SUBSIDENCE HISTORY OF THE RUKWA RIFT IN SOUTH WEST TANZANIA ANALYSED FROM IVUNA WELL

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ABSTRACT

The variation in subsidence rate during rift basin development is a good indication for the Geodynamic history of a sedimentary basin. The sedimentary section of Ivuna Well is herein used to explain the structural evolution of Rukwa Basin within the Western Rift of the East African Rift System. The sedimentary record of Ivuna Well is extracted from published information. The effects of sedimentary load, corrected for compaction and variation in water depth, and lake-level have been removed to obtain the "tectonic subsidence." Curves show two phases of accelerated subsidence related to the fault controlled rifting phases: The Karoo rifting and the Late Cenozoic rifting. Though several phases of rifting are proposed within Karoo time in eastern and southern Africa, it is difficult, with the present information from Ivuna well, to infer them. But the change of gradient of the Geohistory plots within the Karoo section does suggest at least variations of sedimentation rates. The Karoo rifting phase is followed by a steady subsidence which resulted from thermal contraction of the lithosphere thinned during Karoo crustal and lithospheric stretching, while Late Cenozoic rifting is still young at its initial phase of rifting (t = 0).

INTRODUCTION

Although it was long observed that thick sedimentary piles in sedimentary basins cannot be explained by the mechanical load (sediments and water load) alone (Bowie 1927, Sleep 1971), basin subsidence was not well understood until after the theory of plate tectonics was put forward (Dewey & Bird 1970, Dewey 1972, McKenzie 1972). It was then realised that contraction due to a cooling lithosphere plays an important role in the vertical lithospheric motions. McKenzie (1978) first proposed two causes of basin subsidence: the initial crustal and mantle thinning, and then later thermal lithospheric contraction. Regional studies (Steckler & Watts 1978, Sclater & Christie 1980, Bond & Kominz 1984) have shown that this two-stage subsidence prediction is generally consistent to first order, with patterns observed in many rifts and passive margins. Modifications to various aspects of McKenzie's model have been proposed (Royden & Keen 1980, Allen & Allen 1990). However, it is so far agreed that the formation of extensional sedimentary basins is a function of crustal thinning and thermal lithospheric contraction modified by lithospheric strength. Thus, the driving forces of basin subsidence include the mechanical loads and the ability of the lithosphere (flexural rigidity) to support these forces (Weissel & Karner 1989, Kooi 1991). Understanding the basin subsidence is therefore essential in trying to explain the mechanics of lithospheric activities in a particular basin.

By removing the subsidence due to the mechanical load over the basement, the tectonic subsidence is isolated and analysed. This process is known as backstripping (Watts & Steckler 1981). The tectonic subsidence so obtained is the true basin subsidence that would have occurred in the absence of sedimentation. It is, therefore, more directly related to the mechanical origin of the basin. The aim of backstripping is therefore, to extract this component of basin subsidence from the stratigraphic record for various geologic times in the history of the basin evolution.

Tectonic Setting

Rukwa Basin forms part of the western arm of the East African Rift System (Fig. 1). The sedimentary units in this basin reach up to 12 km deep in some places (Morley *et al.* 1992, Kilembe & Rosendahl 1992), this load must have contributed significantly to the basin subsidence. The structural evolution of Rukwa Basin has in the past years been a subject of debate (Kilembe & Rosendahl 1992, Dypvik & Nesteby 1992). This is in part due to lack of fauna in the Red Bed Formation, thus hampering their age determination. The basin has often been considered as a three-stage rift basin (Mbede 1991). In this paper the structural evolution of the Rukwa Basin is explained using the subsidence curves of Ivuna Well drilled within the basin. This is the only well in this basin, which had reached basement (Morley *et al.* 1992), and which can therefore provide a complete picture of the basin history. A two fold rift development model is proposed. It has to be noted, however, that since this study is based on a single well drilled on a basement high, the results can only tentatively be applied to the whole basin.

