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Inverted isograds at Sulitjelma, Norway: the result of shear-zone deformation.

Roger Mason,

Department of Geology,

University College,

Gower Street,

London WC1E 6BT.

Abstract.

At Sulitjelma, Norway, there is a major inversion of metamorphic isograds beneath an inverted but undisrupted ophiolite. The flysch-like Furulund schist in which the inverted isograds occur is also inverted and the early folds in it are downward facing. The isograds cut across the axial surfaces of early folds and across the schistosity. These relationships are explained as the consequence of metamorphism during the progressive development of a large overfold. The inverted limb of the overfold is regarded as a major, thick, gently-dipping shear-zone, separating the lower-grade, lower part of the Caledonian allochthon below from the higher-grade upper part of the allochthon above. The association between stratigraphical inversion, downward-facing of syn-schistosity folds and metamorphic inversion is explained by the progressive development of the shear-zone. It is suggested that the presence of such shear-zones is a common feature of orogenic belts formed by continental collision.

Introduction.

Sulitjelma is a copper mining district in the Caledonian orogenic belt in Norway at 67° N, 15° E, close to the international border with Sweden. The area has been the site of geological research for more than 175 years, the early work being described in a Memoir of the Norwegian Geological Survey by Vogt (1927). This was a pioneering piece of petrological research, including a remarkable account of a sequence of progressive regional metamorphic zones in relatively homogeneous calcareous pelites, the Furulund schists. Vogt recognised that the metamorphic zones are a metamorphic facies series, which he described using ACF triangular diagrams. He described another facies series in the basic igneous rocks which overlie the Furulund schists, the Sulitjelma amphibolites. This classic account of progressive regional metamorphism is deservedly cited in textbooks (Miyashiro 1973, Mason 1978, Turner 1981). Subsequent work (Henley 1970) has improved the location of the garnet isograd, and shown that the biotite and kyanite isograds mapped by Vogt are due to changes in rock composition rather than metamorphic grade. Fig.1. shows the position of the garnet isograd in the part of the Sulitjelma area where it has been accurately mapped. It cuts across the lithostratigraphical units, as Mason (1978) emphasised.

Vogt not only described the metamorphic facies sequence at Sulitjelma, he also put forward a petrological model to explain it. He suggested that heat had been supplied to the Furulund schist from above, being conducted down from the Sulitjelma amphibolites which were part of a large phacolithic intrusion. The heat was ultimately derived from the consolidation and cooling of the basic magma of the phacolith, which had formed by many pulses of intrusion. The metamorphic facies sequence in the Sulitjelma amphibolites themselves had formed by the cooling and hydration of the early intruded base of the phacolith during the progressive metamorphism of the schists below. Vogt's model thus implied that the metamorphic zones at Sulitjelma are inverted.

Boyle (1980) has shown that the Sulitjelma amphibolites and the other basic rocks of Vogt's phacolith are the upper members of a deformed but undisrupted ophiolite. Pillow structures in the amphibolites and the arrangement of the different units of the ophiolite show that it is predominantly upside-down (Boyle <u>et al.</u> 1979). Geis (1978), who discussed Boyle's work with him in 1977, pointed out that if the contact between the Sulitjelma amphibolites and the Furulund schist were also inverted, the occurrence of the copper ore could be explained as volcanic exhalation on an ocean floor, giving rise to ore-bodies of the Cyprus type. Kirk & Mason (1984) have since shown that the whole of the Furulund schist is inverted, and that the earliest folds are downward-facing. It seems likely that the stratigraphical inversion, presence of the ophiolite and inversion of the metamorphic isograds are genetically linked in some way.

Proof that the isograds are inverted.

Between 1976 and 1978 a tunnel was cut from the western end of Lomivann north-westwards through the Furulund schist, the Sulitjelma amphibolites, the Vaknahelleren schist and the varied rocks over the overlying Skaiti Supergroup. The tunnel cuts through the garnet isograd surface, providing a control on the three-dimensional attitude of the surface. The isograd is marked by the appearance of almandine-rich garnet porphyroblasts in schists with the assemblage quartz + muscovite + biotite + oligoclase + epidote + chlorite. Almandine apparently formed by the reaction muscovite + chlorite = almandine + biotite + H_2O. The porphyroblasts are clearly visible in hand-specimen, and the isograd position can be located to within about 20m, both above ground and in the tunnel (Mason 1978,119). Fig.2. is a cross-section along the tunnel near its SE end, the part shown as a heavy line in Fig.1. The field relationships show unequivocally that the garnet isograd surface is inverted, with garnet-bearing schists lying above garnet-free schists. Along the line of the tunnel, as shown in Fig.2., the isograd surface dips less steeply than the amphibolite/schist contact, and does not correspond with any structural feature, such as a thrust or fold-hinge. It is thought that the lower apparent dip of the isograd surface along the line of the tunnel is due to the direction of the cross-section, and that the true dip of the isograd is steeper than that of the contact.

