Crustal attenuation in Afar

by

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With 9 figures in the text

Abstract: The extensive exposures of pre-Miocene continental crustal rocks within Afar pose serious problems in relation to the extent of probable oceanic crust in the Red Sea and Gulf of Aden. Geophysical evidence indicates that these regions of continental crust are much thinner than normal, while surface exposures are characterised by fields of strongly tilted blocks. A hypothesis for the mechanism of such crustal attenuation is presented, which involves normal faulting with block tilting of the upper crustal layers and ductile deformation of the lower layers, with a gradational transition zone. In addition to complying with known data on rock deformation the hypothesis takes account of the fact that crustal attenuation is a progressive process through time. A simple approximate relationship between bedding dip angles and the amount of attenuation is derived for comparison with the results of geophysical work.

Afar – The problem of the fit

The existence of significant outcrops of pre-Miocene sialic rocks within Afar (Fig. 1) poses problems of palaeo-reconstruction if it is accepted that much of the Red Sea and Gulf of Aden are floored by oceanic crust. Furthermore our field observations in the Aisha region, the southern Danakil Alps and at several localities along the marginal escarpments indicate that the younger post-rift volcanics and sediments usually rest on the older sialic rocks with subhorizontal or gently dipping unconformity. This suggests that the total extent of sialic rocks within Afar is considerably in excess of their surface outcrop, even if it cannot be accepted that they underline the greater part of the Afar floor (cf. Black et al. 1972b).

Geophysical and geological evidence

The gravity and seismic evidence presented to date (Makris et al. 1972, Searle & Gouin, 1971, and the contributions by Makris et al., Ruegg, and Berckhemer in the present Symposium) does not resolve the question of how much of Afar is floored by oceanic crust, but does clearly indicate that both within and outside the areas of exposed sialic crust the crustal layers are much thinner than under the plateau regions. The most pronounced thinning occurs near the axial volcanic ranges in the north and in other regions covered by younger volcanics; parts of these areas are probably underlain by oceanic crust. Areas with exposed sialic rocks generally show crustal thicknesses intermediate between the younger volcanic areas and the adjacent plateaus, on the rift margins there are gradations in thickness up to the plateau values.

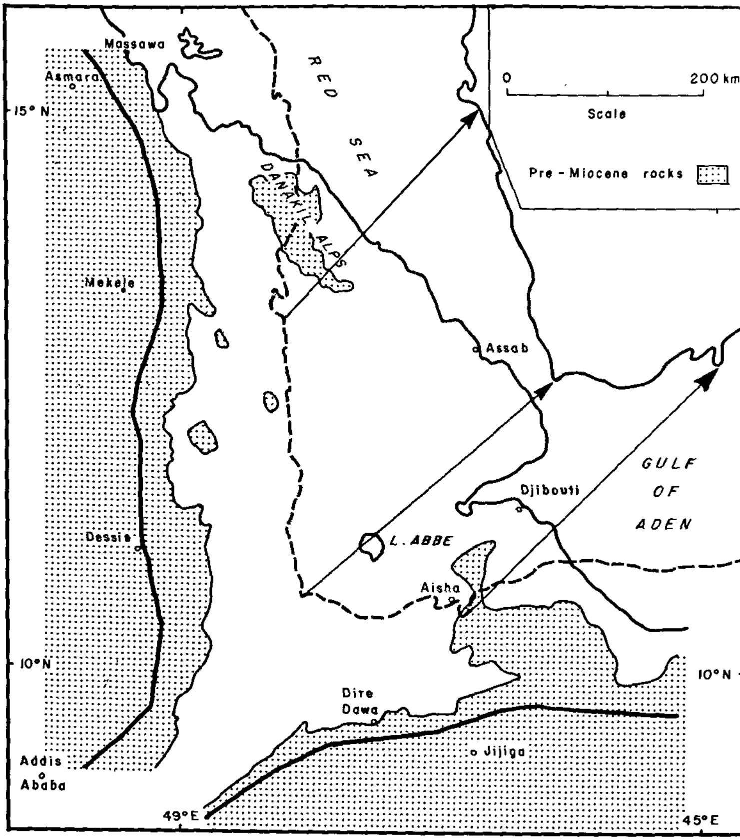


Fig. 1. The Afar. Heavy lines mark the approximate outer limits of rift faulting. The pre-drift position of Arabia is that suggested by Laughton (1966b) on the basis of the probable extent of oceanic crust in the Gulf of Aden. Geology from the Geological map of Ethiopia (Kazmin 1973).