The NW-SE trending Rukwa Rift traverses the similarly trending Early Proterozoic Ubendian tectonic belt {2500 -1800 Ma} (Nanyaro *et al.* 1983). The oldest sedimentary formation known is the Late Carboniferous to Triassic Karoo Super Group (Spence 1954), first deposited when the great Late Paleozoic ice sheet of Gondwana was retreating (Frakes & Crowell 1970, Wopfner 1991). The Late Jurassic/Early Cretaceous time is known to have been a period of active tectonic movements in most parts of the African continent, probably related to the opening of the South Atlantic ocean (Fairhead & Green 1989, Lambiase 1989) which was preceded by the opening of the Proto-Indian ocean. Sedimentation in the Rukwa Basin during

Jurassic/Cretaceous times is still controversially discussed (Kilembe & Rosendahl 1992).

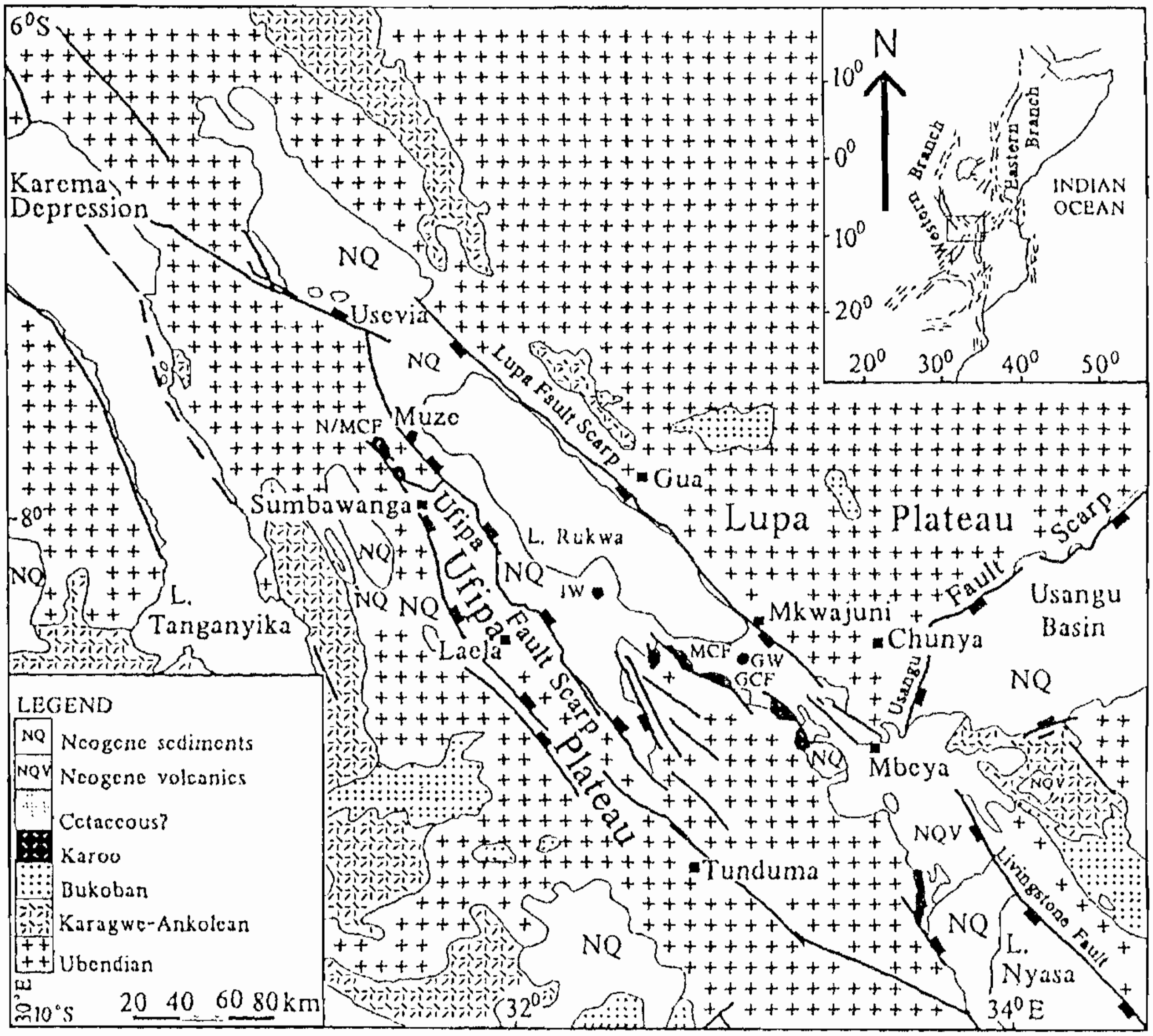

Fig. 1: The Geological Map of South-Western Tanzania showing the location of study area: IW = Ivuna Well; GW = Galula Well; GCF = Galula Coal-Field; MCF = Muasa Coal-Filed; N/MCF = Namwele/Mkomola Coal Field

Various red sandstone occurrences in the basin have in the past been correlated on a lithostratigraphic basis. Their Jurassic and/or Cretaceous age was assumed through questionable long-distance correlation with the Malawian Dinosaur Beds (Dixey 1928). However, Wescott *et al.* (1991) have shown that samples from the Red Sandstone Formation (obtained from the recently drilled Ivuna and Galula wells), which can be tied via seismic profiles with outcropping Red Beds at the southern edge of Rukwa Basin, are of Late Miocene age. Jurassic and/or Cretaceous sediments, though probably deposited in the vicinity of Rukwa Basin, may have, in some parts, been reworked during Late Miocene time.

