NASA-CR-199565

Final Technical Report

for NASA Grant NAGW-3547

Submitted to

National Aeronautics and Space Administration
Dr. Patricia Rogers
Code SLC, NASA Headquarters
Washington, DC 20546

Quantitative Characterization of the Small-Scale Fracture Patterns on the Plains of Venus

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August, 1995

Research Objectives

The objectives of this research project were to:

(1) compile a comprehensive database of the occurrence of regularly spaced kilometer scale lineations on the volcanic plains of Venus in an effort to verify the effectiveness of the shear-lag model developed by Banerdt and Sammis (1992), and

(2) develop a model for the formation of irregular kilometer scale lineations such as typified in the gridded plains region of Guinevere Planitia.

Research Results

(1) The database of "shear-lag" fractures was extended to cover the planet. The distribution of fracture spacings was found to agree well with the predictions of the shear-lag model (See Bowman *et al.*, 1994).

(2) A model for the formation of the irregular lineations was developed. We have interpreted them as shear fractures in the lithosphere which have been covered by a thin surficial layer (Bowman and Sammis, 1994; Bowman and Sammis, 1995).

(3) Using the length distribution of the irregular fractures, we have developed a method for determining the thickness of the elastic lithosphere. This analysis predicts an elastic thickness of ~40 km in the Guinevere Planitia region of Venus.

(4) The proposed mechanisms for formation of both the regular (shear-lag) and irregular (simple shear) fractures have important implications for the resurfacing of Guinevere Planitia. In particular, the shear-lag fractures predict the existence of a thin surficial unit covering the surface of the planitia, which, according to the model, is deposited contemporaneously with the development of the regular fractures. However, the *en echelon* morphology of the irregular fractures implies that they propagated upwards through this surface layer, which further suggests that the fractures are pre-existing cracks in the lithosphere that were re-activated after deposition of the surface layer. Thus, it can be inferred that the event which resurfaced Guinevere Planitia did not involve the disruption of the earlier lithosphere, but rather was accomplished through a period of accelerated volcanism. See appended preprint for details.

Publications Resulting From This Grant

Bowman, D.D., C.G. Sammis, and W.B. Banerdt, Spacing Distributions and Intersection Angles for Kilometer Scale Lineations on the Plains of Venus (abstract), *Lunar and Planet. Sci. Conf.*, *XXV*, 155-156, 1994.

Bowman, D.D., and C.G. Sammis, Determining the Thickness of Venus' Elastic Lithosphere Using Fracture Length Distributions (abstract), *EOS Trans. AGU*, *75*, 413, 1994.

Bowman, D.D., and C.G. Sammis, Implications of Small-Scale Fracturing on Guinevere Planitia, Venus (abstract), *Lunar and Planet. Sci. Conf.*, *XXVI*, 155-156, 1995.

Bowman, D.D., and C.G. Sammis, A Tectonic Model for the Formation of the Gridded Plains on Guinevere Planitia, Venus, and Implications for the Elastic Thickness of the Lithosphere, submitted to *J. Geophys. Res.*, 1995. pre-print attached.

A Tectonic Model for the Formation of the Gridded Plains on Guinevere Planitia, Venus, and Implications for the Elastic Thickness of the Lithosphere

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Abstract. The "gridded plains" of Guinevere Planitia are comprised of a north-east trending set of extremely linear and regularly spaced lineations, and a north-west trending set of more irregularly spaced curvilinear radar-bright structures. The fainter NE set has been interpreted as cooling cracks in a thin but widespread basalt surface layer in frictional contact with its substrate (Banerdt and Sammis, 1992). The brighter NW trending set are interpreted as shear fractures in the lithosphere which have propagated up through the surface basalt flow after the more regular set of cooling cracks had formed. The length distribution of this set of lithospheric shear cracks has a sharp bend at a length of about 80 km. This reflects the transition from 3-D growth of a penny-shaped crack in the lithosphere to the 2-D elongation of a crack which has penetrated the elastic lithosphere. This interpretation implies that the lithosphere is roughly 40 km thick, in agreement with other recent estimates based on flexure and analyses of gravity and topography. This interpretation also implies that the 500 Ma resurfacing event implied by crater statistics is due to extensive flood basalts, but did not involve the destruction of the preexisting lithosphere.