The areas of pre-Miocene rocks exposed within Afar are all intensely faulted by normal faults, and the blocks between the faults are strongly tilted. Typically a series of faults up to a kilometre apart, all or nearly all with the same direction of throw, separate a series of tilted blocks with beds dipping in the opposite direction to the faults. On traversing such areas the same geological sequence may be repeated on each successive fault block. Figs. 2 and 3 illustrate sections from the southeastern and western margins of Afar. Often the dip angles are similar on successive blocks, and fields of tilted blocks with dip angles up to 40° are commonly observed. In the Danakil Alps and east of Maichew angles up to 60° are observed. Locally the dip angles are more variable from block to block and extreme dip angles of up to 90° have been recorded. The fault planes sometimes intersect the bedding at angles of 60 – 70°, but more commonly in areas of steep dips faults perpendicular to bedding are ob-

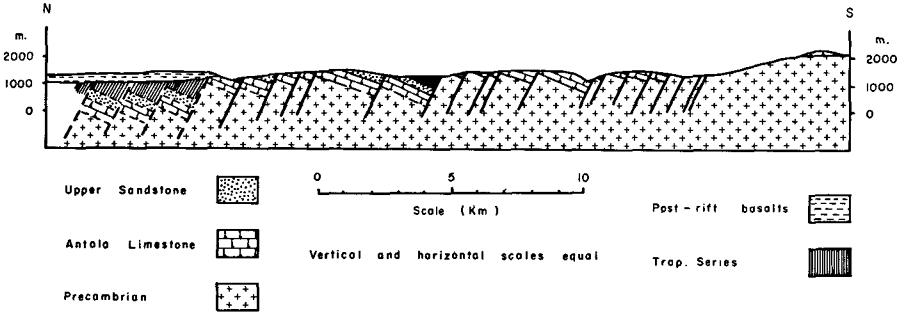


Fig. 2. Cross section of the southern margin of the Afar through a point 3 km east of Dire Dawa. Dips of fault planes could only be determined at a few localities, for this reason all faults are drawn with uniform dips in the section.

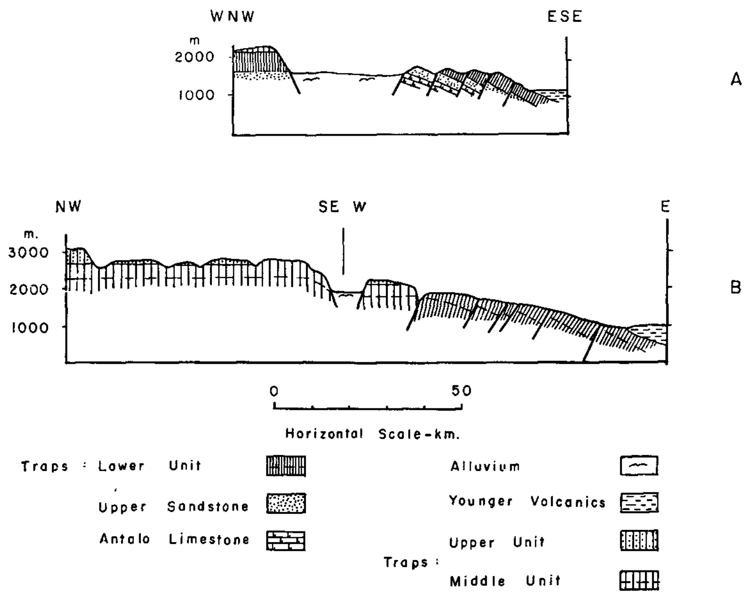


Fig. 3. Cross sections of the western margin of Afar. A – through Corbetta and Mt. Cercer at 12° 50'N.; B – through Magdala, Dessie, Kombolcha, Batie at about 13° 10'N. Redrawn after Abbate & Sagri (1969). Topography with 10x vertical exaggeration, but true dips of structures shown.

served. In areas of strongly tilted blocks the faults may dip at only shallow angles or even show a horizontal attitude. On the escarpments flanking the Afar bedding dip angles often increase progressively from the plateau towards the depression, the escarpment regions being characterised by a series of step faults rather than by the large master faults typical of many continental rifts, notably the crevice type of continental rift (Milanovsky 1972).