Late Cenozoic sedimentation in Rukwa Basin therefore started with the reworking of Cretaceous red sandstones in a mainly fluvial environment during Late Miocene time (Wescott *et al.* 1991). This is the age when rifting is said to have been initiated in other parts of the Western Rift (Ebinger *et al.* 1989b, Pickford & Senut 1990). The present Lake Rukwa was established during Plio-Pleistocene, when the Lake Bed Formation was deposited (Wescott *et al.* 1991). Uplift of the rift flanks evidenced by the changes in drainage pattern across the East African plateau, is said to have been accelerated at the Plio-Pleistocene boundary (Ebinger *et al.* 1989a).

MATERIALS AND METHODS

Backstripping

The process of backstripping was carried out using a program developed at the Free University of Amsterdam (Janssen *et al.* 1993). Backstripping requires delithification or decompaction of the stratigraphic section, even though in reality when sediments are uplifted and the load on top is removed, decompaction will not necessarily be complete. The program "bmod" calculates "basement subsidence" and "tectonic subsidence" for a given well-stratigraphy, incorporating three delithification processes to establish minimum and maximum values for the sediment loaded subsidence (Sclater & Christie 1980, Bond & Kominz 1984, Bessis 1986). The program simulates decompaction of the stratigraphic section by first assuming maximum mechanical compaction in the relationship between porosity and depth. Secondly, it assumes minimum mechanical compaction, and thirdly, it assumes cementation with cement originating from outside the basin, making use of minimum porosity. Because no overpressured sections had been reported for Ivuna Well, the simulated decompaction process was accomplished by moving sediment layers vertically up the exponential porosity-depth relationship of Athy (1930):

$$\phi = \phi_0 e^{-kz}$$

where $Ø_0$ is the surface porosity (normally dependent on the type of lithology), k is a compaction factor constant for a particular lithology and z is the depth. Actually, when depth of the decompacted stratigraphic section is plotted against porosity a clear exponential relationship is obtained (Fig. 2).

