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How successful are analogue models in addressing the influence of pre-existing fabrics on rift structure?

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Abstract

Sandbox models have been widely used to investigate normal fault geometries, evolution and propagation. As modelling attempts to investigate more aspects of normal faulting, the effects of pre-existing fabrics on normal fault geometry developed within the brittle upper crust have become a topic of interest. Analogue models have been developed for oblique rifting and the influence of pre-existing fabrics on transfer zone geometry. These models use pre-cut geometries in underlying plates to impose 'pre-existing' fabrics on the developing normal fault system. However, to really mimic natural systems it is the sand itself that should contain the pre-existing fabrics. The problem is that cohesionless sand has no tensile strength, while the influence of pre-existing fabrics on rift structure in the upper crust attests to the important role played by relatively small variations in rock strength anisotropy caused by pre-existing fabrics. Consequently it is necessary to assess how significant the departures are between model and natural examples and whether a new approach to modelling pre-existing rift structures is required.

1. Introduction

Extensional provinces around the world have a limited range of structural geometries, yet each has its own character. One of the key variables that provides variety to the simple geometries is the influence of pre-existing fabric; this influence has been remarked upon by many workers (e.g. McConnell, 1972; Illies, 1981; Cordell, 1978; Chorowicz and Mukonki, 1980; Dunbar and Sawyer, 1988; Daly et al., 1989; Versfelt and Rosendahl, 1989; Moustafa and Abd-Allah, 1992; Smith and Mosley, 1993; Hetzel and Strecker, 1994; Theunissen et al., 1996). For example the East African rift system preferentially resides within Proterozic mobile belts and avoids Archaean stable cratonic areas (McConnell, 1972; Daly et al., 1989). Also in the East African rift system regional bends in the trends of the rift branches coincide with changing metamorphic fabric orientations within the mobile belts (McConnell, 1972). At a smaller scale transfer zones are commonly located at rift-oblique pre-existing fabrics (e.g. Syrian arc features in the Gulf of Suez, Patton et al., 1994; Precambrian foliations and Karroo brittle structures in Lake Tanganyika, Versfelt and Rosendahl, 1989). Where low angled foliations or low-angled faults exist in the basement, later extensional faults may follow the fabric and be anomalously low angled (e.g. Allmendinger et al., 1983). Pre-existing fabrics trending at highly oblique angles may inhibit fault propagation and lead to more numerous, closely-spaced faults than might be expected for faults in a more isotropic material, or affect the overlying fault geometry in a variety of ways (Coussement, 1995; Le Turdu et al., 1995; Morley, 1996).

Consequently it is important to understand the influence of pre-existing fabrics on a rift system whether we are interpreting seismic data, mapping outcrops or even investigating syn-rift sedimentation.

Since normal fault geometries are so sensitive to pre-existing fabrics, analogue models of extension have been performed which take them into account (e.g. Withjack and Jamison, 1986; Serra and Nelson, 1988; Tron and Brun, 1991; McClay and White, 1995;