Introduction

An accurate determination of the elastic thickness of the Venusian lithosphere provides an important constraint on geophysical models of the planet's evolution. Early studies of Venus assumed that the planet had a relatively thin lithosphere [e.g. Phillips and Malin, 1983; Solomon and Head, 1984; and Banerdt and Golombeck, 1988]. This assumption was justified by the planet's high surface temperature, which was believed to elevate the geotherm, raising the elastic-plastic interface to shallower levels. More recently, a relatively thick elastic lithosphere has been called upon to explain such diverse problems as the support of large volcanic edifices [e.g. Smrekar and Solomon, 1992] and the evolution of coronae [McGill, 1994]. Solomon *et al.* [1994] reported that the large positive free air gravity anomalies beneath large volcanoes on Venus imply an elastic thickness of 30-70 km. This result falls in the upper range of thicknesses found through studies of flexure around coronae. Sandwell and Schubert [1992] interpreted topographic profiles outboard of four large coronae in terms of the flexure of an elastic plate. They found that models for the topography were best matched by an elastic plate whose thickness ranged from 30-45 km. In this paper, we develop a new method for determining the elastic thickness of the lithosphere based on the length distribution of small-scale fractures on the volcanic plains. This technique gives an elastic thickness on the order of 40 km. The interpretation further implies that the extensive resurfacing of the volcanic plains involves a relatively thin (<1 km thick) layer widely deposited over the preexisting lithosphere, and that the old lithosphere is not destroyed in the process.

Small-scale fracture patterns on the volcanic plains

One of the first images returned by Magellan was of the "gridded plains" of Guinevere Planitia (Figure 1a), named for the nearly orthogonal set of lineations visible in the radar images (Solomon *et al.* ,1991). Although such small-scale lineations are common features of the volcanic plains, the orthogonal character at this location has turned out to be unique (Bowman *et al.*, 1994). The fainter, regularly spaced north-east trending set have been interpreted as tensile cracks [Solomon *et al.*, 1991; Banerdt and Sammis, 1992]. They are very narrow and show no internal structure (Figure 1b), to the limit of resolution of Magellan images (75 m/pixel). There does not appear to be any lateral offset along the fractures, suggesting that they were formed purely in tension. Furthermore, the reflectivity of the fractures appears to be constant regardless of illumination direction, thus ruling out asymmetric fault scarps. It seems more likely that they are mode I fractures, having no lateral or vertical displacement beyond simple opening of the crack.

At right angles to the parallel NE fractures is a set of more irregular radar-bright lineations. Because they are orthogonal to the set of tension fractures, these were originally interpreted by Sammis and Banerdt [1991] as compressional features. However, as Solomon *et al.* [1991] pointed out, many of the lineations become grabens further to the north. Thus, the irregular fracture set is also interpreted to have formed in an extensional regime. But as Banerdt and Sammis [1992] noted, a close examination of Figure 1b reveals that the irregular fractures have a distinct curvilinear *en echelon* morphology. This suggests a component of shear in the stress field. Note that the morphology of the irregular set is completely different from that of the regularly spaced NE trending fracture set. Notably, the curvilinear shape, broader width, and inconsistent spacing of the NW trending set argues against a purely tensile stress field during their formation [Banerdt and Sammis, 1992].

The relative timing of the formation of the lineations can be determined from crosscutting relationships between the fractures and several small volcanic constructs in the region. Figure 2 shows a portion of the Gridded Plains with several small volcanoes. The irregular fractures cut the volcanoes, implying that they are younger than the age of the volcanism, while the regular lineations are generally obscured. However, a close inspection of the area circled in Figure 2 shows that, while most of the regular fractures are covered by the volcanism, a few of them cut through the volcanics. Thus, we interpret the formation of the regular lineations to be pre- to syn-volcanic. The irregular lineations generally cut through the volcanics, although there is a slight tendency for the smaller fractures to end at the apron of the flows. Thus, the irregular fractures are interpreted to be latest-syn to post-volcanic.