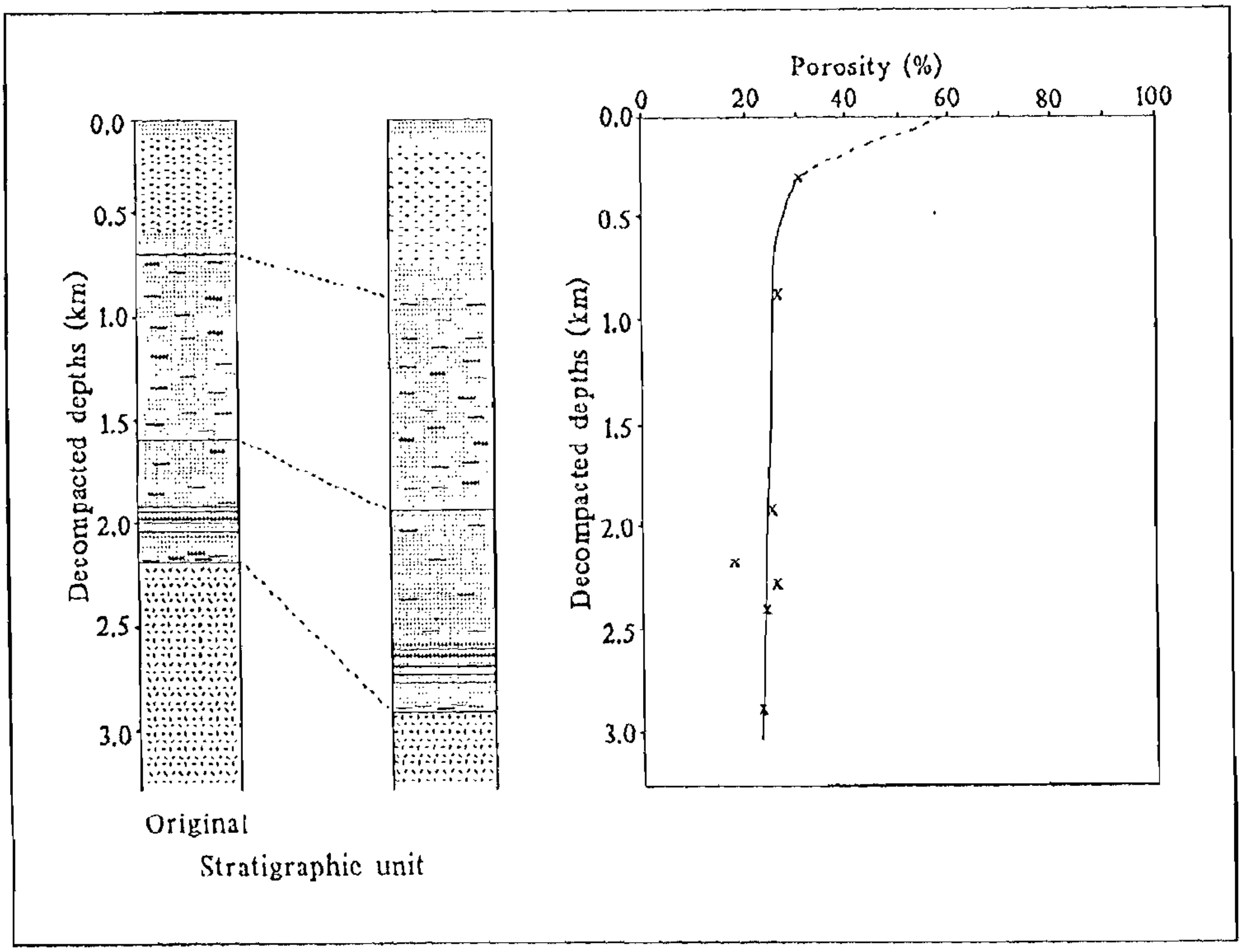

Fig. 2: The original and decomposed stratigraphic unit of Ivuna well and the porosity/depth relationship. It reveals the exponential relationship between porosity and depth

Because the lithology of different sections in the well are mainly shaly sandstone, only fractions of net sand and shale were entered to define the lithology (Table 1).

Table 1: Net sand in meters and Log calculated porosities for Ivuna Well (Anon 1988). Notice that because the lithology is mainly shaly sandstone only net sand is displayed.