Hypotheses and constraints

While it is evident that fields of normally faulted, tilted blocks are formed by extensive processes, the manner in which the faults are accomodated at depth remains a problem. From a geometrical viewpoint two solutions have been proposed. Firstly, the fault planes are essentially fixed and strongly curved; the block movement is then analogous to a landslip due to removal of support in front of the block. Secondly, if faulting takes place on a series of subparallel straight or curved fault planes, progressive movement causes rotational tilting of both the blocks themselves and the fault planes bounding them (Thompson 1971). Hamblin (1965) has demonstrated that tilting, or reverse drag is associated with fault planes in the Grand Canyon region, but such a mechanism raises problems where extensive fields of steeply tilted blocks occur. This is shown by Anderson (1971) in his description of part of SE Nevada where the geometry of curved fault planes seems to require their convergence in a subhorizontal zone of décollement at a depth of a few kilometres. Movement along such subhorizontal fault planes most probably requires high fluid pressures to overcome frictional drag between the two surfaces (Hubbert & Rubey 1959), but in an area of extension tectonics it seems unlikely that such high pressures could develop. Furthermore since gravity appears to be the only driving force for the faulting, areas of block tilting where the faults dip towards the higher plateau regions cannot be explained by such a process. Concommitent rotation of the blocks and fault planes is seen in extension experiments illustrated by Cloos (1968). An important limitation to this process is that, once again, further fault movement becomes difficult when the attitude of the fault plane becomes subhorizontal.

Marinelli (1971) has suggested that crustal attenuation in the Afar margins occurs by faulting and block tilting in the upper crust, while ductile deformation occurs at depth. This is in accord with the work of Griggs et al. (1960) and others who have demonstrated that ductile behaviour in rocks, as in most other materials, is enhanced by high temperatures and confining pressures, i. e. that it increase with depth in the crust. Furthermore under conditions where ductile behaviour is exhibited, steady state creep without sudden failure can occur at strain rates less than a certain value. This upper limiting value of strain rate increases rapidly with temperature. This means that in a homogeneous crust undergoing extensive strain there will be a certain depth below which ductile behaviour occurs, and above which elastic strain is periodically released by faulting. This depth will increase with increasing strain rate, in a homogeneous crust the gradual onset of deformation will lead to the initiation of fault planes at the top of the crust, and their propagation downwards as the strain rate increases. In a real crust, such as that around Afar, the Mesozoic and Tertiary cover is probably far more ductile than the underlying metamorphic Precambrian, so that faulting is likely to initiate at the top of the Precambrian and propagate both upwards and downwards. In the less brittle cover formations and deeper in the crust, faulting will probably be preceded by ductile shear folding. A continuous downward propagation of fault planes with increasing strain rate should occur in the absence of abrupt discontinuities of mechanical properties at depth in the crust.

A hypothesis for crustal extension of a continental margin, with ductile deformation of lower layers accompanied by normal faulting with graben formation in the upper layers, was proposed by Bott (1971). He considered that faulting would be limited in depth by a brittle/ductile transition at a depth of about ten kilometres. While the absence of deep focus earthquakes in regions of extension tectonics certainly implies that faulting is confined to perhaps the upper 30 km. of the earth, the actual depth to which faults will extend is difficult to determine, and will in any case vary with rock type, strain rate and the geothermal gradient. Even if a realistic strain rate is postulated and a certain geothermal gradient assumed, there is little data available on steady state creep in silicate rocks, and all data must be considerably extrapolated to predict behaviour at geological strain rates some 10^6 times slower than laboratory experiments. Furthermore the existence of discrete fault planes in the upper crust will cause strain rates in the layers immediately beneath to be variable, with maxima close to the ends of the fault planes. Faults will therefore extend rather deeper than would be predicted from overall strain rate value.

In formulating a hypothesis for crustal extension with accompanying block tilting we have sought a solution compatible with both the observations and theory described above and the following constraints:

1. Crustal attenuation must be a progressive process, and at any time the faulting and ductile movements occurring must be geologically feasible ones. Thus while we would agree with Hafner (1951) that the orientation of the stress ellipsoid may change with depth, leading to a flattening of faults deep in the crust, we cannot accept a model which requires major movements along subhorizontal fault planes at any stage.
2. For simplicity we will assume that ductile strain near the base of the crust is purely extensive; i. e. simple shear does not occur parallel to the crustal layers. This means that provided gain or loss of material by igneous intrusion does not take place, all crustal layers will suffer the same amount of proportional thinning.

