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SHORT NOTES

Dip analysis as a tool for estimating regional kinematics in extensional terranes: Discussion

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INTRODUCTION

Scott *et al.* (1994) presented a stimulating and perhaps widely applicable method to determine the regional maximum extension direction in extensional terranes on the basis of dips. They emphasize that their method (hereafter referred to as the dip direction method) is particularly useful for elucidating the maximum extension direction from seismic reflection data. Scott *et al.* applied the dip direction method to seismic reflection profiles from the Malawi rift zone, a part of the East African Rift for which numerous seismic data exist (Scholz *et al.* 1989), but which also lacks corroborating subsurface well data. Nevertheless, Scott *et al.* conclude that the direction of extension for the Cenozoic Malawi rift zone was northwest–southeast. Since syn-rift sediments of various Phanerozoic rifting events are exposed in the northernmost part of the Malawi rift zone, we would like to compare the dip directions obtained from reflection seismic data by Scott *et al.* (1994) to those exposed in outcrop, and thereby discuss some limitations of the dip direction method applied to seismic data. We suggest that the dip direction method led Scott *et al.* to an inaccurate interpretation of the extension direction for the Cenozoic Malawi rift zone. In particular, we would like to address the following questions:

(1) How can a multi-stage extensional history be resolved, i.e. how can a relative or absolute age be assigned to subsurface dipping units without stratigraphic well control?

(2) What was the pre-extensional dip of the acoustic basement?

(3) What, if any, significance has been attributed, in the particular example of the Malawi rift zone, to the subhorizontal attitude of the younger lake sediments?

We would like to stress that because of limited exposure of Cenozoic rift-related sediments, our study area is much smaller than the area covered by the study of Scott *et al.* (1994). Furthermore, our study area is located at the shoaling side of the Karonga basin (Fig. 1) where pronounced recycling processes resulted in a condensed section. Cenozoic fault throws are smaller than the offsets at the border fault segment on the opposite side of the basin. However, the method of Scott *et al.* is virtually scale-independent; hence, the conclusion of a NW–SE-trending extension direction for the Malawi rift zone should apply to all basins of this rift zone and can be tested in our 150 km^2 study area.

MULTI-STAGE EXTENSION

The stretching direction in the dip direction method is determined from the true dip of an originally horizontal surface associated with infra-basinal (acoustic) basement blocks as revealed at the intersection of seismic profiles. Accordingly, the method yields the integrated maximum extensional direction for all events younger than the acoustic basement. The method as currently implemented cannot resolve more than one event or a changing extension direction during a single event.

The Precambrian basement underlying the Malawi rift zone, however, has a multi-stage extensional history

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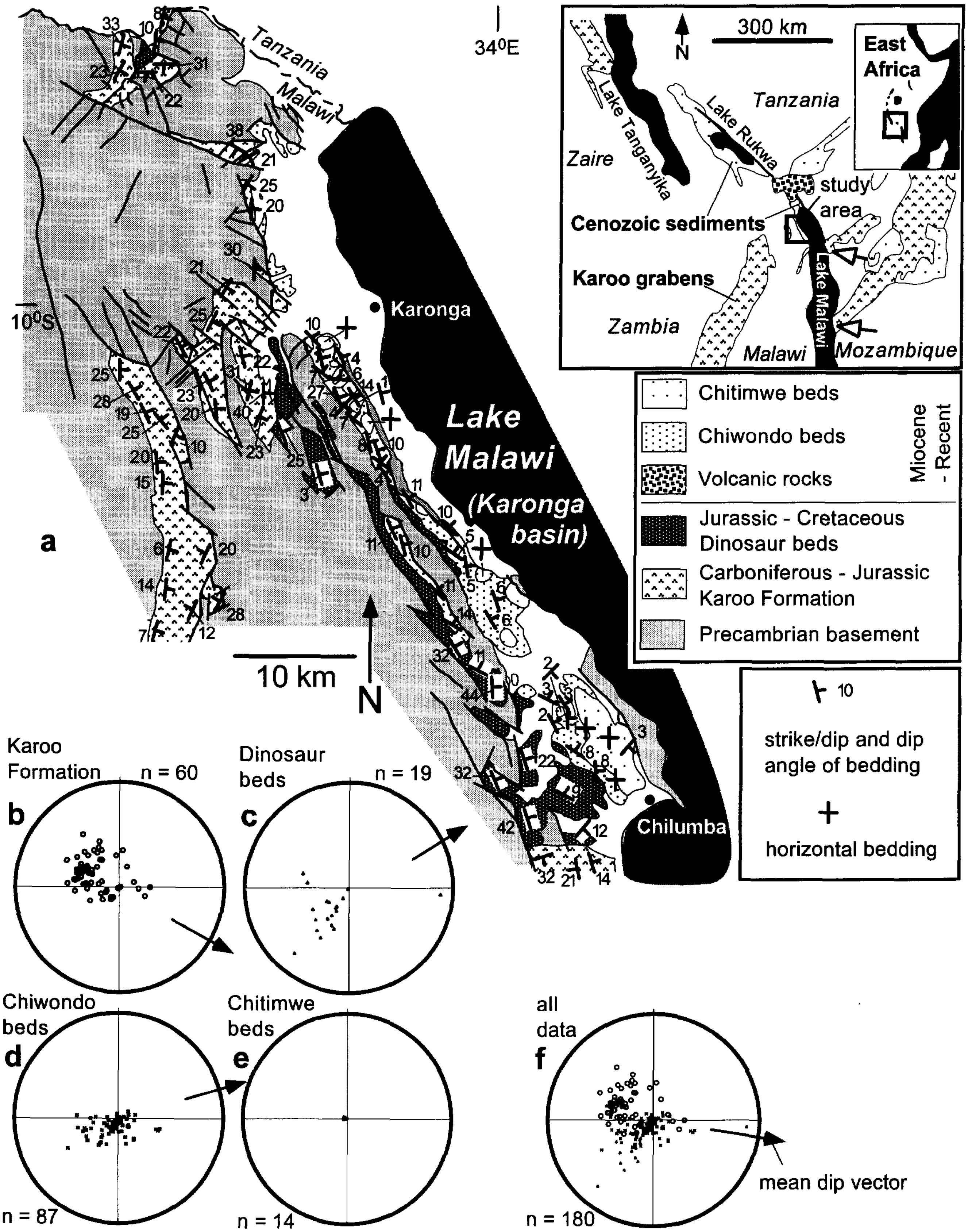