INTERVAL (M)	NET SAND (M)	POROSITY (%)
305 – 699	96.0	27 - 30
699 – 1588	675.7	27 - 30
1588 – 1737	39.6	19 – 26
1737 – 1929	28.0	25 – 27
1929 – 2292	96.0	25 - 27

After decompaction, the total load of sediments must be estimated and removed from the basin, in which case the basement will rebound isostatically to give the "tectonic subsidence". Notice that the paleo water depth and the level changes must also be accounted for on isolating the tectonic subsidence (Steckler & Watts 1981). For the purpose of this work it is assumed that the water depth (W_d) throughout the basin's development is zero. This is because, lithologically, in the section of Ivuna well, both Karoo and Red Beds are suggested to be of mainly alluvial to fluvial origin (Wescott *et al.* 1991). Moreover the present Lake Rukwa is shallow (13 m deep at the most). Sediment facies and fauna within the Lake Beds suggest that the lake has remained shallow through most of its history (Morley *et al.* 1992). It has to be noted however that the assumption is actually over simplification of the decompaction process because elsewhere the K1, K2, K4 and K5 section are suggested to have been deposited under more or less permanent water covers (Spence 1954, Dypvik & Nesteby 1992). However the lack of detailed paleontological information in Ivuna well has hampered the sub-division of the various Karoo sections.

Being a rift basin at its early stage, an Airy-type model is assumed for backstripping, i.e. sediment and water load are locally supported by the basement. However, it is important to note that the geometry of the basin and the strength of the lithosphere (flexural rigidity) determine whether, upon loading, the basement response can be described flexurally or according to an Airy-type model. The local isostatic basement response assumed in this calculation is only for simplicity. The assumption made is not always valid because the young rift basins in East Africa show considerable strength (Ebinger *et al.* 1991).

RESULTS AND DISCUSSION

The difference between the original and the decompacted stratigraphic section (Fig. 2) shows that there was more than 20% increase of the sediment thicknesses on decompaction. The subsidence curves (Fig. 3) show the "tectonic subsidence" which represents effective (unloaded) basement depth at the time when the sediments were first deposited. It is this subsidence with time that is the real subsidence which results into the basin development. The "basement subsidence" is the total basement subsidence taking into account compaction.