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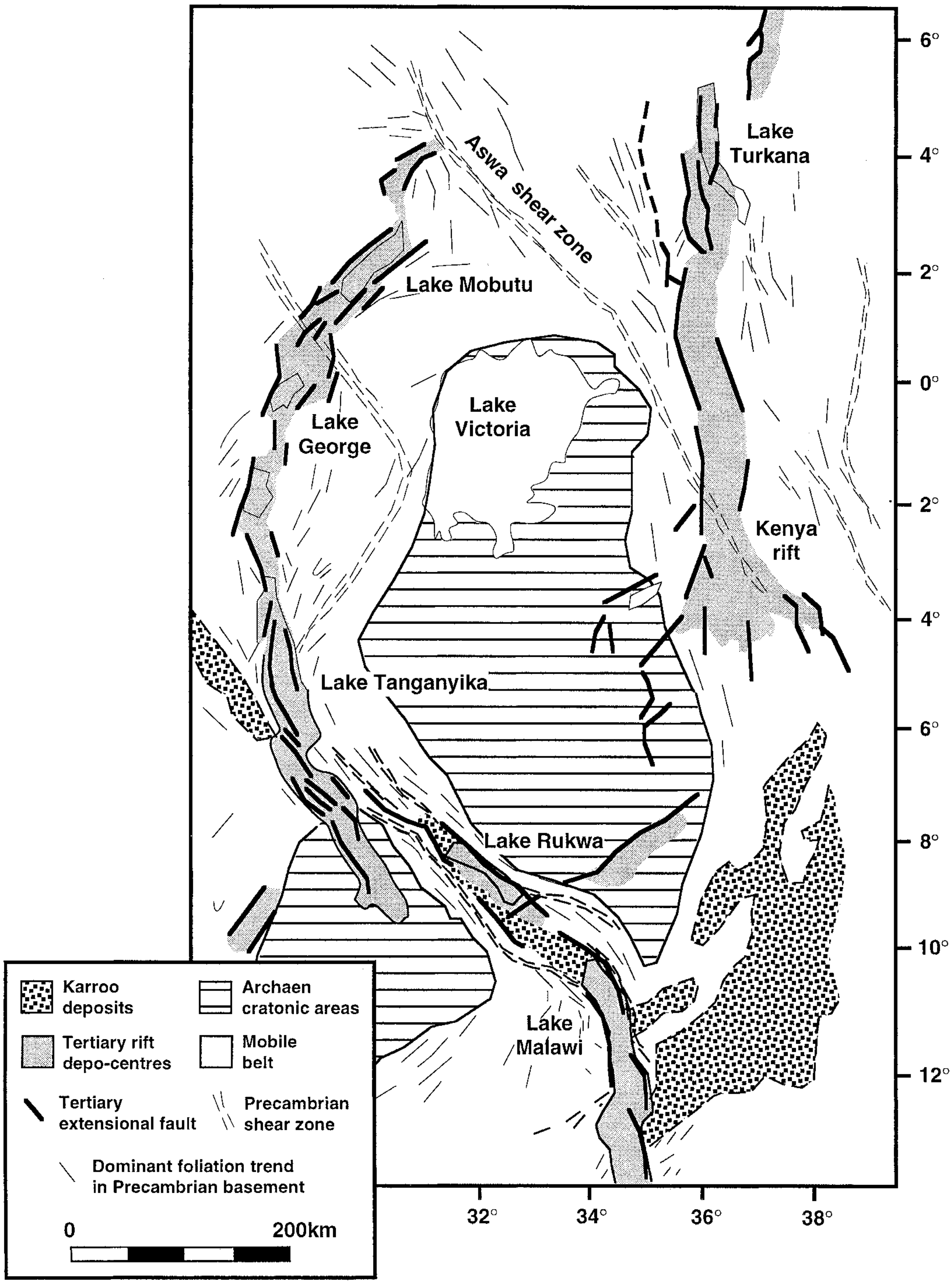

Fig. 1. Geological map of East Africa illustrating the influence of Precambrian basement fabrics on the location and geometry of the Tertiary rift system (modified from Morley, 1995).

Bonini et al., 1997). These models have focussed upon how variations in the degree of oblique extension affect the structural geometry. To do this the rift geometry is pre-defined by cutting shapes into two rigid plates that are pulled apart. In some cases a rubber strip, representing a broad zone of extension was added between the two plates (Withjack and Jamison, 1986; Tron and Brun, 1991; McClay and White, 1995). Extensional structures are then examined in layers of material (usually sand or clay) that overlie the plates. Such analogue models do bear a resemblence to some natural examples. However to appreciate what the models are showing requires an understanding of how natural examples and the models differ.

One of the important steps in modelling currently being undertaken is the investigation of pre-existing fabrics on rift structure. This note examines how far such modelling has succeeded in modelling natural examples. First it is necessary to briefly review the nature of pre-existing fabrics that affect rifts.

2. Reactivation of pre-existing fabrics

Natural pre-existing fabrics fall into two main classes: pervasive and discrete. Pervasive fabrics are present throughout a large volume of rock and impose strength anisotropy. Most commonly they comprise metamorphic rock fabrics such as slaty cleavage, schistosity and gneissic foliation. Discrete fabrics are isolated planes or zones such as fault planes and shear zones, that contrast in strength or material behaviour with the surrounding rock volume.

Rocks that display pervasive fabrics do not usually display isotropic fracture strength. For example the well known laboratory tests on the strongly anisotropic Martinsburg Slate reported by Donath (1961) showed that fracture dip and orientation were strongly linked to the cleavage orientation. Even when the dip of the faults was different from that of the cleavage the strike of both the cleavage and the fractures remained similiar. Youash (1969) demonstrated that the tensile strength of rocks loaded at 0–60° to pre-existing discontinuities is only 25–75% to that of similar samples loaded at 90°.