The Vaknahelleren schist, shown at the NW end of the cross-section in Fig.2., is cut by the tunnel and lies in the hinge-zone of a major syncline (Boyle et al. 1979). In the tunnel this schist contains porphyroblasts of kyanite, which are also found at the surface above the line of the tunnel. Because the kyanite porphyroblasts are less common than the corresponding garnet porphyroblasts near the garnet isograd, it is not possible to locate the position of a kyanite isograd as accurately as that of the garnet isograd. However, in the surface outcrop of the Vaknahelleren schist, kyanite porphyroblasts are not found east of the line of the tunnel, although the field-relationships are complicated by the presence of post-metamorphic faults. The kyanite isograd in Fig.2. has been constructed on the assumption that the tunnel cuts the Vaknahelleren schist just above the isograd, which is reasonable in view of the field relationships. If the garnet isograd is projected NW along the section, the distance between the garnet and kyanite isograds becomes unacceptably narrow, and the bend shown in the garnet isograd has been put in to make the spacing more reasonable. It has the merit of reflecting the curve in the surface outcrop of the isograd seen west of the tunnel in Fig.1.

Thus Vogt's suggestion that the metamorphic gradient at Sulitjelma is inverted is confirmed. It is not certain whether the inversion is local, as he thought, or whether it is regional. The garnet isograd has been mapped north of the Sulitjelma mountains by Cooper et al. (1979), in a position which implies that it bulges eastwards round the ophiolite. Andreasson & Lagerblad have reported metamorphic inversion further south in the Scandinavian Caledonides, and regional syntheses emphasise that the higher nappe units of the Scandinavian allochthon are of higher metamorphic grade than those below (Gee & Zachrisson 1979, Kulling 1982). In the present state of knowledge, therefore, it seems preferable to assume that the inversion is regional, and therefore a product of a large-scale tectonic and thermal process rather than of a local process such as heating by intrusion of the gabbro.

It has also been suggested that Barrow's metamorphic zones in the Grampian Highlands of Scotland are inverted (Chinner 1966). Large-scale regional inversions of metamorphic isograd surfaces have also been recorded widely in the Himalayas (e.g. Arita 1983, Bhattacharyya & Das 1983). Such inversions are generally explained by models of the type developed quantitatively by Oxburgh & Turcotte (1974), involving the thrusting of large slabs of hotter rocks above cooler, followed by incomplete thermal relaxation (Fig.3). Such models, including versions modified to allow for the input of heat by friction on the thrust surface (e.g. Graham & England 1976) require a major thrust horizon near or above the inverted isograds, and at Sulitjelma there is no such horizon (Boyle et al. 1984).

A shear-zone model to account for the inversion.

As an alternative, a tectonic and thermal model is proposed in which the Furulund schist acted as a gently-dipping major shear-zone in which the ophiolite and Furulund schist were inverted (Fig.4). It has been argued elsewhere (Boyle et al. 1984) that the major structure of the Sulitjelma region is an eastward-closing major anticline, of which the shear-zone discussed here would be the inverted lower limb. Evidence in support of this interpretation is the frequent mineral lineation and widespread boudinage developed in the Furulund schist, and the absence of any major folds, although minor folds are common (Kirk & Mason 1984). There is also evidence that the overturning was progressive and relatively slow compared with the development of the metamorphic fabric, because the early forlds are downward facing relative to the penetrative schistosity and the lineation is partly syn-kinematic with the growth of garnet and hornblende porphyroblasts (Henley 1970).

