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Tectonics of the lower crust: a view from the Usambara Mountains, NE Tanzania

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Abstract—In the Pare and Usambara Mountains, NE Tanzania, approximately 4000 km^2 of granulites display regular moderate northeast dips of layering and foliation and down-dip plunge of pervasive stretching lineation. Folds, other than scarce tight microfolds, appear to be absent; thrusts, only mapped in the North Pare Mountains, are probably numerous elsewhere. The granulites pass up, without any evidence of stratigraphic, structural or metamorphic break, into slightly lower-grade metasediments, including conspicuous marbles. These rocks show major tight folds. Comparison with the Turoka Fold in south Kenya, here re-interpreted as a sheath fold, supports interpretation of the stretching lineation in the Usambara granulites and overlying metasediments as the transport direction, transverse to the N–S Mozambique Belt. The regional lineation pattern indicates correlation of the transverse Usambara and Turoka lineations with those transverse to the Mozambique Belt farther north in Kenya. These are dated at ~830 Ma; it is concluded that the Usambara stretching lineation, foliation and associated structures were also formed at that time. The fabrics show that this intense deformation took place in granulite facies conditions. The gradual change from their intense planar and linear deformation to the slightly more inclined fold and thrust deformation in the overlying metasediments is interpreted as implying an initially nearly flat shear zone in the lower crust during the Mozambique Belt orogeny; continuing movement imbricated and refolded the initially flat foliation, giving the northeastward dip across the granulites. The curved trend of the stretching lineation through the Usambara Mountains is attributed to strains during the late Mozambiquian deformations.

INTRODUCTION

THE Usambara and Pare Mountains in NE Tanzania (Fig. 1) expose one of the largest (*ca* 4000 km^2) of a series of areas of granulites within the Upper Proterozoic Mozambique Belt (Holmes 1951) of Tanzania. This particular area of granulites is of special interest because it displays regularly dipping planar structures, attributable to deformation in the lower crust, almost unaffected by the later shear belts, upright folds and other late Mozambiquian deformations which complicate most of the Mozambique Belt. Along the northeastern side of the mountains, these lower crustal structures can be seen to pass up, gradually and without a break, into quite different mid-crustal structures. This discussion is based partly on a short visit to the Usambara Mountains and on previous work elsewhere in the Mozambique Belt, but mainly on interpretations of previously published maps, especially 1:125,000 sheets 73, 89, 90, 108 and 109 of the Tanganyika (now Tanzania) Geological Survey and reports and maps of the Kenya Geological Survey (Fig. 2; see also Fig. 3c). Such interpretation is needed because it was the policy of the Tanganyika Geological Survey that their geologists should spend their time in the field, mapping: very little supporting laboratory work was done, and explanations of the geology were limited to summary marginal notes, and no sections, on the maps. Little work has been published on the area since the mapping in the 1960s. Exposures in the Usambara Mountains are good, with excellent clean faces on recent road cuts on the Mombo–Lushoto road; exposures of the overlying metasediments on the Umba Steppe northeast of the mountains are much poorer.

STRUCTURES IN THE USAMBARA GRANULITES

Mapped structures, apart from many later faults, are conspicuously absent in the Usambara Mountains. The appearance of simplicity is such that the area was once cited as an example of non-orogenic high-grade metamorphism (Harpum 1970). The layering and foliation dip rather uniformly, mostly at between 15° and 30°, towards the northeast. Marker horizons, more mafic than the surrounding granulites and probably originally dolerite sills, are mapped continuously, apart from later fault displacements, for many kilometres without interruption by thrusts or reversals by folds; for example, a group of four or five of them can be followed for over 30 km along the western escarpment of the Usambara Mountains (Fig. 2). Occasional thin bands of marble, graphitic and psammitic gneiss follow the same strike. Some folds, both tight and open, appear nearer the structural top of the granulites. As soon as one looks at the outcrops, intense deformation is obvious. The foliation, marked by flattened and elongated mineral aggregates and grains, is parallel to the compositional banding. There is a pervasive lineation on the foliation surfaces, marked by elongated minerals (hornblende, sillimanite) and mineral aggregates, especially quartz and also pyroxenes. Tight to isoclinal microfolds are not common, but can be seen in some of the road cuts; some of them have a strong axial plane foliation. The plunge of the lineation is very constant towards the northeast; the plunge of the microfolds is in the same general direction and here, as in most areas of the Mozambique Belt in Tanzania and Kenya, the lineation has generally,