Formation of the regular lineations

The formation of the parallel NE trending fractures was discussed in detail by Banerdt and Sammis [1992] and Bowman *et al.* [1994]. They were interpreted to have formed according to a shear-lag model. This mechanism is commonly used in materials science to describe the fracturing of thin brittle layers deposited on metal substrates. (e.g. Hu and Evans, 1989; and Zok and Spearing, 1992) According to conventional materials science applications of the model, the substrate is assumed to be in tension. As the substrate extends, it exerts a traction on the base of the brittle surface layer causing it to fracture in tension, forming very regularly-spaced parallel fractures. Banerdt and Sammis pointed out that a uniform contraction of the surface layer is mechanically the same as a uniform extension of the substrate. Thus, the fractures predicted by the shear-lag model for an extending substrate can also be produced by a cooling, contracting surface layer.

In relation to Venusian tectonics, the shear-lag model has important implications. The nature of the contact between the surface layer and the underlying lithosphere has an important influence on the development of the fractures. As Banerdt and Sammis (1992) pointed out, the spacing of the fractures, X_c, should be related to the thickness of the surface layer, h, according to the relation

$$X_c=\frac{\sigma_t h}{\tau}, \tag{1}$$

where σ_t is the tensile strength of the surface layer, and τ is the basal shear stress. For the materials science example, τ is the yield stress of the metal substrate. However, for the geological case, the surface layer is allowed to detach from the substrate, in which case τ is the frictional strength of the interface, given by

$$\tau=\mu\sigma_n \tag{2}$$

where μ is the coefficient of friction and σ_n is the normal force across the interface due to the weight of the overlying rock. If we assume that the surface layer is homogeneous, then the shear stress can be rewritten as

$$\tau=\mu\sigma_n=\mu\rho g h \tag{3}$$

where ρ is the density of the layer and g is the acceleration of gravity on Venus. Substituting back into Eq. (1), we find that

$$X_c=\frac{\sigma_t}{\mu\rho g}. \tag{4}$$

Thus, the fracture spacing predicted by the shear-lag model should be independent of the thickness of the surface layer, a result supported by the observation that the spacing is constant over large distances (Banerdt and Sammis, 1992; Bowman *et al.*, 1994).

What geologic conditions might lead to the formation of such an extensive surface layer? The most likely candidate is a flood basalt. The scale of the regions exhibiting the shear lag fractures requires a massive outpouring of lava. The thickness of the unit may vary locally without effecting the fracture pattern, since Eq (4) implies that the fracture spacing is insensitive to the thickness of the surface layer. If the surface unit was emplaced in one event, then the large spatial size of the layer suggests that a very low viscosity lava flow must be the parent. However, the surface need not be emplaced in only one event. The shear-lag model only requires that the surface unit be frictionally coupled to the substrate.

The origin of the surface layer may be tied to global tectonic events. To explain the remarkably uniform crater distributions on the surface of Venus, many workers have invoked various schemes for resurfacing the planet (see Solomon, 1993 for examples). It is possible that the surface unit called for by the shear-lag model is the same layer invoked by many authors as a resurfacing mechanism (e.g. Strom *et al.*, 1994). Due to the high surface temperature of the planet, this lava flow will cool slowly. As it cools, it contracts and forms the observed regular fractures. The long linear form of the cracks is probably a function of a pre-existing tectonic bias (Banerdt and Sammis, 1992).

Formation of the irregular fractures

As Banerdt and Sammis [1992] pointed out, the shear-lag model can not be used to describe the irregular fractures. The shear-lag model requires that the stress field in the surface layer be one of simple tension, with the resulting fractures forming as mode I cracks perpendicular to the tensional stress axis. However, the irregular shape of the fractures suggests that they are not simple mode I fractures, as required by the shear-lag model. As noted above, the morphology of the irregular fractures suggests that the stress field during their formation also included a component of shear. The general morphology of the irregular fractures was reproduced in the laboratory by An (1995) by deforming a clay cake in simple shear. As shown in Figure 3, the resultant network of shear fractures is morphologically similar to the irregular fractures in the Gridded Plains, with one important difference: the laboratory fractures lacked the distinctive *en echelon* structure of the fractures on Venus.