The East African rift system follows pervasive metamorphic fabrics in Precambrian orogenic belts. This is particularly well displayed in the western branch of the system (e.g. McConnell, 1972; Dunbar and Sawyer, 1988; Daly et al., 1989; Versfelt and Rosendahl, 1989; Smith and Mosley, 1993; Theunissen et al., 1996). For example the Rukwa rift lies at approximately 45° to the general N–S trend of the rift system, but parallel to the dominant foliation in Precambrian basement (McConnell, 1972; Ring, 1994; Theunissen et al., 1996; Fig. 1).

Discrete planes or zones of weakness exert a local influence on rift faults. Unlike pervasive fabrics, which can influence the orientation of the majority of faults in an area, discrete fabric elements tend to produce trends that are atypical for an area. If the discrete fabrics are zones of weakness then they may be re-activated in preference to the creation of new fractures in the intact country rock. The competing factors that determine whether new fractures are created or older structures are reactivated are: (1) The variations in orientation between the pre-existing fabric and the ideal orientation of new fractures with respect to the principal stress axes, and (2) the difference in strength between the intact rock and the pre-existing fabric (e.g. Ranalli and Yin, 1990).

In addition to being zones of active displacement, pre-existing discontinuities can act to inhibit fracture propagation if the frictional shear strength of the discontinuity is sufficiently low relative to the tensile strength of the surrounding material (Teufel, 1979; Teufel and Clark, 1984). In low mean stress environments the angle between the propagation direction and cross-trends is important. Fractures preferentially turn into discontinuities at low angles (30–60°), whilst propagating across them at high angles (Blanton, 1982). Hence some discontinuities may affect not only the dip and orientation of faults, but also their length.

One aspect of oblique discrete fabrics that is commonly a contentious issue in rifts is whether they acted as an 'active' through-going structure that has a unique sense of shear (effectively behaving as a through-going strike-slip zone) or whether the fabric acts only 'passively' as a local influence of fault terminations and orientations. An example of a large discrete fabric element in the East African rift system is the Aswa shear zone, which is a Precambrian mylonitic zone which trends NW–SE and intersects Tertiary extension structures in the vicinity of the central Kenya Rift. Chorowicz and Mukonki (1980) proposed that the Aswa shear zone was an active trend like a continental transform fault, as was the Tanganyika–Rukwa–Malawi oblique trend (Fig. 1). This model requires NW–SE regional extension. More recent work in the central Kenya rift, in the region on trend with the Aswa shear zone, has shown that the NW–SE-trending faults are not a linked fault system, and do not display a uniform sense of shear, hence the fabric is essentially passive (Grimaud et al., 1994; Coussement, 1995).

3. Analogue models of pre-existing fabrics

Most modern analogue models use sand to mimic the brittle upper crust (e.g. Tron and Brun, 1991; McClay and White, 1995; Bonini et al., 1997). For many experiments where isotropic rock strengths are assumed the model scaling is appropriate and produces good results. The main problem comes with trying to model situations where strength anisotropy in basement plays a role. The sand does not contain pre-existing fabrics. It is the pre-cut plates underlying the sand that contain the discrete pre-existing fabric. In such a set-up analogue models fail to closely represent natural examples for three important reasons:

1. Sand as an analogue for the brittle upper crust might scale properly and have the correct frictional characteristics, but it lacks cohesion between its