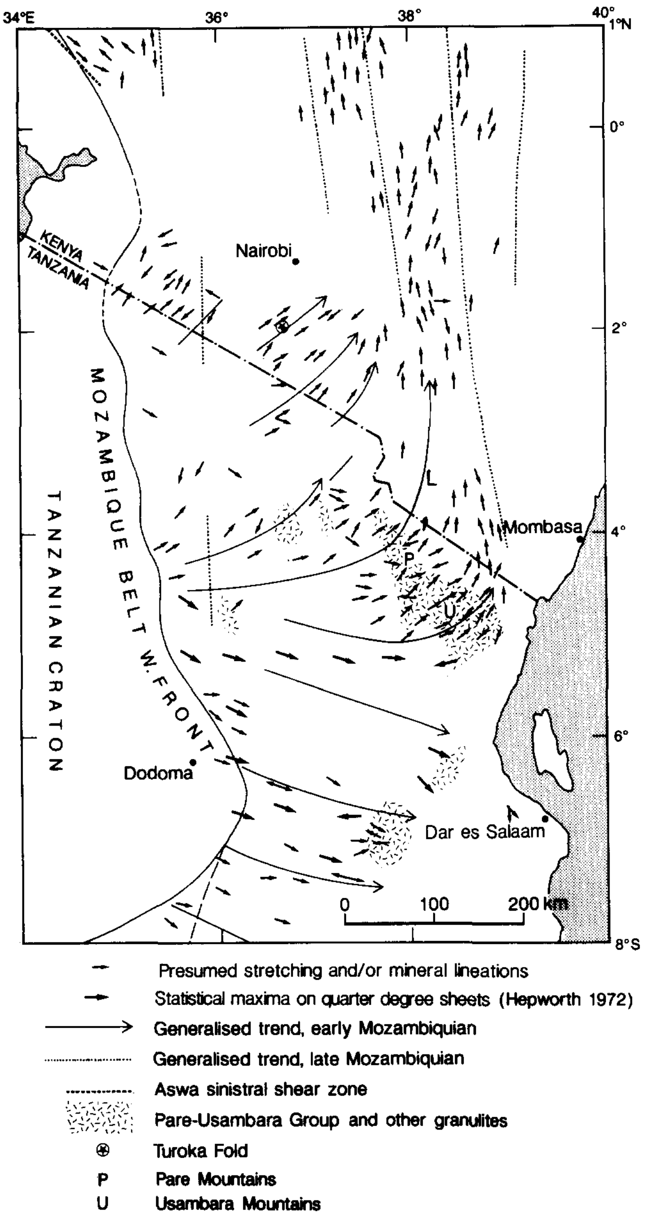

Fig. 1. Map of the stretching lineations in the Mozambique Belt of Kenya and Tanzania based (see text) on maps published by the Geological Surveys of Tanzania and Kenya (on which lineations are not usually specified as stretching lineations); Weiss (1959), Saggerson (1962), Hepworth (1972) and author's observations in Kenya and Tanzania.

though not always, been interpreted as parallel to the fold hinges, particularly after a detailed structural study by Weiss (1959) of the Kajiado area in Kenya. My own data from the Mombo–Lushoto road cuttings in the Usambara Mountains (see Fig. 2) showed a spread in trend of 17 stretching lineations of 28° (from 046° to 078°, mean 062°), while plunge directions of 14 recumbent isoclinal minor folds showed a spread of 82° (022°–104°, mean also 62°). The three-dimensional geometry of these folds could not be seen. The data are consistent with, but of course insufficient to prove, a sheath fold interpretation (discussed below). Some of the folds are associated with shear zones along the foliation. Extension is also shown by boudinage of mafic lenses, probably originally sills or dykes. In one lens, the trend of two boudin axes was about 140° and the NE–SW extension by boudinage was large (≫100%); the extension by separation of the lenses themselves was much greater. Small extensional ductile and semi-brittle extensional shear zones and faults are not rare; no statistically significant preferred orientation was recognised from the small number measured. One small extensional fault is cut by a pegmatitic vein with the bluish-grey feldspars typical of granulite-facies metamorphism, showing a late extensional phase while still in granulite-facies conditions.

RELATION OF USAMBARA STRUCTURES TO THOSE IN THE OVERLYING METASEDIMENTS (UMBA STEPPE GROUP)

Metasediments of the Umba Steppe Group (Bagnall 1964) outcrop on the plains northeast of the Usambara and Pare Mountains. They are distinguished from the Pare–Usambara Group granulites in containing more conspicuous and thicker crystalline limestones, associated with graphitic schists and psammitic gneisses, the absence of mapped mafic sheets, in their slightly lower grade of metamorphism (upper amphibolite facies) (Bagnall 1964) and in their structures, as discussed below. There is, however, no evidence of any stratigraphic, structural or metamorphic discontinuity between the two Groups and no boundary is drawn between them on the published maps. The boundary shown on the map, Fig. 2, and section, Fig. 3, is arbitrarily drawn at the base of the lowest major crystalline limestone. A more indefinite but similar line, usually slightly lower structurally, would be obtained by plotting the upper limit of pyroxene granulites, except for two outcrops of pyroxene granulite (at 38°4′E, 4°30′S and 38°38′E, 4°17′S), structurally above the lowest limestone. The clearest evidence that granulite facies metamorphism is not restricted to the Usambara granulites but in some places extends into the Umba Steppe Group comes from the direct northward continuation of the Group at Lualenyi, SE Kenya (L on Fig. 1), where a graphitic marble contains vanadium grossular garnets which indicate granulite-facies conditions (Key & Hill 1989). The Umba Steppe Group is correlated (Bagnall 1964) with the Masai Steppe Group on the opposite, southwest side of the Pare and Usambara Mountains; their equivalents cover large parts of the Mozambique Belt of Tanzania and Kenya (Shackleton 1986, fig. 4). Farther west in Tanzania, the metasediments also seem to reach granulite facies (Hepworth 1972).

Despite the poor exposures, tight major folds are obvious on the map (Fig. 2) and on NW–SE sections normal to the lineation plunge (Fig. 3a). Few associated thrusts have been mapped, but repetitions and discontinuities imply that more must exist. The axial traces of the folds trend about N–S, consistently oblique to the lineation plunge: the axial planes are gently to moderately inclined to the east. Their three-dimensional geometry is not clear. In places, superimposed folding produces mushroom-shaped outcrops (Type 2, Ramsay 1967, p. 351), e.g. at 38°37′E, 4°28′S (Fig. 2).

Foliation and lineation trends are similar to those in the Usambara granulites, the gradual swing towards a more northerly plunge of lineation continuing—see Figs. 1 and 2, which show representative values; many more are shown on the published maps of the area, 1/4 Degree Sheets 89 and 90. Oriented thin sections of one rock (P.S. Bagnall colln., 461) from the North Pare Mountains (~37°50′E, 4°05′N) showed spindle-shaped lenses of clear, slightly strained quartz mosaic in a fine-grained matrix of oligoclase, quartz and small biotite flakes with antiperthitic porphyroclasts. The quartz lenses, measured in sections normal to X, Y and Z, showed $X{:}Y{:}Z = 30{:}2{:}1$. The original nature and shape of the lenses is not known, but it is clear that there has been a very large extension parallel to the stretching lineation (and shortening normal to it). This must imply a very large relative movement of layers in this direction.