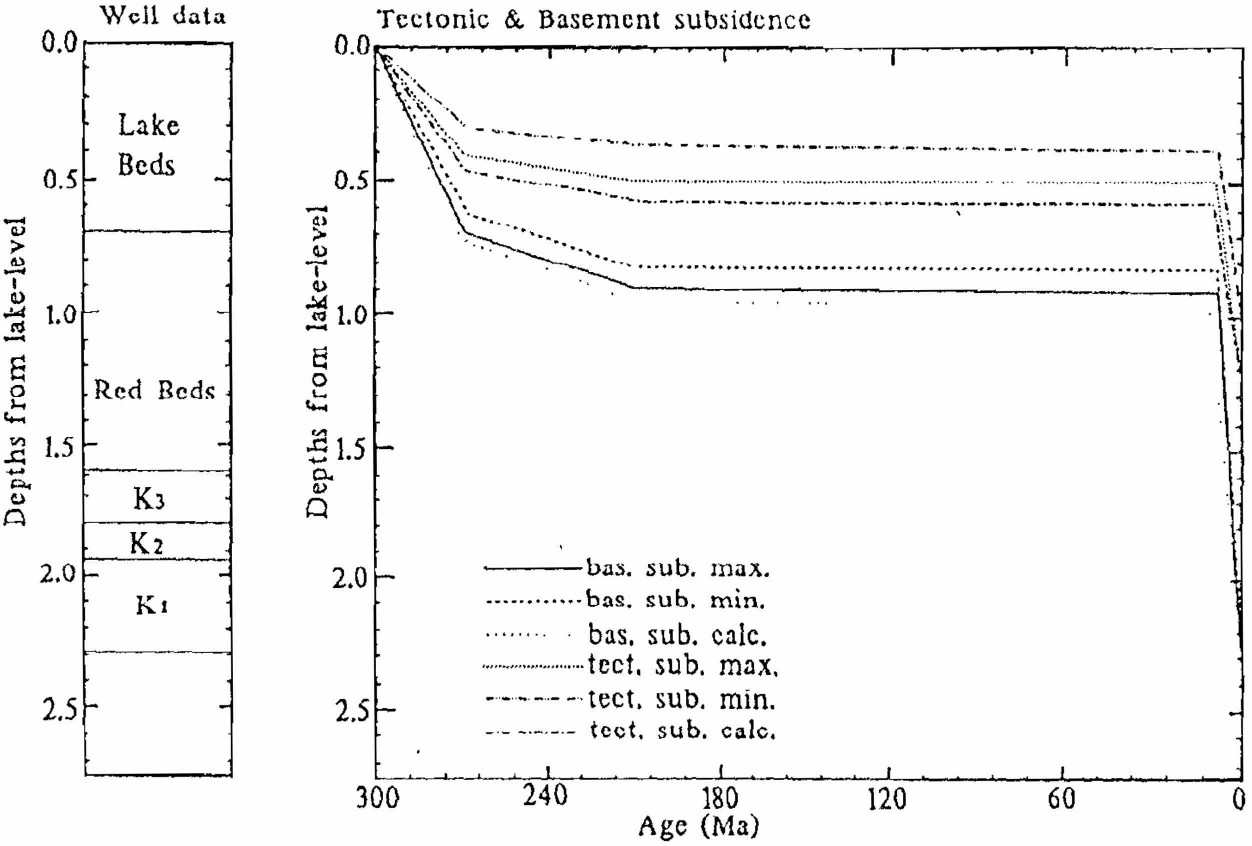

Fig. 3: Tectonic and basement subsidence curves of Ivuna Well. Notice the rapid initial fault controlled subsidence stages during Karoo rifting followed by a long period of thermal subsidence. The late cenozoic rifting is still at its initial rifting phase.

The decompaction curves (Fig. 3) suggest a two-phases rifting during Karoo time; first a rapid subsidence during the early part of Karoo time which can be related to the initial fault-controlled subsidence. This is followed by a slow subsidence phase in the later part of Karoo time which represents the post-rift thermal subsidence phase. The Karoo thermal subsidence phase in eastern Africa, is also dated by apatite fission track data (Mbede *et al.* 1993, Van der Beek *et al.* 1998) that date the erosional surfaces of the country surrounding Karoo basins (Dixey 1945). The last part of figure 3 is characterized by a steep curve which represents the rapid subsidence which the basin is still undergoing on its initial phase of the Late Cenozoic rifting. The geohistory plots (Fig. 4) were prepared by considering the 1 km sediments eroded on top of Karoo unconformity (Dypvik *et al.* 1990). This represents an uplift phase after the initial fault-controlled subsidence had ceased. The intra-rift unconformities within Karoo are represented by the changes in slope of the geohistory plots; this probably implies variation of sedimentation rates in the various Karoo sequences or they may have been induced by changes in tectonic subsidence and represent various rift phases. Also, it is to be noted that, sediments removed on top of intra Karoo rift unconformities were not taken into consideration. Their inclusion would have given a clear picture of tectonic activities at that time. The Late Cenozoic Rukwa Basin is at its initial stage of rifting (t = 0), so the present Late Cenozoic subsidence can be considered as the fault-controlled initial subsidence of McKenzie (1978). Seismic interpretations (Morley *et al.* 1992, Kilembe & Rosendahl 1992, Mbede 1993) support this because most Late Cenozoic faults cross-cut the Late Tertiary to recent sedimentary section and are still active.