A possible mechanism and its implications

These considerations lead us to a hypothesis for crustal extension illustrated in fig. 4. Due to the uncertainties concerning the depth to which faulting extends outlined above it is impossible to give a precise scale to the figure, but the depth would be of the order of 10 – 30 km. and vertical and horizontal scales are equal, so that true dips are shown. This hypothetical model has the following implications:

a. There is a progressive transition with depth from faulting to ductile deformation with no abrupt zone of decollement.
b. During attenuation, rotation of both bedding and fault planes takes place, initially steep fault planes becoming shallower with time.
c. Neglecting the effects of erosion, deposition, intrusion and warping due to differential vertical movements, a direct relationship is implied between the bedding dip angle of the fault blocks and the amount of crustal attenuation.

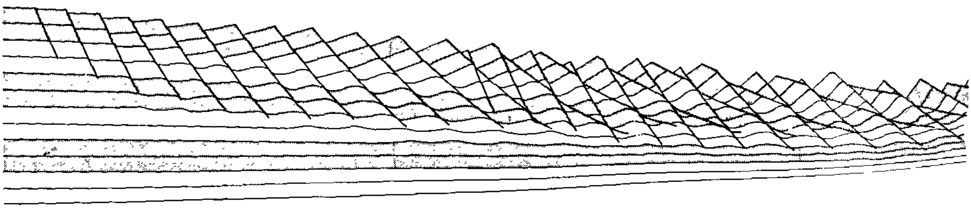
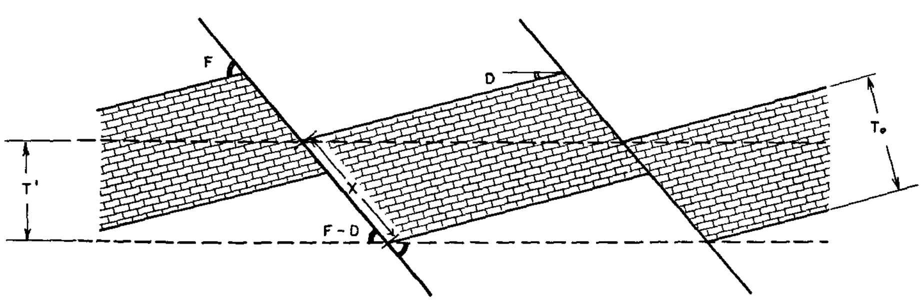


Fig. 4. Hypothesis for crustal attenuation. Progressive thinning takes place with time, a similar pattern of increasing attenuation may occur spatially between plateau and Afar floor.

This relationship is illustrated in fig. 5, 6 and 7. If all the attenuation was accompanied by movement on the initial set of normal fault planes dipping at 60 – 70° relative to bedding, block tilting to bedding dip angles of 60° would imply not only that movement was occurring on subhorizontal fault planes, but also that the crust had reached almost zero thickness. Both geological and geophysical evidence indicate that this is not the case. What appears to happen is that once bedding dips exceed about 20–30° the initially vertical joint surfaces present in most areas reach an attitude more favourable for normal fault movement than the original fault planes, which are now inclined at angles around 40° or less. Because of the dense spacing of joint surfaces faulting now becomes active on a large number of planes and many of the faults actually seen in the field are of this type. In an earlier paper (Black et al. 1972b) this observation led us to conclude that faulting had been initiated on these surfaces from the start. We now believe this is unlikely (cf. 1, above) and that these are



$$X = \frac{T_o}{\sin F} \qquad T' = X \sin(F - D)$$

$$\therefore \quad T' = \frac{T_o \sin(F - D)}{\sin F}$$

Fig. 5. Geometric relationships of crustal attenuation by block tilting. If fault planes were initially vertical this relationship would reduce to $T' = T_O \cos D$.