STRUCTURES IN THE USAMBARA MOUNTAINS

The Usambara and Pare Mountains rise nearly 2 km above the floor of the Pangani Rift along their west and southwest sides. They were formerly described as Tertiary horsts (e.g. Baker *et al.* 1972) although evidence of faults at their northeast sides is lacking. McConnell (1972) showed them as tilt blocks with the foliation dipping away from the Tertiary faults on their west and southwest sides, and from the Pangani Rift, but to account for the observed dips would require a throw of

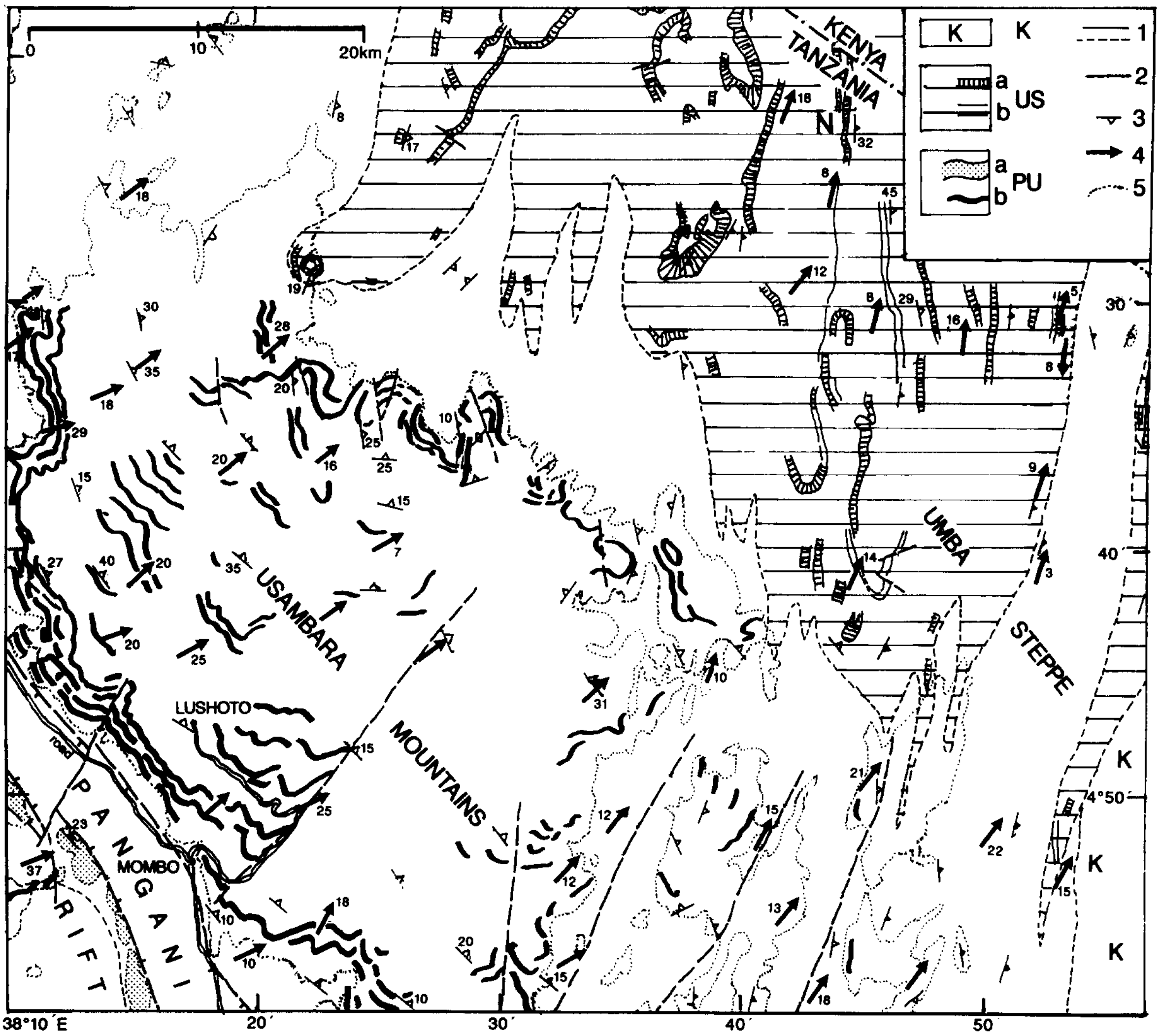

Fig. 2. Simplified geological map of part of the Usambara Mountains and Umba Steppe, based on Tanganyika (now Tanzania) Geological Survey 1:125,000 1/4 Degree Sheets 90, 109, 110 with 91. Inferred boundary between Pare–Usambara Group (granulites) and Umba Steppe Group (metasediments) is inserted.

K—Karoo
US—Umba Steppe Group
a—marble
b—graphitic gneiss and quartzite } Upper Proterozoic
PU—Pare–Usambara Group
a—migmatite
b—mafic marker bands

1—geological contacts (definite and inferred); 2—faults; 3—foliation, with value of dip shown; 4—representative stretching lineations, with value of plunge shown; 5—limit of main outcrops;
N—Ngomeyi.