Fig. 1. (a) Geologic-tectonic map of the Karonga basin of the Malawi rift zone showing strike and dip of Phanerozoic rift-related sediments. Faults are shown by bold lines. (b)–(f) Poles to bedding and mean dip direction for (b) Karoo sediments, (c) Dinosaur beds, (d) Chiwondo beds, (e) Chitimwe beds, and (f) all data. Inset shows position of the Malawi rift zone within the southern portion of the East African Rift and location of the study area (boxed). The two arrows indicate regions where Karoo grabens cross Lake Malawi. A comparison of the northern half of fig. 4 of Scott *et al.* (1994) to the inset map, offers the possibility that most the NW–SE-trending dip directions of Scott *et al.* (1994) coincide with the supposed locations of Karoo grabens underneath the lake. In the remainder of the northern half of Scott *et al*'s. fig. 4, approximately WSW–ENE- to E–W-trending dip directions prevail which coincide with our on-land dip directions for the Dinosaur and Cenozoic lake beds.

(Castaing 1991, Ring 1994). The first rifting event resulted in deposition of the Karoo Formation (Fig. 1). Uplift and erosion along the flanks of the Malawi rift zone has led to the removal of an unknown thickness of Karoo strata and only isolated remnants of Karoo Formation are preserved along the downthrown side of some tilted fault blocks. The overall stretching direction during this extensional event is thought to be northwest–southeast (Castaing 1991). The mean dip direction of the Karoo beds in northern Malawi is also northwest–southeast (Fig. 1b). The next extensional event led to the deposition of the Dinosaur beds (Dixey 1927) which mostly lie unconformably on top of Precambrian basement. The direction of extension is thought to be northeast–southwest (Castaing 1991) which agrees with the mean dip direction of the Dinosaur beds (Fig. 1c). The last rifting event led to the formation of the Cenozoic Malawi rift zone. The older lake beds (Chiwondo beds) either rest unconformably on top of the Dinosaur beds, onlap the Precambrian basement, or are in fault-contact with either of these two units. The younger lake beds (Chitimwe beds) always lie unconformably on Chiwondo beds. The mean dip direction for the Chiwondo beds is east-northeast–west-northwest (Fig. 1d); however, it should be noted that the uppermost Chiwondo beds (strata younger than 1.6 Ma) and the Chitimwe beds (Fig. 1e) are horizontal (dips are on the order of 0°–2°, Ring & Betzler 1993). If the dip data for all rift-related sediments were combined, they would indicate an ESE–WNW-trending bulk dip direction (Fig. 1f).

Seismic-stratigraphic sequences within the northern basins of Lake Malawi include the 3–4.5 km thick Nyasa/Baobab unit, the 1 km thick Mbamba unit and the 50–75 m thick Songwe unit (Scholz *et al.* 1989), all of which are postulated to be Cenozoic in age (e.g. Ding & Rosendahl 1989). The extent and pattern of Dinosaur and Karoo deposits underneath the lake are not known. From the exposure of the Karoo Formation, it can be inferred that two Karoo grabens cross the lake (arrows in inset of Fig. 1).

Scott *et al.* (1994) were not specific about the nature of the acoustic basement underneath Lake Malawi. Because of the multi-stage extensional history of the region the nature of the acoustic basement is critical for any interpretation of the extension direction for the Cenozoic Malawi rift zone. Ding & Rosendahl (1989) suggested that the contact of the Karoo Formation and/or the Dinosaur beds with the Cenozoic lacustrine sediments corresponds to the top of the acoustic basement. However, locally the Nyasa/Baobab unit may rest directly on top of the Precambriam basement (Ebinger *et al.* 1993) indicating that, at least in this case, the metamorphic basement represents the acoustic basement.