The shear-zone was initiated in the thick Furulund sediments by the propagation upwards of a thrust in the crystalline basement (Fig.4a). As crustal shortening proceeded, the isograds were rotated (Fig.4b). Eventually, as translation on the shear-zone increased, the isograds became inverted (Fig.4c). The model suggests that there should be a change in the dip of the isograds across the boundary of the shear-zone, and perhaps the bend shown on the map (Fig.1) and in the cross-section (Fig.2) reflects this. There was more shearing in the relatively incompetent Furulund schist than in the Sulitjelma amphibolites. The model implies that during deformation the rate of migration of the isograds was slow compared with the rate of shearing.

The Sulitjelma area does represent a zone of change in tectonic style from brittle thrusting in the east of the Caledonian orogenic belt to plastic folding in the west (Nicholson & Rutland 1969). This change is explicable if there is a major plastic shear-zone present. The shear-zone model also explains why there is no agreement on the presence or absence of thrusts in the lithostratigraphical succession at Sulitjelma, and among those who think there is thrusting, little agreement about the positions of the thrusts.

A similar change in style and metamorphic grade occurs widely in the Scandinavian Caledonides at about this level. It is therefore suggested that for Scandinavia, the shear-zone model provides a more plausible explanation for metamorphic inversion than a thermal relaxation model, and that it may be applicable to orogenic belts formed by overthrusting during continental collision in general.

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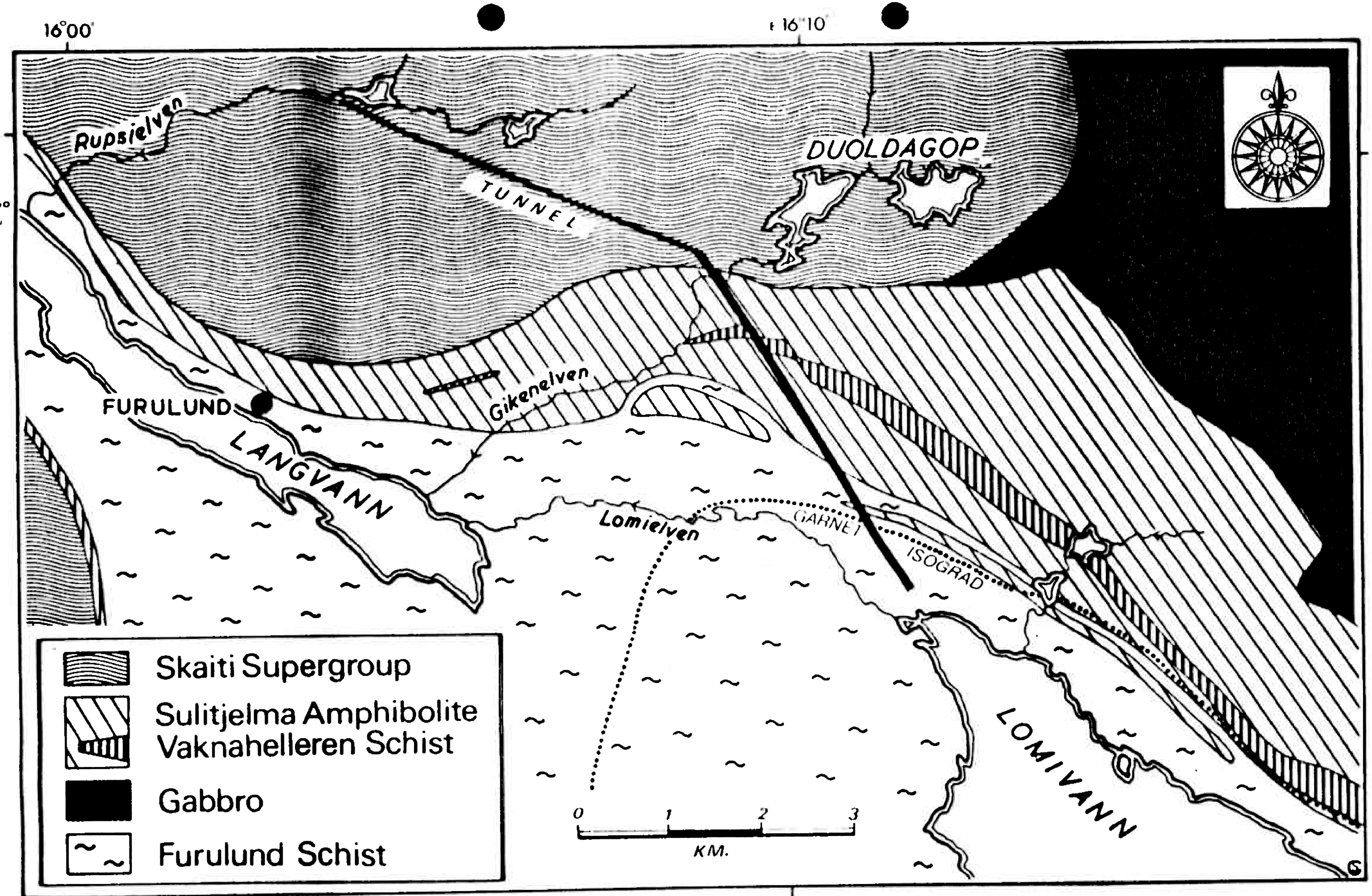
Figure Captions.