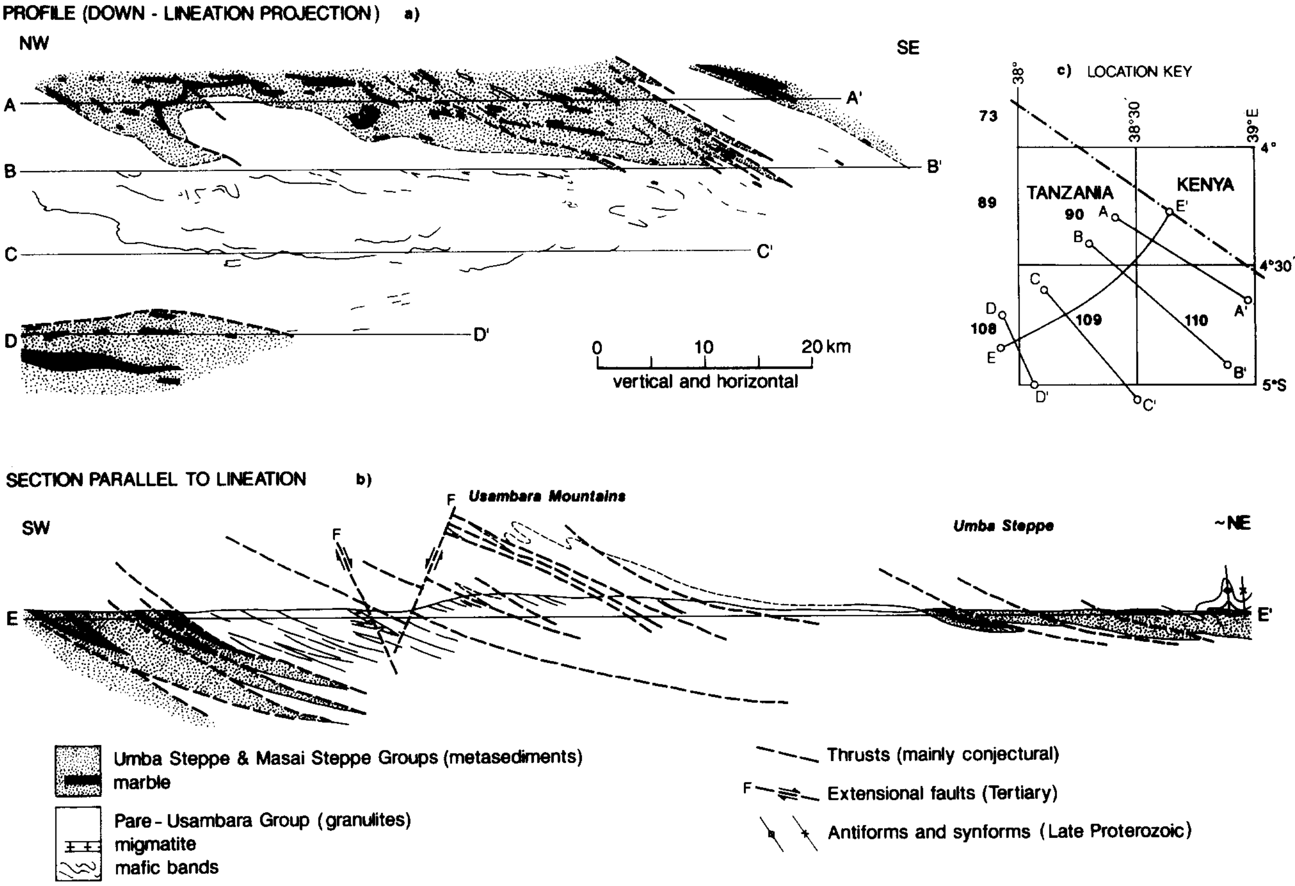

Fig. 3. (a) Profile of the Umba Steppe and Usambara Mountains normal to the stretching lineation. (b) Section parallel to the lineation. (c) Location of lines used for the profile and line of section; numbers of 1/4 Degree Sheets.

ca 15 km at the west side of the Usambara Mountains. He showed the southeastern part of the Usambara Mountains, where the foliation mainly dips eastwards, as an eastward-tilted block separated from the main Usambara tilt block by a narrow rift trending NNE. However, it is clear from the map (sheet 110/91, Hartley & Moore 1965) that the NNE-trending faults there (Fig. 2) have only small throws, that there is no topographic indication of a NNE-trending rift, and that the eastward foliation dip is not related to a Tertiary tilt block but affects not only the southeastern part of the Usambara Mountains but also the rocks of the Umba Steppe and those much farther north (Fig. 1). It is a regional trend, attributable to the late Mozambiquian deformation, although perhaps locally affected also by post-Karoo tilting since the Karoo beds immediately east of the Usambara Mountains dip eastwards like the metamorphic rocks. The generally E to NE dip of foliation and plunge of lineation continue west of the Pangani Rift despite the easterly downthrow of the Tertiary faults at the west side of the Rift. It must be concluded that the prevalent eastward plunge of the stretching lineation (Fig. 1) across the Mozambique Belt of N Tanzania is not due to Tertiary tilt but is Mozambiquian.

The interpretation of the eastward to northeastward plunge of the stretching lineation and dip of foliation is crucial for the tectonic interpretation of the Pare–Usambara granulites and regions to the west. The earliest recognized structure in the granulites, and in deep-crustal rocks elsewhere in the Mozambique Belt in Tanzania and Kenya, is a foliation parallel to the compositional layering. In the succeeding phase, the foliated rocks were deformed by recumbent folds and thrusts (Bagnall 1962, Hepworth & Kennerley 1970, Hepworth 1972, Key *et al.* 1989). In the second phase, the amphibolite-facies, mid-crustal rocks (e.g. Umba Steppe Group) were deformed by recumbent and overturned folds and thrusts, but in the lower-crustal granulite-facies rocks of the Usambara Mountains mapped folds are absent and the scarce folds seen in outcrops are tight, small-scale, often rootless and associated with thrusts almost parallel to the compositional layering. In the Umba Steppe Group no thrusts are mapped (exposures are poor), but they must exist in association with tight recumbent folds and repetitions of sequence. One thrust can, for example, be inferred at Ngomeyi (N, Fig. 2), immediately south of the Kenya border. Here a graphitic marble, underlain by a graphitic sillimanite gneiss, and dipping gently eastwards, truncates, at a very acute angle, what is apparently the same pair structurally below. The repetition and truncation are surely due to a thrust, which itself appears to be gently folded a few kilometres south of the truncation.

In the North Pare Mountains, in the granulite terrain, a number of thrusts have been mapped; the ENE-dipping Changube Thrust is traced for about 25 km.