Our work (Ring & Betzler 1993, Betzler & Ring 1995) shows that the lithologic properties (e.g. mineralogy, porosity, density) of the sandy, and less frequently shaly, Dinosaur beds are not fundamentally different from those of the Chiwondo beds suggesting roughly similar seismic velocities for both units. Moreover, the lowermost unit of the Chiwondo beds is made up of recycled Dinosaur beds. We observed a slight angular unconformity between the Dinosaur and Chiwondo beds; however, at least another three unconformities of a similar angular break have been found within the Chiwondo beds. This suggests that the contact between the Dinosaur beds and the Chiwondo beds is probably difficult to image in seismic profiles. The Karoo Formation is also chiefly composed of sandstones. These sandstones are somewhat more compacted than the overlying Mesozoic–Cenozoic beds and seismic velocities should therefore be higher in the Karoo rocks than the Cenozoic–Mesozoic strata. The layering of the various units that make up the Karoo Formation is distinctly more pronounced than in the Dinosaur and Chiwondo beds. In theory, the seismic data should show a down-section change which may enable the identification of the upper boundary of the Karoo Formation. The lithologies of the Precambrian metamorphic rocks of northern Malawi are highly heterogeneous and often steeply dipping. Therefore, the reflectivity pattern should be different from that of the Karoo Formation. However, on the eastern rift shoulder in Tanzania, the metamorphic basement is overlain by Proterozoic to Paleozoic sediments (e.g. McConnell 1972), the uppermost units of which are largely unmetamorphosed and roughly match in overall mineralogy and density most of the clastic Karoo rocks.

We conclude that seismic data alone (i.e. without additional well data) are not invariably able to differentiate between distinct rock units, making it difficult to characterize the nature of the acoustic basement at each seismic profile intersection. Furthermore, erosion of earlier extension-related sediments (Dinosaur beds and Karoo Formation in the case of the Malawi rift zone) may have reduced the thickness of these sediments to such a degree that they cannot be detected by seismic surveys, although the extensional events related to deposition of Karoo and Dinosaur beds are recorded by the dip of the metamorphic basement. We question how the dip direction method was able to attribute all tilting to just the more recent tectonic event, i.e. how the dip directions of Scott *et al.* (1994) have been corrected to reflect Cenozoic extension only. These authors apparently assumed that the formation of the Cenozoic Malawi rift zone alone was responsible for tilting of the acoustic basement.

DIP OF THE ACOUSTIC BASEMENT

Scott *et al.* (1994) assumed that the surface of the acoustic basement was horizontal at the onset of extensional deformation. The present erosional surface over most of eastern and southern Africa neither has a horizontal attitude nor does it have a systematic dip. In the case of an unsystematic dip of the surface of the acoustic basement, the application of the dip direction method may lead to artificial results.

HORIZONTAL ATTITUDE OF RIFT SEDIMENTS

The last point concerns the horizontal attitude of those exposed lake sediments which are younger than 1.6 Ma. All studies that constrain the extension direction for parts of the East African Rift from fault kinematic data on faults in *dated* horizons found that the regional extension direction in the East Africa Rift rotated from SW/WSW–NE/ENE to WNW/NW–ESE/SE after 1.6 Ma (Ring *et al.* 1992, Delvaux *et al.* 1993, Ring & Betzler 1993 and Ring 1994, for the Malawi and Rukwa rift zones; Strecker *et al.* 1990, Strecker & Bosworth 1991 and Bosworth *et al.* 1992, for the Kenyan and Ethiopian rift zones). A major outcome of this change in the direction of regional extension in the Cenozoic East African Rift was a strike-slip reactivation of pre-existing N- to NW-trending normal faults. In a strike-slip-controlled extensional setting block rotation about a vertical axis would cause problems if the dip direction method of Scott *et al.* (1994) was applied.

CONCLUSIONS

We conclude that the method as outlined in Scott *et al.* (1994) is a useful tool for the following:

(1) Extensional terranes in which extension-related sediments are exposed.

(2) Subsurface rifts for which test holes provide adequate stratigraphic control on the interpretation of seismic reflectors (i.e. for which the application of the method does not rely on the unconstrained interpretation of seismic data).

(3) Relatively simple extensional terranes that are dominated by normal- and oblique-slip and for which the dip of the pre-rift basement is known.

In the case of a changing extension direction during a single rifting event, which is quite common in continental extensional settings (e.g. Illies & Greiner 1978, Golombek *et al.* 1983, Doser & Yarwood 1991 and references given above for the East African Rift), and in the case of multiple superimposed extension events, the method is difficult to apply. Furthermore the nature of the acoustic basement should be tightly constrained.

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