Fig.1. Geological sketch-map of the northeastern part of the Sulitjelma mining district, Norway, showing the position of the garnet isograd after Henley (1970) and the line of the tunnel mentioned in the text. The heavy line indicates the part of the tunnel shown in the cross-section Fig.2.

Fig.2. NW-SE cross-section along the tunnel, showing the position of the garnet isograd surface, and of an inferred kyanite isograd. The tunnel is the heavy horizontal line above the 700m level. Vertical scale = horizontal scale.

Fig.3. Thermal relaxation model to account for the metamorphic inversion. $T_1 < T_2 < T_3$, isotherms in sediment pile above crystalline basement. (a) Thrust propagates upwards from crystalline basement through overlying sediments. (b) Ramp brings hot rocks in overthrust block above cooler sediments. (c) Isotherms relax after thrusting to yield a local thermal inversion. Note that the thrust lies in or above the thermal inversion.

Fig.4. Shear-zone model to account for the metamorphic inversion. Isotherms labelled as in Fig.3. (a) Thrust in crystalline basement propagates upwards through sediments as a shear-zone. (b) Increasing deformation in shear-zone rotates sediments and isograds. (c) Continuing deformation in shear-zone overturns sediments and isograds.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Vaknahelleren Schist
Gabbro
Furulund Schist