From the brittle deformation indicated by slickensides, with down-dip striae, this thrust was thought to be later than the isoclinal folding (Harpum 1970). Other thrusts were also mapped in the North Pare Mountains (Bagnall 1962). That there are many more unmapped thrusts is suggested by the repetitions, especially towards the western side of the Usambara Mountains, of an association of graphitic gneisses, marble and quartzites. In the North Pare Mountains (Sheet 73) bands of graphitic gneiss are mapped continuously for up to 10 km; in the South Pare Mountains (sheet 89), exposures are discontinuous but one zone, about 1 km wide, containing scattered outcrops of graphitic gneiss and serpentinite, can be followed for about 50 km and outcrops of these two rock types are repeated, though very sporadically, west of the principal zone. These repetitions of similar and distinctive rocks are surely tectonic. There is no indication that the bands hook back round fold hinges; they seem to be long slivers. This evidence suggests that throughout the Pare and Usambara Mountains, there are repetitions due to thrusts. McConnell (1972) postulated other thrusts under the Pangani Rift, on the assumption that migmatites which occur there are due to thrust melting. The mapped distribution of these migmatites in the area (sheet 73) does not support this: many are scattered apparently randomly as small patches with no indication of any related thrusts, whereas only one small patch is shown close to the Changube and adjacent thrusts in the North Pare Mountains.

The Masai Steppe Group to the west of the Pare-Usambara granulites is correlated with the Umba Steppe Group on their northeast side because they appear to be lithologically and metamorphically identical (Bagnall 1964). Their contacts with the granulites are difficult to define and arbitrary. Since the granulite-facies assemblages clearly indicate a deeper crustal level than the high-amphibolite facies of the Usambara Steppe and Masai Steppe Groups, it is not possible to argue that the apparent structural sequence, with the Masai Steppe Group below and the Umba Steppe Group above, is an original stratigraphic sequence. The regional evidence also clearly supports correlation of the Masai and Umba Steppe Groups (Shackleton 1986, fig. 4).

A profile obtained by down-lineation plunge projection is shown in Fig. 3(a). Such a profile is thought to be wrong, for reasons given below.

There is no evidence on the maps of any sudden major stratigraphic or metamorphic break between the granulites and the metasediments with marble bands of the Masai Steppe Group. This suggests that the apparent superposition of the granulites on the Masai Steppe Group is not due to a single major thrust. It has been suggested above that there must be many more thrusts than could be mapped in the Pare and Usambara Mountains. These thrusts must dip very slightly more steeply than the layering and primary foliation, the array of thrusts resulting in a serrated contact as shown between the Pare–Usambara granulites and the Umba Steppe Group in a schematic section (Fig. 3b). The contact has a low envelope-dip. The regional dip of the major units is apparent from a map of the Mozambique Belt of Tanzania and Kenya (Shackleton 1986, fig. 4) and from the repeated appearance, right across the belt in northern Tanzania, of the lower crustal granulites (Hepworth 1972) (Fig. 1). It is possible that the alternation in the North Pare Mountains, of strips and lenses of the graphitic gneiss–marble–quartzite association reminiscent of the Umba Steppe Group with the granulites, is actually a tectonic interleaving of the Pare–Usambara granulites and the Umba Steppe Group. This is consistent with the convergence, towards the northern end of the North Pare Mountains, of the Umba Steppe Group to the east, and the Masai Steppe Group to the west, a convergence which suggests a low northward plunge of the complex upper surface of the granulites. Presumably the Umba Steppe and Masai Steppe Groups meet beneath the cover of Tertiary volcanic rocks of Kilimanjaro.

This interpretation of the structure of the Pare–Usambara area involves an initial phase of ductile shearing to produce the first foliation parallel to the compositional layering, and a succeeding phase of SW-directed imbrication. It means that the primary thickness of lower crust that is exposed in the Usambara Mountains is very much less than the nearly 20 km which results from down-lineation projection (Fig. 3a). The initial intense ductile shearing produced a foliation which may have been nearly flat. In the second phase, ductile shearing and thrusting were still very close to the compositional layering in the granulites, but steepening gradually upwards, so that the axial planes and thrusts intersect the overall NW–SE trending granulite–Umba Steppe Group contact at a low angle (Figs. 2 and 3a).

The down-plunge projection (Fig. 3a) ignores the effects of repetitions, especially by thrusting, during the second deformation. As indicated schematically in Fig. 3(b), the layering does not continue indefinitely down the plunge of the lineation: there are innumerable reversals and truncations. Consequently the projection greatly exaggerates the structural thickness of the units. The projection does however show the upward change, with folds towards the top of the granulites, increasing in amplitude in the Umba Steppe Group, and a slight upward steepening of their axial surfaces.

REGIONAL EVIDENCE

The Mozambique Belt of Tanzania and Kenya is believed to show the effects of a series of superimposed orogenies, including the Ubendian–Usagaran ~1920–1820 Ma and the Kibaran ~1400–1300 Ma (Cahen *et al.* 1984), the Samburuan–Sabachian ~830–820 Ma and the Baragoian–Barsaloian ~620–570 Ma (Key *et al.* 1989). Only the last two, here referred to as early and late Mozambiquian, are relevant to the Usambara Mountains region. In north-central Kenya, the early Mozambiquian, represented by an earlier (Samburuan) phase which gave rise to a foliation parallel to the compositional layering, was followed by the Sabachian phase, represented by low-angle thrusts and recumbent folds plunging within an arc between NW–SE and WSW–ENE, but mostly about WNW–ESE. Lineations on the thrusts trend about NW–SE. Superimposed on these early Mozambiquian recumbent structures and lineations, transverse to the Mozambique Belt, are quite different late Mozambiquian structures: upright folds and steep shear zones trending about N–S (Key *et al.* 1989).