In terrestrial settings, *en echelon* fracture segments such as the ones in the gridded plains are commonly seen in soil layers above a basement fault or fracture (e.g. Tschelenko, 1970; Engelder, 1987). As movement occurs on the basement structure, the fracture propagates upwards through the soil layer. During this upward propagation, the stress field of the fracture rotates to accommodate the shear at the base of the soil. This rotation creates the observed *en echelon* morphology. (Engelder, 1987) Furthermore, the rotation of the stress field induces a tensile moment on the fracture, causing the formation of small grabens within each *en echelon* segment. Formation of the grabens may be enhanced by a component of contraction orthogonal to the regular fracture set, due to contraction of the cooling surface layer. These grabens are clearly visible in the Magellan images, and are indicated with an arrow in Figure 1b. Thus, to account for the formation of the *en echelon* irregular fracture set, a thin surface layer is again required - the same one required by the shear-lag model. However, in this case the observed *en echelon* fractures are being controlled by a series of subparallel shear fractures in the lithosphere which actually predate the deposition of the surface layer.

The proposed fracture mechanisms and geologically constrained sequence of fracturing discussed above can be used to construct a tectonic history of the Gridded Plains as idealized in Figure 4. The first event in this sequence is fracturing of the elastic lithosphere in simple shear. The plains are then covered by a flood basalt. As the flood basalt cools, it contracts to form the regularly spaced shear-lag fractures. Immediately following the formation of the shear-lag fractures, localized volcanism occurs, obscuring segments of the regularly spaced parallel lineation sets. Finally, the older lithospheric fractures propagate upwards through the surface flood basalt, dissecting the late-stage volcanism. The component of thermal contraction orthogonal to the shear-lag fractures is accommodated by these irregular fractures.

Distribution of Irregular Fracture Length Scales

An inspection of Figure 1a reveals that the irregular fractures have two distinct populations. The first population consists of shorter fractures with lengths between 2 and 80 kilometers. The second population consists of very long fractures with lengths ranging from 80 to 1000 kilometers. Within the Gridded Plains, there are approximately 2600 irregular fractures with lengths greater than 2 kilometers. The shorter fractures occur much more frequently, making up approximately 99% of the fractures in the Gridded Plains. While the 17 longer population II fractures visually dominate images of the region, numerically they comprise less than 1% of the total number of fractures. However, their significance is evident when viewed in a plot of the cumulative length distribution (Figure 5). In this plot, the two populations of fractures are clearly visible as distinct line segments with different slopes.

The two populations of lineations represent fractures with two distinct propagation modes. When the fractures are short compared to the thickness of the elastic thickness, they can be modeled as simple shear fractures in a semi-infinite elastic half-space. The fractures themselves can be approximated as semi-circular cracks centered on the surface of an elastic plate, as shown in Figure 6. Thus, the depth to which any given crack has propagated is equal to the radius of the semi-circle, while the surface length of the fracture is equal to its diameter. The length distribution such a system of cracks will produce can be qualitatively understood by simple damage mechanics.

As an elastic plate undergoes continued fracturing, the volume of intact (unfractured) material decreases. The decreased volume of intact material must still accommodate the same external stress. Therefore, the remaining volume of rock will experience a higher local stress, which will cause the layer to nucleate fractures at a higher rate. Thus, the number of fractures nucleating in the plate will increase with time. At any given instant, the continually increasing nucleation rate will be observable as a uniform *decrease* in the number of fractures with increasing fracture length, producing a negative slope in a cumulative length distribution plot (Figure 5, population I).

However, the lithosphere of Venus is not a semi-infinite elastic half-space. As the cracks propagate downwards, they eventually penetrate deep enough to reach the base of the elastic lithosphere. At this point, ductile shear displacement can occur on the base of the crack on a time scale comparable to that of crack growth. The effect is to increase the stress concentration at the vertical leading edges of the advancing crack, thus increasing its apparent propagation velocity. Thus, fractures which have penetrated the elastic lithosphere will have markedly longer fracture lengths than might be expected if they had continued propagating in an elastic half-space. In the cumulative length distribution plot, this results in a shallower slope for the population II fractures, as in Figure 5.