Fig. 1

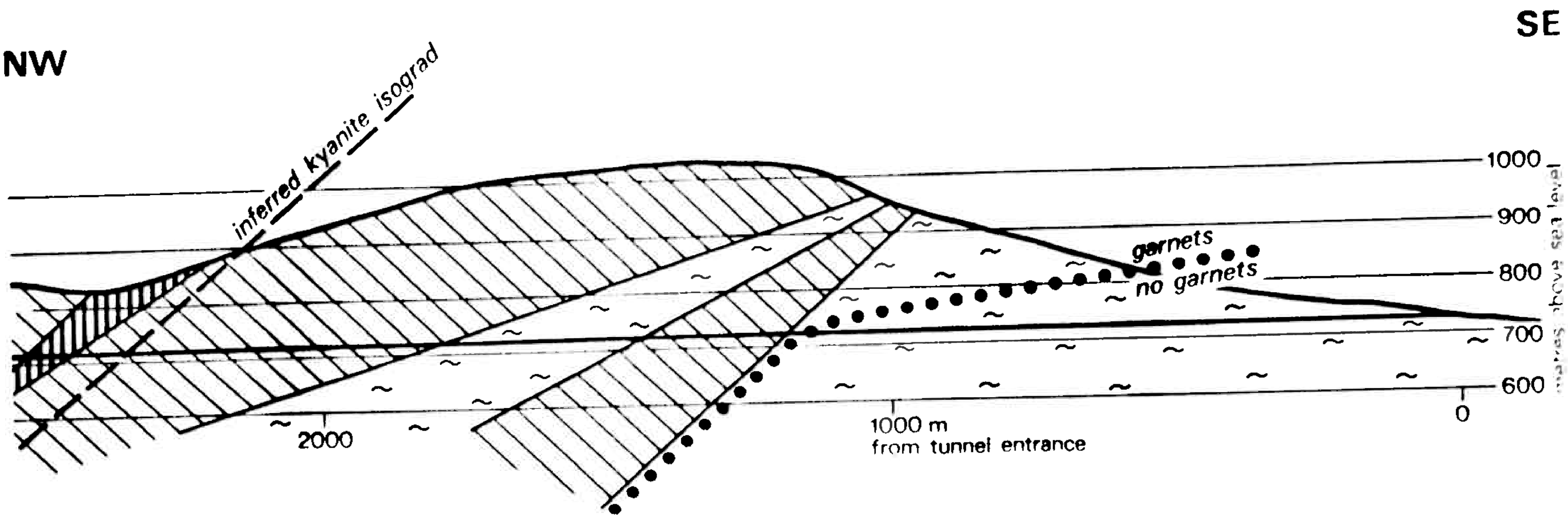
NW
SE
inferred kyanite isograd
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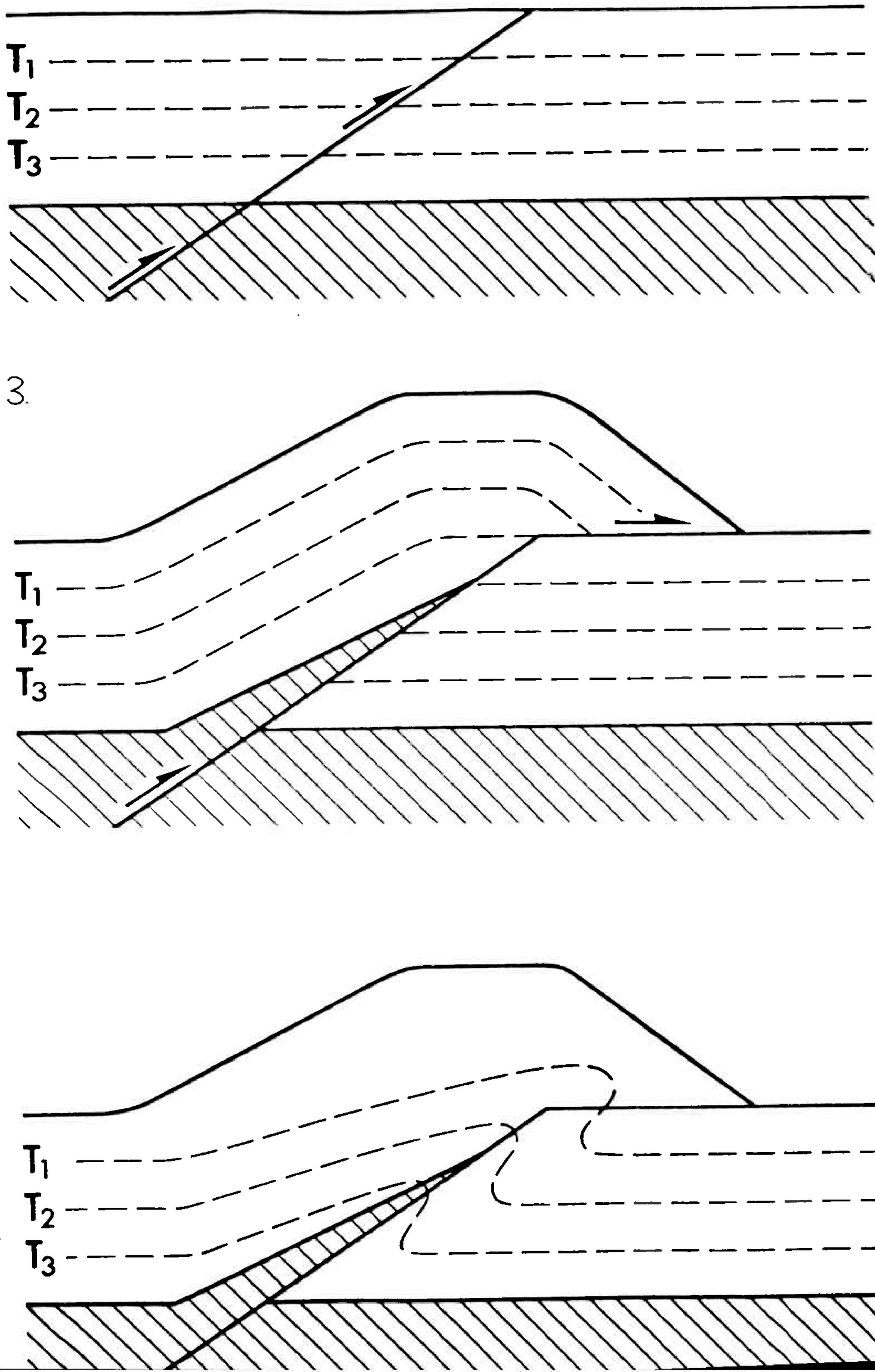
Fig 2.