The regional structural pattern is best shown by a map of the stretching lineations (Fig. 1). As explained, the geologists of the Tanzanian and Kenyan Geological Surveys mostly did not distinguish between stretching, crenulation and other lineations, all of which were assumed to be parallel to the fold axes. The stretching lineation map (Fig. 1) is based on the author's observations in Kenya and Tanzania, on Weiss's detailed description of the lineation at Turoka (Weiss 1959), and on the mean trends of the Kondoan lineation across northern Tanzania, this being the only one of those plotted (Hepworth 1972, fig. 2) which is a stretching lineation (*ibid.*, in discussion). The lineations in the Maralal area, north central Kenya (Shackleton 1946), originally seen as mineral lineations (mostly sillimanite), are now recognized as stretching lineations. Other lineations are selected from those on published maps by their consistency of trend and plunge with known stretching lineations in nearby areas, but some of those shown on Fig. 1 are probably not stretching lineations.

The N–S late Mozambiquian structures, and most obviously the lineations, which usually plunge gently northwards (Fig. 1), are dominant more or less continuously from north-central Kenya nearly as far as the Pare–Usambara Mountains (Fig. 1). On the basis of similarity in structural styles, deformation sequence and orientation, the structural sequence recognized in north-central Kenya was traced into SE Kenya (Key & Hill 1989). Carrying the correlation southwards, the two deformation phases in the Usambara and Pare Mountains are correlated with the early Mozambiquian (Samburuan and Sabachian) phases in north-central Kenya. Farther west in northern Tanzania, towards the western Mozambique front, the early Mozambiquian Kondoan phase, of recumbent folds and thrusts, with a stretching lineation transverse to the Mozambique Belt, was also correlated with the early Mozambiquian farther north in Kenya, on the basis of deformation style and relation to later upright roughly N–S structures (Hepworth 1972). Early transverse lineations, associated with recumbent structures, are seen over much of the Kenyan and Tanzanian parts of the Mozambique Belt, but the trend of the lineation curves gradually across the area (Fig. 1). This curvature in trend is clearly seen within the Usambara Mountains (Bagnall *et al.* 1963, Hartley & Moore 1964) (Fig. 1). In SE Kenya, this curvature continues, taking the lineation trend to N–S, indistinguishable on the map from the late Mozambiquian lineation. The two are distinguished there by the recumbency of the folds associated with the early Mozambiquian lineation, compared with the upright folds associated with the late Mozambiquian. However, this apparently clear distinction is probably not so simple. There cannot be two stretching lineations in the same rock; the observed lineation trends may be the result of a series of incremental strains with the late Mozambiquian strains becoming dominant towards the east side of the Belt. If so, the folds must also have been reoriented by successive strains.

INTERPRETATION OF THE TRANSVERSE EARLY MOZAMBIQUIAN STRUCTURES

The transverse early Mozambiquian structures have been explained in different ways. Very detailed structural work in the Kajiado area of Kenya (Weiss 1959) was interpreted as demonstrating that the Turoka fold there (Fig. 4) was cylindroidal, parallel to the stretching lineation. It was supposed to have evolved in three stages: first, intense monoclinic strain produced flexural-slip folding on all scales about a regionally constant fold axis. Shearing and unrestricted transport tore apart initial sedimentary layers into isolated tectonic inclusions. One layer was rolled up into a cylinder about a core of granulite gneiss. Second, changes in the pattern of stress changed the symmetry of strain to orthorhombic. P_{max} rotated towards the vertical. Thirdly, the whole field was rotated about a horizontal axis to give the observed plunge (of about 20°/062°). A profile, constructed by projecting down this plunge, showed a thickness of over 3 km in a distance of 8.5 km (Fig. 4b). Most subsequent workers on the Kenyan and Tanzanian Geological Surveys accepted that the folds were parallel to the stretching lineation.

The process by which the rocks in the Turoka fold became rolled into a cylinder such that the marble was completely continuous (there is one small erosion gap) round the axial core of granulitic gneiss seems completely unbelievable. Moreover a tectonic profile from the western Mozambique Belt front to the Usambara Mountains based on this assumption of cylindroidal folding, using the published lineation data, would lead to an estimate of over 200 km thickness of crust! Similar down-plunge projection from the Usambara Mountains north to the equator gives a further estimated thickness of over 180 km. Superimposed deformations, now demonstrated in many areas (e.g. see Hepworth 1972, Key *et al.* 1989), mean repeated reversals and repetitions rather than down-plunge continuity, so profiles cannot be drawn simply by projecting down the lineation plunge.

There are very few estimates of strain in the whole region. A typical Sabachian fabric is estimated at $X:Y:Z = 8:6:1$ (Key *et al.* 1989). My estimate from a sample from the North Pare Mountains is $X:Y:Z = 30:2:1$. Clearly there are, at least locally, very large extensional strains transverse to the Mozambiquian orogenic trend and they are associated with compressional