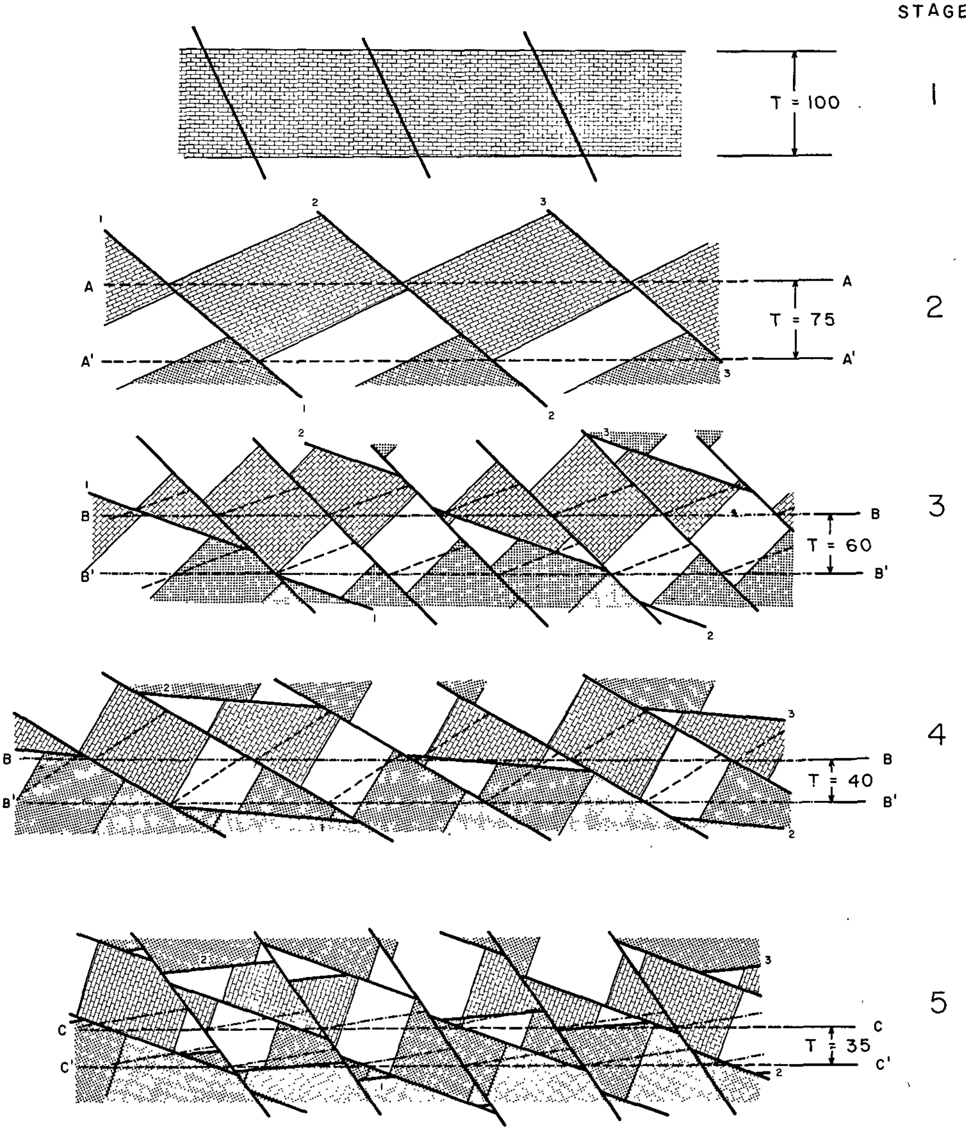


Fig. 6. Progressive block tilting. Following rotation on the initial set of fault planes joint surfaces perpendicular to bedding become favourably oriented for further fault movement. During this second phase of faulting the amount of attenuation can be obtained by considering the effects of faulting and rotation on the layer between the lines A–A and A' – A' (stage 2). Similarly in stage 5 the effect of faulting and rotation on the layer between B–B and B'–B' is considered. The mean thickness of any unit (T) is reduced from 100% (undeformed) to 35% in this example.

the second generation of faults. Because block tilting can occur by successive movement on two or more fault planes, bedding dip angles of up to 60° or more are reached with a crustal thinning of little more than 50% (fig. 6). This figure also illustrates how a third set of normal fault planes may be initiated as the angle of block tilting exceeds about 60°; this is rarely observed in practice. The curves in fig. 7 represent the dip/crustal thickness relationships derived from the preceding figures. In view of the practical problems of ascertaining the initial dip of the first faults, and of knowing the bedding dip angles at which movement was transferred to the second or third sets of faults, only an approximate derivation of the amount of crustal attenuation is possible. For this purpose the simple straight line relationship:

$$100\,T' = T_o\,(100 - \text{Dip}^{\circ})$$

(where T' is present crustal thickness, T_o original crustal thickness, and bedding dip is measured in degrees) gives a remarkably close fit to the data for dip values of up to