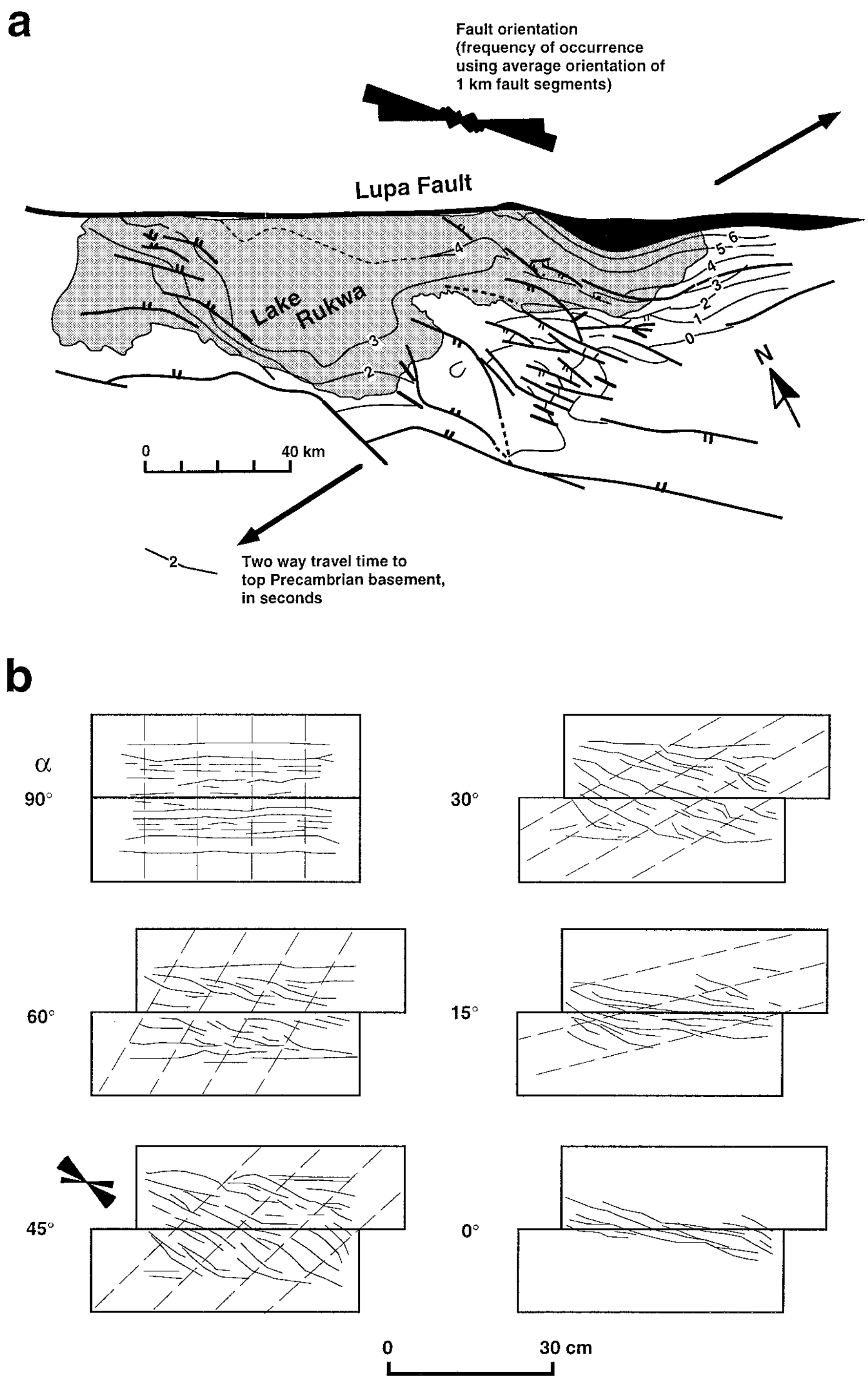

Fig. 2. (a) Structural map of Lake Rukwa (simplified from Morley et al., 1992) compared with the results of sandbox modelling. (b) Different patterns of faulting as a result of varying the angle of oblique opening (after Tron and Brun, 1991).

component grains, and cannot have any tensile strength. Conversely a rock volume buried to any significant depth has some degree of cohesion across it, and possesses some tensile strength. This is not a problem for experiments on isotropic materials, because when scaling models (commonly down to 10^{-5}) the low tensile strength can be treated as approximately zero. However it does become a problem for investigating problems concerning pre-existing fabrics in rocks because experimentally it has been shown that strength anisotropy affects the orientation and dip direction and amount of faults (e.g. Donath, 1961; Youash, 1969) which matches observations from numerous natural examples.

Consequently there is the rather paradoxical situation that the models are scaled correctly, yet sand cannot be considered as a properly scaled material for investigating problems concerning tensile strength anisotropy associated with pre-existing fabrics. There appears to be an important difference between zero tensile strength and approximately zero tensile strength.

2. In nature it is the rock forming the upper crust which contains the fabric anisotropy, while in the analogue models the pre-existing fabric is imposed at the base of the analogue upper crustal material. When a rubber sheet is used to define the location of the rift there are two possible fabric elements that play a role: The rubber sheet itself, and the sharp transition from the rubber sheet to the pre-cut plate. In the models documenting low values of oblique extension ($\alpha<60^\circ$) the fabrics oblique to the extension direction form at the rift boundaries, and originate close to the boundaries of the pre-cut plate and the rubber sheet (e.g. Tron and Brun, 1991; McClay and White, 1995). Between the oblique boundaries the fabrics tend to lie orthogonal to the extension direction. The rubber sheet does not appear to impose any oblique fabrics internal to the rift.