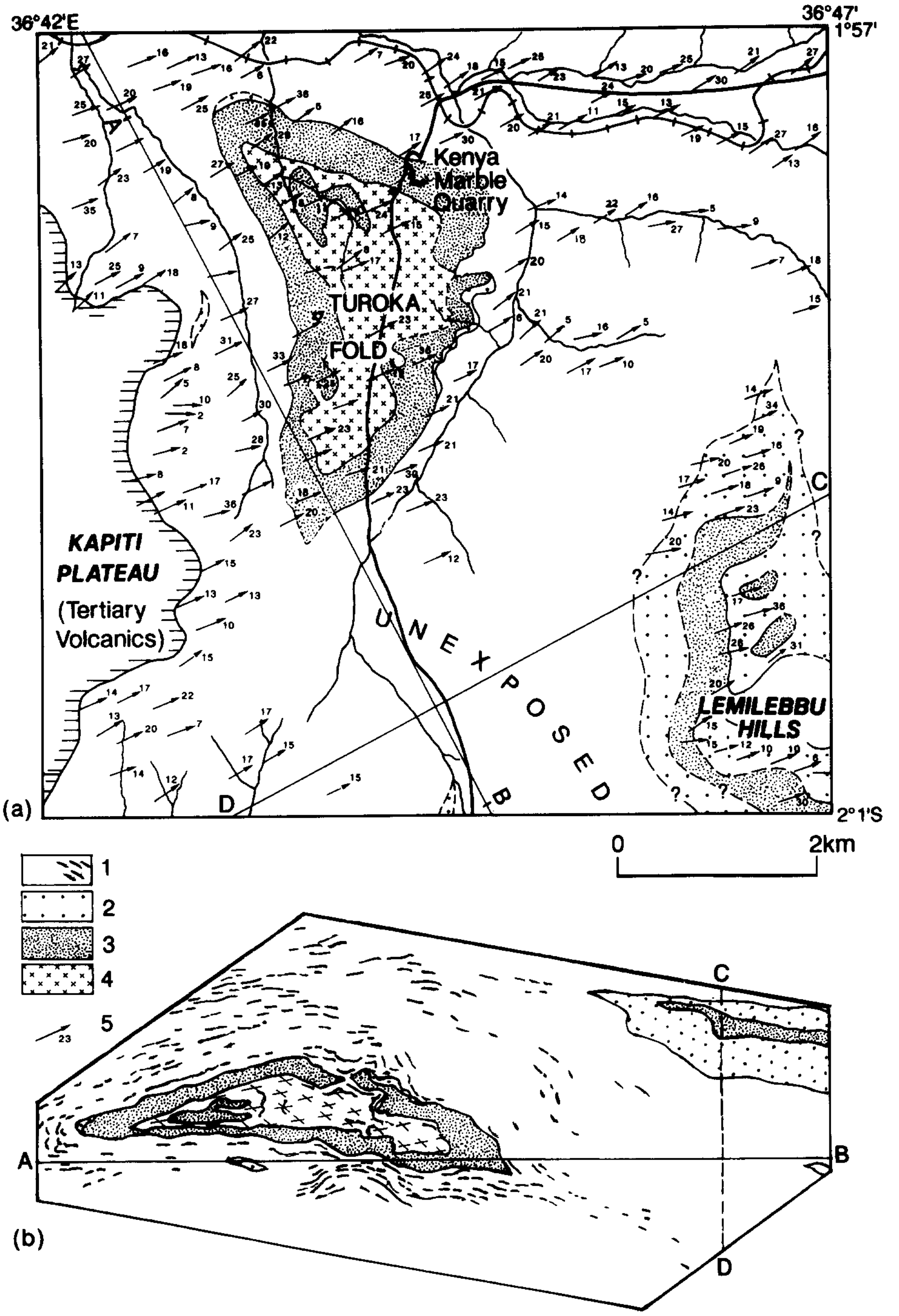

Fig. 4. Structural map (a) and profile normal to the lineation (b) of the Turoka area, Kenya, after Weiss (1959). 1—undifferentiated (non-granulitic) gneiss; foliation indicated on profile; 2—quartzite; 3—marble; 4—granulitic gneiss; 5—trend and plunge of fold axis or lineation (undifferentiated).

structures. It is therefore to be expected that sheath folds would have been formed, so one possible interpretation of the Turoka fold is that it is a sheath-shaped antiform. Study of Weiss's data indicates a downward divergence of foliations at the north and south hinges, consistent with an antiformal sheath fold interpretation. An alternative interpretation is that it is an interference fold of Ramsay's Type 2 (Ramsay 1967, figs. 10–13).

The Turoka structures mapped by Weiss continue southwards into the Namanga–Bissel area (Joubert 1957), where there are other arcuate folds like the Turoka fold. The stretching lineation plunges in the same direction (~60°E) as in the Turoka fold. There are weak and discontinuous warps parallel to the lineation, but no indication of cross-folds such as would be required to explain the structures as interference folds of Ramsay's Type 2: within a few kilometres both northeast and southwest of two of the arcuate folds, marble bands trend continuously about NW–SE, with little deflection as they pass the arcuate folds; two adjacent but en échelon arcuate folds expose the same quartzite, but one shows a slight synformal cross-fold, the other an antiformal one. The interference fold interpretation is thus not supported and the sheath fold interpretation seems more plausible.

West of the Pare–Usambara granulites the maps show many major recumbent folds. Two seem to show equivalent hinges on either side of a broad N–S-trending antiform, about 30 and 50 km west of the Pare Mountains granulites (Shackleton 1986, fig. 4). Lines connecting the hinges trend about E–W, about parallel to the stretching lineation. If the hinges were straight before the N–S arching, the amplitude of the folds is more than 40 km. They can hardly be explained as sheath folds due to movement parallel to the stretching lineation: they appear to imply very large northwards movement, normal to it. This seems to take us back towards Weiss's postulated transport normal to the lineation at Turoka, some 200 km to the north. Attempts to determine, from stereoplots of foliation, the axial plunges of other recumbent folds west of the Pare–Usambara granulites gave poor and conflicting results; 35°/030° (Lolabukoi fold, about 37°35′E, 4°3′S, Sheet 89) and 24°/145° (Sonyai fold, about 37°25′E, 4°3′S, Sheet 88). The stretching lineation plunges northwest in both areas. The folds in the Umba Steppe Group (Figs. 2 and 3) are overfolded towards the west or northwest, but data on the maps are not enough to give plunge directions. Looking at the regional evidence as a whole, there seems no doubt that the movement associated with the early stretching lineation was transverse to the Belt, parallel to the lineation, primarily because of the very large extensions indicated by it. The associated thrusts, which result in innumerable repetitions, and the recumbent folds, indicate plate convergence rather than divergence. The interpretation of the recumbent folds with axial trends roughly parallel to the lineation is not clear.

Whatever the interpretation of the fold geometry, the field evidence in the Usambara Mountains remains clear that the essentially planar structures in the structurally lower part of the Usambara Mountains become gradually, though only slightly, steeper upwards, through the granulites and into the Umba Steppe Group. This is shown by the fact that the axial surfaces of the folds, which amplify upwards from the upper part of the granulites into the Umba Steppe Group, are inclined more steeply than the enveloping surface of the contact between the granulites and the Umba Steppe Group, which is itself parallel to the layering and foliation in the granulites (see Figs. 2 and 3a).