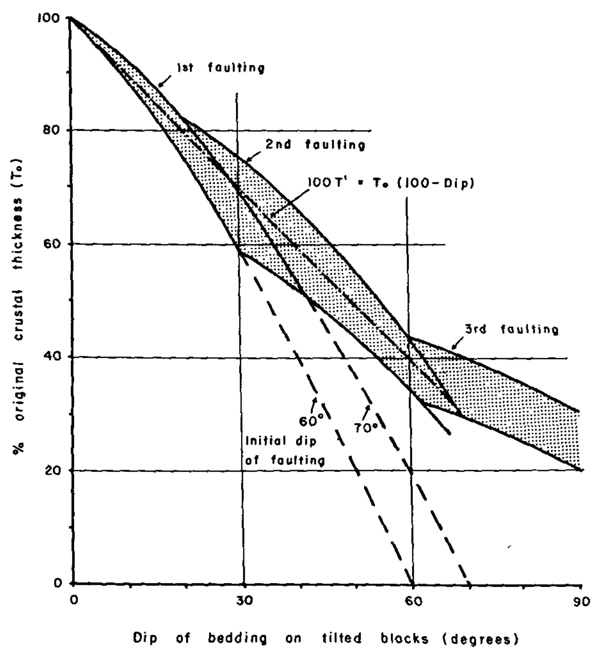


Fig. 7. Relationships between bedding dip and amount of crustal attenuation due to progressive movements, in the same sense, on up to three sets of parallel or subparallel fault planes. Attenuation is expressed as a percentage of initial crustal thickness using the relationship derived in Figs. 5 and 6. Since the precise relationships depend not only on bedding dip angle, but also on the initial dip of the first fault planes, the bedding dip angle at which movement becomes transferred to the joint surfaces (second faults) and the time of initiation of the third faults and their dip, there will be a range of possible thickness values for any given bedding dip angle. The shaded region of the graph covers the range of most probable dip/thickness relations.

60°; higher dip values being encountered rarely. In fact the values obtained using this relationship will be conservative, since it has been assumed that the successive generations of faults will share the same direction of downthrow and possess similar strike directions. In the high proportion of cases where sets of near perpendicular joints exist the second faults will have the same direction of throw as the first; this need not be so for the third set however. A new set of faults with the opposite sense of throw will cause the blocks to rotate back towards the horizontal again. Major changes in strike direction between early and later faults have been observed in several parts of Afar, e. g. the Aisha area (Black et al. 1972b).

Sudden bedding dip changes between adjacent fault blocks are observed at many localities in Afar. They may result from the type of mechanism proposed here, where sets of faults with opposing dips and directions of throw interfinger. The geometry of such interfingering is complex and we have not attempted any analysis. Equally we see no reason why a mechanism such as the one proposed here should exclude local formation of strongly curved fault planes which may better explain such rapid changes of dip. Our attention has been drawn to one type of sudden dip change however; this