   One of the problems with trying to model oblique extension is that the natural examples are highly varied. Oblique extension occurs because of some anomalous and highly variable fabric associations, in this regard every oblique rift is likely to have its own particular characteristics. This can be seen in rose diagrams of fault orientations where approximately extension-perpendicular rift segments of different rifts exhibit fairly similar patterns, while the oblique segments have markedly different patterns (e.g. fig. 12 in Morley, 1995). Consequently it is difficult to define what comprises a generic oblique extension rift. Obviously there are real problems concerning how a model can be built, but this has tended to drive how oblique extension models have been made without really asking the question: What kind of pre-existing fabrics are represented by the model? For example does the rubber sheet represent a Rukwa-type oblique extension where the rift is associated with a pervasive fabric, or an oblique rift formed due to a few discrete fabric elements such as the central Kenya rift (e.g. Chorowicz and Mukonki, 1980; Coussement, 1995; Le Turdu et al., 1995)?

3. Natural rifts develop where there is commonly a variety of pre-existing fabric orientations, locations and types. Some oblique fabrics are used, others are ignored. In natural rifts the fault pattern is a result of the orientation of the regional stresses, the local re-orientation of the stresses by active structures within the deformed zone, and the interaction of fabric elements within the brittle material. In the analogue models the pre-cut plates may affect the local stress orientations in a way that is completely unlike the natural examples, and is simply too dominant. The pre-cut plate will re-orient stresses via the base of the sand layer, not from within it.

3.1. An example of an oblique extension: the Rukwa rift

The basic models of transfer zones and oblique extension using simple analogue models (e.g. Withjack and Jamison, 1986; Serra and Nelson, 1988; Tron and Brun, 1991; McClay and White, 1995; Bonini et al., 1997) have been explored, and despite their drawbacks do offer useful insights into rift geometries and kinematics. One reason for citing the Rukwa rift here is that its Tertiary kinematic evolution has proven controversial, ranging from pure strike-slip motions (e.g. Chorowicz and Mukonki, 1980; Scott et al., 1989) to oblique extension (e.g. Morley et al., 1992), and more recently to dominantly oblique extension but a short phase of strike-slip motion (e.g. Delvaux et al., 1992; Ring et al., 1992). During the earlier stages of the controversy I hoped that the results of analogue modelling would help demonstrate the Rukwa fault pattern was characteristic of oblique extension of about 45–30°, and indeed there does seem to be a good correspondence (Fig. 2), which suggests strongly oblique extension. However I remain concerned as to whether the fabric elements controlling the model are really similar to those controlling the pattern in Lake Rukwa, and whether it is coincidence or a fundamental oblique extension geometry.

The major boundary fault in the late Tertiary Rukwa rift is the Lupa fault. It reactivates a Late Palaeozoic age fault (discrete fabric) which in turn follows (pervasive) Precambrian metamorphic fabrics. In the modelled boundary, faults are somewhat similar since they are also located at a discrete fabric element (rubber sheet–rigid plate boundary). The problem lies in understanding the pattern of the secondary faults in the models: for up to $\alpha = 45^\circ$ oblique extension, they lie perpendicular to the extension direction, hence appear to not be influenced by pre-existing fabric. At $\alpha = 30^\circ$ and less, they lie at an acute angle to the boundary fault and non-orthogonal to the regional extension direction, in effect they form Riedel shears whose orientations are not affected by pre-existing fabric.

The question that remains for the Lake Rukwa example is: Do the secondary fault orientations represent (1) a Riedel shear orientation or (2) the underlying trend of Precambrian foliations? From the trends in surrounding Precambrian outcrops the answer is that the faults tend to follow Precambrian foliations. Hence the similarity between modelled and natural patterns is largely coincidental.