The metamorphic assemblages, developed during and after the deformations, indicate, from comparison with assemblages at Furua, farther south (~36°30′E, 9°00′S) and studied in detail (Coolen 1980), original depths in the granulites of the order of 25–30 km. This, and the higher temperature (approximately 800°C) in the granulites, therefore higher ductility, indicate that the rather rapid though continuous change at the top of the granulites can be taken as marking the top of the Mozambiquian lower crust. What therefore we see in the Usambara granulites is an upward transition from originally very gently inclined planar shearing in this upper part of the lower crust, to slightly more inclined shearing, folding and thrusting in the middle crust above.

The structures are so complex, and so little understood, that it would be unrealistic to estimate the thickness of the exposed lower crust in the Usambara Mountains. The apparent thickness suggested by the profile, Fig. 2, is almost certainly too large. The best hope for a reliable estimate would be a series of P–T determinations. In the Furua area, the range estimated was 7–12 kb (Coolen 1980), corresponding to depths from about 25 to 40 km, but this estimate includes a considerable range of uncertainty.

The association of the stretching lineation with tight folds and thrusts, especially in the Umba Steppe Group, clearly demonstrates that the granulite facies metamorphism in the Mozambique Belt occurred during crustal compression and not extension (cf. Hepworth & Kennerley 1970, p. 479, Hepworth 1972, p. 491); the extension transverse to the Mozambique Belt is here interpreted as extension sub-parallel to the direction of shear (Ramsay & Graham 1970), the shear zone being in the ductile lower crust. The thrusting of the planar deformed granulites over the folded Masai Steppe Group (Fig. 3a, A–A′), and tilting, represents a later deformation phase, as indicated by previous work (Bagnall 1962, Harpum 1970).

CONCLUSIONS

(1) In the Usambara Mountains and the Umba Steppe one can see a stratigraphic, structural and metamorphic continuity from the granulites to the Umba Steppe Group of metasediments. There is no evidence that the granulites represent a pre-Mozambiquian basement; the granulite facies metamorphism locally extends into the Umba Steppe Group and has been dated as late Proterozoic.

(2) The Usambara granulites represent the early Mozambiquian lower crust, the Umba Steppe Group (and the equivalent Masai Steppe Group) represent the middle crust. The transition represents an original depth of approximately 25 km.

(3) The major part of the granulites shows rather uniformly and gently dipping very high-strain planar structures—compositional layering and banding, foliation, shear zones and pervasive stretching lineation. The dip of the layering gradually becomes less regular upwards until in the structurally overlying Umba Steppe metasediments there are major overturned folds and presumably many unmapped thrusts. Lineation and foliation are continuous from the granulites. The structures steepen upwards, slightly and gradually as they change from planar, sub-parallel to compositional layering, to folds and thrusts slightly steeper than the overall dip of the layering. The structural change downwards from upper crust to lower crust reflects a rather rapid increase in ductility, shown by higher strains and disappearance of buckling.

(4) Extensional strains are probably everywhere high. Measurements of strain ellipsoids in one sample gave $X{:}Y{:}Z = 30{:}2{:}1$. Because the strain indicators are usually granulite-facies mineral aggregates, it is very

likely that they only represent the later part of the strain. The real extension may be much higher.

(5) The structures are correlated with the early Mozambiquian, Samburuan–Sabachian, ~830–820 Ma, of north-central Kenya (Key *et al.* 1989). A rough metamorphic date of the Usambara granulites gave 812 ± 37 Ma (Spooner *et al.* 1970, revised by Cahen *et al.* 1984). The late Mozambiquian, Baragoian–Barsaloian, (Key *et al.* 1989), ~620–570 Ma, becomes dominant only north of the Usambara Mountains, just across the Tanzania–Kenya border, and has the character of steep major ductile shear zones, not a collisional orogeny.

(6) Sections normal to the northeast lineation plunge show folds overturned northwestwards. Associated thrusts are not mapped but clearly must be present. Sections parallel to the lineation plunge are speculative. The Pare–Usambara granulites are apparently thrust over the Masai Steppe Group metasediments. This thrusting is attributed to a slightly later phase than the main planar deformation. Combination of the profile and section indicates that the dip of the thrusts, northeastwards in the granulites, becomes more easterly in the Umba Steppe Group.

(7) Regional stratigraphic and metamorphic evidence shows that the regional envelope-dip of the granulite–upper amphibolite, i.e. lower–middle crust, transition, across the array of intricate serrations caused by thrusts and folds, is very low (< 1°).

(8) The effects of Tertiary rift faulting on the overall structure of the Usambara Mountains region are trivial compared with those of the Mozambiquian deformation.

(9) A regional lineation map shows that the supposed stretching lineation (not always so described on the maps), curves across the Mozambique Belt of central and northern Tanzania, from plunging approximately east-southeast in the west, through east, to northeast in the Usambara Mountains, and N–S or NNW–SSE through much of the eastern part of the Mozambique Belt in Kenya. The trends are less regular at higher tectonic levels, suggesting higher, more ductile, strains in the lower crust and an upward transition to folds and thrusts normal to the transport direction. Most of the N–S lineation trends are the effects of the late Mozambiquian deformation. The early Mozambiquian structures, at present exposure levels, are recumbent and regional; the late Mozambiquian are upright and only intense in discrete N–S zones.

(10) The overall E–W-trending lineation, transverse to the Mozambique Belt to which it belongs, is interpreted as the transport direction. Most of the minor folds and possibly many of the major folds parallel or subparallel to it, are interpreted as acute sheath folds and not cylindroidal folds. The granulite metamorphism was associated with plate-convergent, not plate-divergent, deformation. The structures imply very large but unquantifiable translations.

(11) The apparent tectonic thickness, *ca* 10 km, of the lower crust exposed in the Pare–Usambara Mountains is an imbricated packet, probably representing much less than 10 km original thickness.

(12) In the Usambara Mountains region we are looking at the upper part of an originally gently inclined shear zone in the lower crust.

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