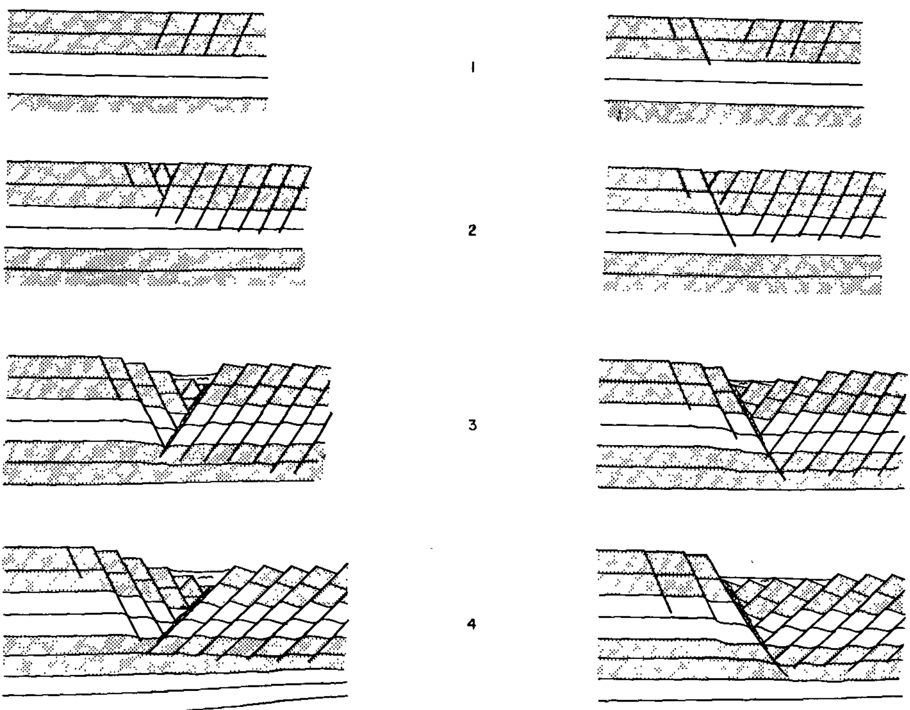


Fig. 8. Two possible modes of development of a marginal graben, following the hypotheses of crustal attenuation presented in this paper. Compare the cross sections of Fig. 3.

is observed along part of the western margin of Afar where fields of tilted blocks dipping towards the depression at angles of 20 – 60° are separated from the plateau to the west by a marginal graben some 10 km. in width with a sediment infilling (Fig. 3). Further to the south the blocks are tilted towards the depression at angles of 10 – 20° or less and the marginal graben is absent. Fig. 8 illustrates possible modes of development of such a marginal graben according to our hypotheses (cf. Marinelli 1971).

Fig. 9 is a preliminary attempt to provide estimates of crustal thickness in the exposed areas of sialic rocks within Afar. Comparison with Figure 1 shows a considerable alleviation of the space problem if these estimates of attenuation are valid, because the area occupied by a section of crust will increase in inverse proportion to the amount of attenuation.

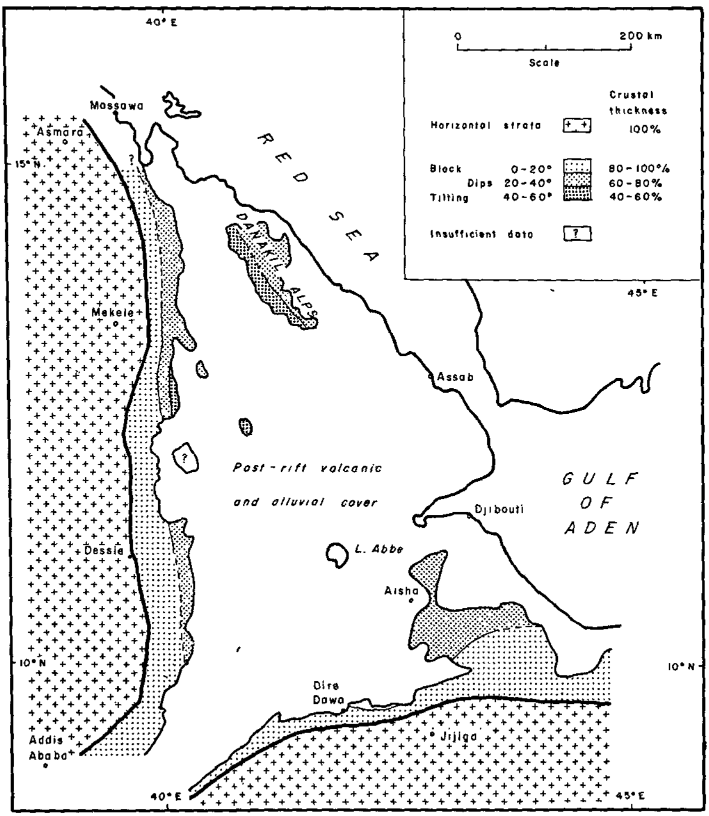


Fig. 9 Application of the dip/crustal thickness relationship derived from Fig. 7 to the outcrops of sialic crustal rocks within Afar.

A considerable amount of further work is needed to test the hypotheses presented here, in particular comparison with geophysical results, detailed field examination of faulting and laboratory work with models. Much previous work with models, from the pioneer work of Cloos (1930) onwards, has used media with homogeneous mechanical properties; whereas a variation of mechanical properties with depth is required.

Acknowledgements

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Complete literature at the end of the volume, p. 391–416