a

Fig 3.

b

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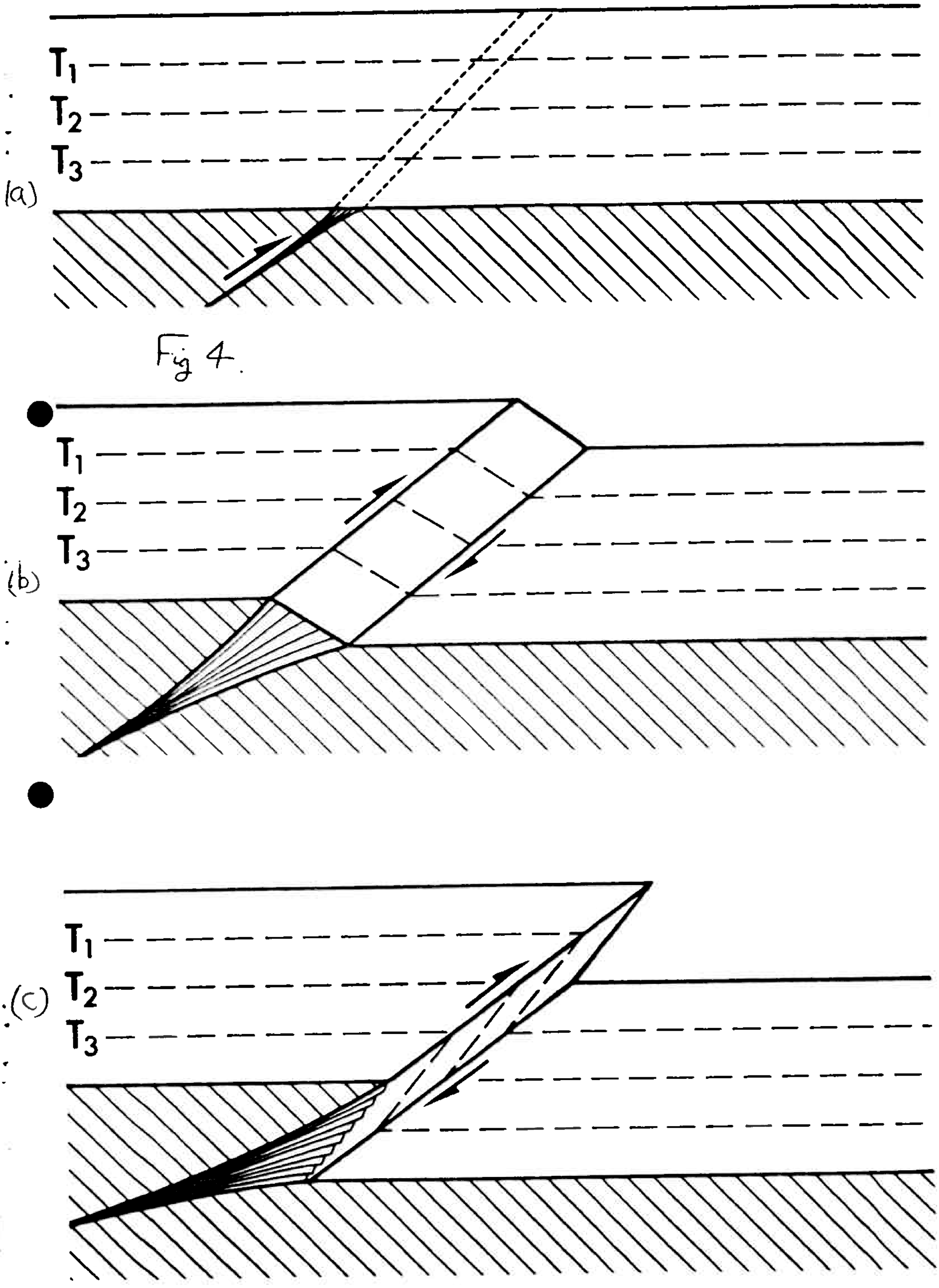

Fig 4.