspondingly, be viewed as an antithetic block related to movement along the main fault. The flexure in trend across the zone may also be related to this transcurrent movement.

3. The Shilavo Anomaly

The Shilavo anomaly is an approximately E-W trending positive Bouguer gravity axis. No data are available on the western end of the anomaly.

The Shilavo anomaly has been extensively investigated by reflection seismic surveys (Gewerkschaft Elwerath, 1967) and an excellent correlation of seismic structure and gravity closure is noted. The two separate closures on the Shilavo anomaly are both coincident with structure on a deep reflector considered to be the base of the Hamanlei Series. A discrete basement reflection is masked by severe reverberations and the significance of basement tectonics in the development of the structure is not known. However, thinning of the Hamanlei Series is quite apparent on the seismic records indicating that the zone was structurally active in the Jurassic.

The thickness and age of the transgressive Adigrat Sandstone has been recognized in the northern Ogaden Basin as significantly controlled by structural and/or erosional relief on the Pre-Cambrian basement (Mohr, 1962). Moreover, the Adigrat Series grades upward through marls and silts into the Hamanlei Limestone Series. It is reasonable, therefore, to suggest that the Jurassic structure on the base Hamanlei at Shilavo reflects Adigrat structure that, in turn, is related to basement relief. This suggestion of basement relief is further indicated by the fact that the Shilavo anomaly cannot be satisfactorily explained by the Jurassic structure alone. A significant part of the anomaly must relate to basement structure and/or composition.

The seismic data shows major NE and NW faulting that defines a pattern very similar to the interpreted faulting on the Daghabur anomaly. NNE faulting on the western edge of the control area suggests that the Shilavo Bouguer gravity anomaly may swing SW beyond the limit of control and closely resemble, in form, the Daghabur , anomaly. These indication that the Shilavo Bouguer gravity anomaly is related to basement relief and that the structures are, at least, Jurassic in age lend significant support to the interpretation of the Daghabur residual anomaly as a basement horst block.

It is interesting to note that the Tenneco well Calub No. 1, seems to coincide with the main positive Bouguer anomaly of the Shilavo trend (Oil & Gas Journal, Jan. 29, 1973). This well tested a significant deposit of natural gas and may indicate that the Marda Fault Zone is important for hydrocarbon exploration efforts in the Ogaden Basin.

4. The Abred Anomaly

The Abred anomaly is located near the Ethiopia/Somalia border and is named after the Elwerath exploratory well Abred No. 1 on a large anticlinal structure coincident with a main positive Bouguer anomaly of approximately 15.0 mgls amplitude. This anomaly is poorly controlled on the southeast side but an indication of NW-SW linearity is apparent. A NW-SE trending negative anomaly occurs northwest of the positive anomaly. This negative anomaly is flanked on the NE side by a positive gravity axis which may extend to the southeast. Abrupt changes of trend of the gravity gradient zones are characteristic of this area giving the anomalies a box-like appearance and are,perhaps, indicative of faulting.

The area was extensively investigated with reflection seismic techniques. A fault controlled anticlinal dome was mapped on the base Hamanlei reflection (correlative with the Shilavo area), almost coincident with the main positive Bouguer gravity anomaly. The seismic surveys indicate NW-SE and NE-SW faulting on the flank of the Abred structure. A synclinal axis was mapped over the main negative anomaly. The axes and crests of the seismic structures are not precisely coincident with the gravity anomalies and the reasons for this apparent offset are not precisely known. Seismic data in this area were of poor quality and it is possible that the slight miscorrelation reflects the difficulty of interpreting the seismic data. Regardless, the area of the seismic structure and the gravity anomalies are coincident, and indicate an association of the gravity anomalies with subsurface structure. In this instance, similar to Shilavo, the magnitude of the anomaly dictates that significant basement-related density contrasts are coincident with the Jurassic structure. This situation has analogies in Saudi Arabia where Jurassic structures associated with N-S basement horsts can readily be located by gravity surveying - yet the structures, as mapped, do not fully explain the Bouguer anomalies (Aramco, 1959).

The well, Abred No. 1, was drilled on the crest of the structure interpreted from seismic data. The well penetrated 3100 metres of sediments above crystalline (?) basement. Reservoir rocks in the (Middle Jurassic) Upper Hamanlei Limestone Series and Adigrat Sandstone Series tested saltwater. The absence of any oil and gas was attributed to the relative youth of the structure (Gewerkschaft Elwerath, 1967). Alternatively, the crest of the structure may be more closely coincident with the gravity anomaly. This would imply that the Abred well tested the flank of the structure, rather than the crest, and did not properly evaluate the hydrocarbon potential of the structure. The Abred well does not, therefore, downgrade the potential significance of the Marda Fault Zone for oil exploration.