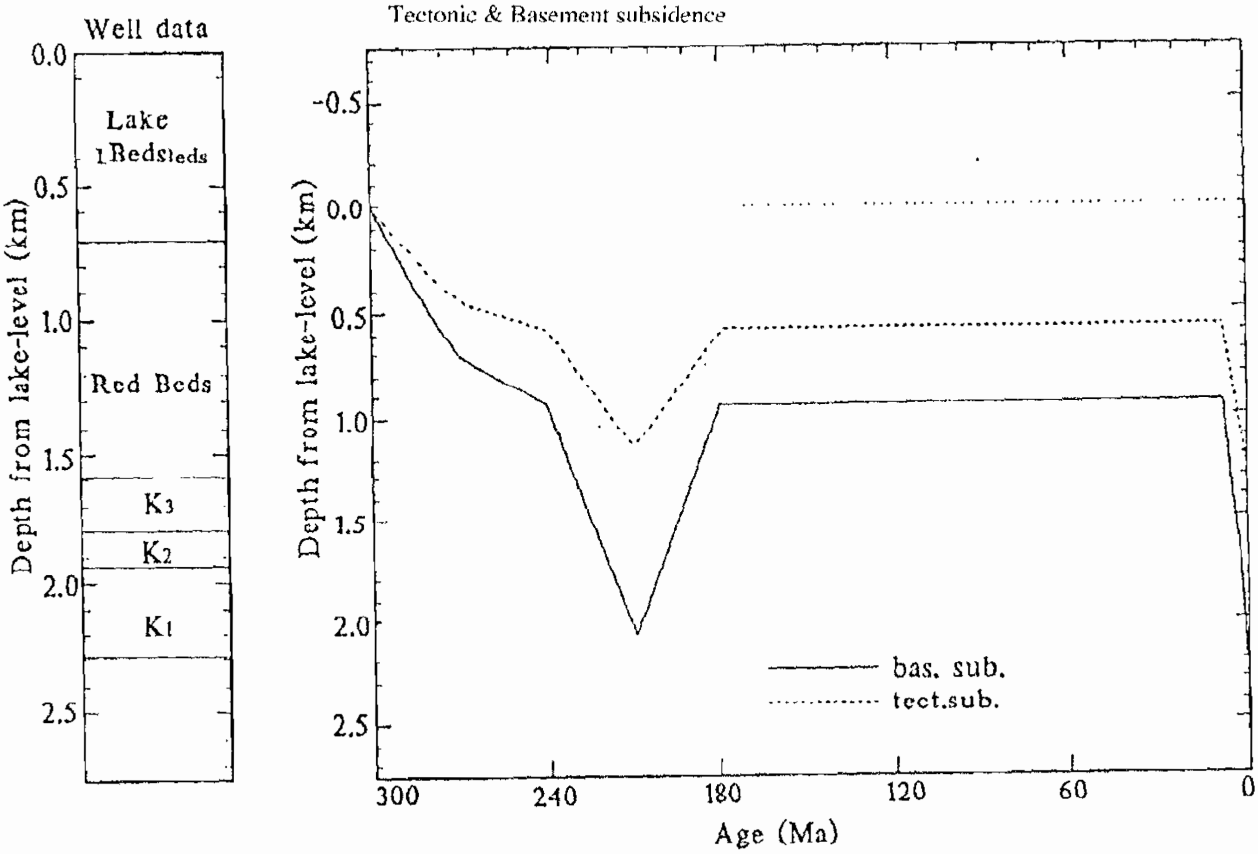

Fig. 4: Geohistory plots of the Ivuna Well prepared by taking into account the 1 km of sediment eroded on top of unconformity while the intrarift uncomformities within Karoo are noticeable by the change of the slope of the subsidence.

The process of backstripping takes into consideration a number of factors which have to be interpreted from geological information. Such parameters are normally subject to error, depending on the availability and reliability of information used for interpretation. To reduce the error, backstripping is normally carried out on several wells within the basin where sequences are thick and the sedimentary record is as complete as possible. Ivuna Well was drilled on a basement; subsidence patterns here may not be representative of the entire basin. Wells in deeper parts of the basin would have given a more complete subsidence history. However, this was the only well with a complete stratigraphic information so far in this basin.

The largest error is perhaps contributed by assuming local ($T_e = 0$) rather than regional flexural isostatic compensation when carrying out this study. Observations within extensional basins suggest that some basins are isostatically, regionally compensated rather than locally (Weissel & Karner 1989, Ebinger *et al.* 1991, Kusznir & Ziegler 1992, Karner *et al.* 1992). Even if local isostatic compensation can be assumed for the syn-rift stage, the post-rift Karoo thermal subsidence stage should have been flexurally compensated. Inclusion of flexure term would tend to predict larger subsidence for smaller amount of extension (Weissel & Karner 1989).