The following conclusions may be drawn from comparison of modelling results with natural examples:

1. Only discrete pre-existing fabrics have been modelled.
2. Pervasive fabrics that commonly form the dominant fabric element in oblique rifts have not been included in models.
3. The models therefore represent oblique extension with the passive fabric influence and most discrete fabric influences stripped out, consequently they are dominated by the following trends:
   (a) For $\alpha = 90–30^\circ$ any fault in an oblique rift that is not influenced by pre-existing fabrics will tend to lie sub-orthogonal to the regional extension direction.
   (b) For $\alpha = 30–0^\circ$ any fault in a highly oblique rift that is not influenced by pre-existing fabrics will tend to adopt the primary strike-slip fabric orientations (usually dominated by Riedel shears).

These are useful results from analogue models, but I do not believe they have been stated in this way before because the nature of the pre-existing fabrics has not been critically discussed. The models produce a fault population whose orientation is predominantly not influenced by pre-existing fabrics, while in natural oblique rifts it is the converse. Natural oblique rifts only exist due to the dominant influence of pre-existing fabrics.

4. Discussion

If a more effective means of modelling a variety of pre-existing fabric types can be developed a wide range of problems could be tackled. For example, in areas such as the central Kenya Rift certain surface fault patterns are being used to infer the role played by pre-existing fabrics (e.g. Coussement, 1995; Le Turdu et al., 1995). It would be very helpful to have a range of analogue model data to show what kind of underlying fabrics can produce the surface patterns. First it would be necessary to define differences in structural style according to whether the underlying fabrics are passive or active. While active fabrics might be simulated using pre-cut forms underlying the rift, passive fabrics cannot be simulated in this way. Passive fabrics can only be simulated by finding a way of imposing strength anisotropies on the sand layers, or clay cake. While the task of imposing strength anisotropy on the modelling materials is clearly difficult, there would seem no other way forward.

Some contentions about the role of pre-existing fabrics are difficult to prove using only natural examples. For example, Morley (1996) suggested that the relatively simple fabric patterns of East Africa permitted longer, more widely spaced dominant faults to form, in comparison with those in parts of the North Sea where more complex fabric patterns could have led to shorter, lower displacement dominant faults and more closely spaced minor faults. Analogue models testing whether pre-existing fabrics can exert such influences on fault length, spacing and displacement would be very valuable, but clearly requires building discrete and pervasive fabric strength anisotropy into the material layer.

With regard to how the change in modelling techniques can be achieved, it unfortunately seems easier to criticize the existing models than to provide an easy solution. Scaling the fabric elements to geological conditions is clearly a problem, as would be getting fabrics aligned within a cohesive material. Maybe within clay, mica flakes could be used, or thin, flat magnetic flakes, that could be aligned by a magnetic field. Scaling might not be perfect, but then so much less so is the present solution.

Numerical models provide another avenue for investigating pre-existing fabrics, although currently models of any real complexity are difficult to formulate and too intensive on computing power. Progress has, however been made, for example a simple two-dimensional finite element model for fractured pervasive fabrics has been developed by Patton and Fletcher (1998) and for discrete fabrics (fault reactivation) by Ferrill et al. (1998). Models of fault linkage and propagation (e.g. Cowie, 1998) potentially offer another mode of investigation, which emphasizes the early development of faults where the elastic behaviour of rocks needs to be considered. Cohesionless sand has no elastic response, so an important part of the the influence of pre-existing fractures on early fault development might be missing from the analogue models.

5. Conclusions

Analogue models of rifts, in particular those investigating transfer zones and oblique extension recognize and try to take into account the important role of ‘pre-existing’ fabrics on rift structure. Perhaps one flaw is trying to use a general case pre-existing fabric, without specifying the real nature of the fabric that is being modelled, i.e. is the fabric intended to be pervasive (represented by the rubber sheet?) or discrete (represented by the change from a rubber sheet to a rigid board?). They all use a pre-cut form in underlying rigid plates to define the pre-existing fabric, and deform an overlying material layer that has isotropic strength. This model fabric corresponds most closely to a discrete type of fabric in nature. To more effectively model natural examples it should be the material layer that contains the strength anisotropy.

The main conclusion of this note is to suggest that rift analogue models using the traditional methods have already been taken as far as they are useful. In assessing the applicability of the models it is necessary to appreciate the range of likely responses from different fabric types. Further experiments using rigid plates to define pre-existing fabrics the rift structure may not produce more useful data because they are too different from the origins of natural pre-existing fabrics (excepting discrete active fabrics). There remains much useful work to be done using analogue models to explore the influence of pre-existing fabrics, but it requires building fabric anisotropy into the material layers, not the rigid plates. While this is not a trivial problem to solve, it would seem to be the best way forward.

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