SUMMARY

The four surveyed areas on the Marda Fault Zone are characterized by large amplitude Bouguer gravity anomalies. In addition there is an apparent change in the character of the Bouguer gravity field across the fault zone. The limited data available west of the zone show a dominant E-W trend abruptly turning to N-S near the eastern escarpment of the Rift Valley (Purcell, 1975a). Residual anomalies, related to surface volcanics and suprabasement relief, are superimposed on the regional field which, excluding a major negative anomaly in the extreme west near Ginir, is relatively smooth. By contrast, the Bouguer anomaly field east of the surface fault zone, is characterized by large amplitude anomalies (Gewerkschaft Elwerath, 1967) presumably related to intrabasement density contrasts. No overall trend is apparent. It is possible, therefore, that a change in basement type occurs in association with the Marda Fault Zone.

The anomalies near Shilavo and Abred have been extensively investigated by reflection seismic surveys. The seismic data reveal an excellent correlation of Lower Jurassic structure with the Bouguer gravity anomaly. The seismic structure is mapped on a Base Hamanlei reflection and show distinct thinning of the Hamanlei unit. This demonstration of Jurassic structural growth and the conformable relationship of the Hamanlei Limestone Series with the underlying Adigrat Sandstone suggest that the structures are related to structural and/or erosional relief on basement at the time of the Mesozoic transgression.

The gravity and seismic data therefore demonstrate the significance of this lineament. Tertiary movements related to the rifting of the Red Sea and Gulf of Aden must be viewed as a reactivation of an older fault zone, at least Lower Mesozoic and probably Pre-Cambrian in age. The major Bouguer anomalies may relate to a juxtaposition of different basement types by Pre-Cambrian faulting.

The control of Tertiary rift structures by Pre-Cambrian lineaments is common in eastern Africa (King, 1970) and the Marda Fault Zone seems to provide another example. The significant length and age of the zone dictates that more consideration be given to this major lineament across the Horn of Africa in any consideration of Tertiary rifting or Mesozoic sedimentation in the region.

Acknowledgements

The writer is indebted to the Ministry of Mines of the Ethiopian Government for their permission to utilize their files of Gewarkschaft Elwerath data in the Abred and Shilavo area. Special acknowledgement is also due the management of Whitestone International, Inc. and L.L. & E International, Inc. for permission to publish the data in the Daghabur area.

D. Emilia reviewed the magnetic data with the author. Thanks are made to C. Wood and P. Gouin who reviewed the manuscript.

References

Aramco, 1959, Ghawar Oil Field, Saudi Arabia A.A.P.G. Bull., 43, 34-54.

Black, R., W.H. Morton and Tsegay Hailu, 1974, Early Structures around the Afar Triple Junction, Nature, 248, 496-497.

Geologic Survey of Somalia Republic, 1973, Geologic Map of Somalia Republic Preliminary Edition Displayed at 2nd Conf. Afr. Geol. Addis Ababa.

Gewerkschaft Elwerath, 1967, Report on Exploration in the Ogaden District, Ethiopia, Ministry of mine files, Addis Ababa.

Gouin, P. and P. Mohr, 1964, Gravity Traverses in Ethiopia (Interim Report) Bull. Geophy. Obs., Addis Ababa, 7, 185-239.

Kazmin, V, 1972, Geological Map of Ethiopia, Geological Survey of Ethiopia, Addis Ababa.

King, B.C., 1970, Volcanicity and Rift Tectonics in East African, in "African Magmatism and Tectonics", ed. T.E.N. Clifford and I.G. Gass, Edinburg.

Makris, J., H. Menzel and J. Zimmermann, 1972, A Preliminary Interpretation of the Gravity Field of Afar, North-east Ethiopia, Tectonophysics, 15(1-2), 31-40.

Makris, J., H. Menzel, J. Zimmermann, and P. Gouin, 1975, Gravity Field and Crustal Structure of North Ethiopia, in "Afar Monograph", eds. A. Pilger and A. Rosler, Claustal.

Mohr, P., 1962, The Geology of Ethiopia, Addis Ababa.

Mohr, P., 1975, Structural Elements of the Afar Margins: Data from ERTS-1 Imagery, Bull. Geophy. Obs., Addis Ababa, 15, 83-88.

Morton, W., 1974, A Wrench Fault in Ethiopia, 1974 Annual Rep. Geol. Dept. H.S.I. Univ., Addis Ababa.

Purcell, P.G., 1975, Preliminary Notes on Gravity Survey Northern Somalia Plateau, Ethiopia, Bull. Geophy. Obs., Addis Ababa, 15, 141-148.

Purcell, P.G., 1975b, The Marda Fault Zone, Ethiopia, Nature (in press).

Skeels, D.C., 1963, An Approximate solution to the problem of Maximum Depth in Gravity Interpretation, Geophysics, 28, 724-735.

Erratum

p. 133, par. 1. line 7:
"floor etc..." should read " fault across the floor"...etc.