Uncertainties in the porosity-depth relationship used for computation can also contribute to an error in the calculated tectonic subsidence. Sclater and Christie (1980) assume that the mass of the column remains constant during decompaction. Porosity modifying mechanisms such as cementation may contribute a potentially significant load to the compacting sediments (Gallagher 1989). Even for normally pressured sections the exponential relationship has proved to be appropriate only for shale and chalk (Sclater & Christie 1980). Effects of diagenetic processes are known to produce curves that deviate from the exponential relationship (Selley 1978, Mangara 1980). Other porosity-depth relationships put forward include that of Falvey and Deighton (1982):

$$1/\phi = 1/\phi_0 + cz$$

and of Baldwin and Butler (1985):

$$\phi = 1 + (z/a)^b$$

where a and b are both lithological parameters, z is depth and c is a constant.

The decompaction program used in this study considers the effect of cementation, with cement originating from outside the basin. The calculated subsidence which takes into account cement from an external source shows that if the impact of cementation was taken into consideration in the mechanical compaction, the computed subsidence would have been much higher. Calculations gave an error of 36% and 14% for the maximum and minimum tectonic subsidence, respectively, and 16% and 5% for the maximum and minimum basement subsidence curves, respectively. However, this error is uniform for the whole curve and should not affect the present interpretations which are based on comparison of the subsidence curves at various geologic intervals.

The analysis of stratigraphic sequences and subsidence curves has enabled the following scheme of Rukwa Basin development to be proposed. The primary graben system was initiated during Late Carboniferous at the beginning of Karoo tectonic events. Corrected unannealed apatite fission track ages suggest that general uplift was initiated at about 300 Ma (Mbede *et al.* 1993). Analysis of erosional patterns and fission track ages (Mbede 1993) suggest that Lupa

Fault may represent a Karoo border fault of Rukwa Basin which has been reactivated during the Late Cenozoic rifting, while the Ufipa Scarp represents a Late Tertiary feature. The higher rift flank uplift on Lupa Fault during Karoo rifting, may have exposed the upper crustal rocks we observe today.

Subsidence within Ivuna Well argues for the primary graben which must have been centred within the present basin, and later became a region of major faulting. This gave way to the Early Permian rapid subsidence, with areas of greater extension subsiding more rapidly (c.f. Morley *et al.* 1992). The rift flanks were gradually uplifted and when extension terminated, a general subsidence took over as a result of thermal contraction. The originally uplifted rift flanks were therefore subsequently eroded and by the end of Karoo rifting the lithosphere had stabilised. This suggests that the Late Jurassic/Cretaceous Red Beds were deposited in basin caused by the Karoo thermal subsidence stage in a mainly fluvial environment, and are probably preserved in the deeper parts of the basin adjacent to Lupa border fault. In some parts, the Red Beds have probably been reworked in the Late Tertiary time as is the case in the northern Nyasa Rift (Mbede 1993).

Active rifting accompanied with rapid subsidence started again in the Upper Miocene time. The oldest Late Cenozoic fauna recorded in this basin are of this age (Wescott *et al.* 1991). This was the beginning of the Late Cenozoic rifting episode which is still at its initial fault-controlled subsidence. Reflection seismic studies suggest that most faults of this age extend into the underlying basement (Morley *et al.* 1992). This implies that the crust has undergone brittle failure producing isostatic fault-controlled subsidence and reactivating most of the Karoo faults (Kilembe & Rosendahl 1992). The extent of the Late Cenozoic rift relative to Karoo rift is not yet clearly explained, while on the western flank outcrops of Karoo rocks are preserved, it is possible that the higher erosion rates on the eastern flank during Karoo thermal subsidence may account for their absence. But the fact that Lupa is the Karoo border fault for this basin probably explains their absence on the eastern flank.

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