The specific fracture length at which the distribution changes from population I to population II fractures is a function of the thickness of the lithosphere in the region. At this critical fracture length, the crack has penetrated to the base of the elastic lithosphere, but has not yet begun to "run away". Thus the penetration depth of these cracks can be used as an estimate of the elastic thickness of the lithosphere. Since we have assumed that the fractures propagate as semi-circles centered on the surface of the planet, the depth to which the crack has propagated is equal to half the surface fracture length. In the Gridded Plains of Guinevere Planitia, the change between population I and population II fractures occurs at a fracture length of 80 km, which corresponds to an elastic thickness of approximately 40 km.

Discussion

In theory, fracture length distributions represent a powerful new tool for determining elastic lithospheric thickness. However, as with any geophysical model of the lithosphere, it is important to understand what we mean by the "elastic thickness". Any discussion of the elastic properties of a material imply a certain rate dependency. In the case of plate flexure models, the elastic thickness is determined by the response of the lithosphere on time scales determined by the strain rate in the Venusian lithosphere. The elastic thickness implied by fracture length distributions is determined by the depth at which the rate of plastic creep is faster than the rate of elastic fracture growth. Unfortunately, we do not know the growth rate of the fractures seen on Venus. However, the close correlation in elastic thicknesses on Venus as determined by fracture lengths and flexure models suggests that the observed fracturing occurred on a time scale comparable to that required to induce flexure in the lithosphere. If the time scales are indeed comparable, then fracture length distributions could yield a useful tool for verifying the elastic thicknesses predicted by flexural models.

Unfortunately, the application of this method requires rather special geological circumstances. The formation of such large scale fracturing requires a relatively simple tectonic environment. A successful application of the technique requires that a region with dimensions significantly greater than the thickness of the lithosphere be modified only by fracturing due to distributed simple shear. For instance, in the case of Venus, the hypothesized 40 km thick lithosphere implies that the fractures will not begin to "run away" until they have reached a surface length of 80 km. To observe the different populations of fractures in Figure 5, the fractures must be allowed to propagate to lengths of several hundred, (if not thousand) kilometers. If other active geologic processes, such as the formation of corona or deformation belts, occur in the same region, they would tend to obscure or modify existing fractures, thus changing the observed length distribution.

Acknowledgements

The authors wish to gratefully acknowledge Bruce Banerdt for his many helpful discussions. We would also like to thank Remberto Magbanua for his tireless efforts at the computer.

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Figure 1a. The "gridded plains" of Guinevere Planitia. Note that the image is dominated by short fractures; very few fractures span the entire width of the region. The width of the image is ~490km. The inset shows the location of figure 1b. (Portion of Magellan image C1-30N333)

Figure 1b. Magnification of the gridded plains. The north-east trending shear lag fractures are indicated by a black arrow. The white arrow shows the location of a small graben formed by local rotation of the stress field in a thin surficial layer. Note the distinctive *en echelon* nature of the north-west trending fractures. See text for details.

Figure 2. Localized volcanism in the gridded plains. The arrows indicate small shields and their associated flows which have been dissected by the irregular north-west trending fractures. The regular lineations generally are covered by the lava flows from the shields. However, while the regular lineations are generally obscured by the volcanics, they can occasionally be seen to cut through the flows, as in the circled region on the right side of the image.

Figure 3. Fractures developed in a layer of clay deformed in distributed simple shear. Sense of shear is right-lateral. Note the similarities to the fractures in figure 1a. Photo courtesy of Linji An.

Figure 4. Inferred tectonic history of Guinevere Planitia. First, through-going fractures form in the lithosphere (a). The plains are then overlain by a thin volcanic surface layer (b). As this layer cools (c), it decouples from the original lithosphere to form the shear-lag fractures. Fracturing occurs concurrent with localized volcanism. As localized volcanism continues (d), the original through-going shear fractures propagate to the surface, forming the en echelon fracture set.

Figure 5. Fracture length distribution for the gridded plains region of Guinevere Planitia. The points labeled I in the plot are fractures that have not yet broken through the lithosphere. The points labeled II are through-going fractures that have begun to "run-away" relative to the population I fractures. The sharp decrease in the number of population II fractures which occurs at a length of 300 km is a result of the limited spatial extent of the gridded plains.

Figure 6. Hypothesized model of lithospheric fracture propagation. Ductile creep in the substrate increases the stress intensity factor at the shallower levels of the advancing crack front, causing the fracture to rapidly increase in length.

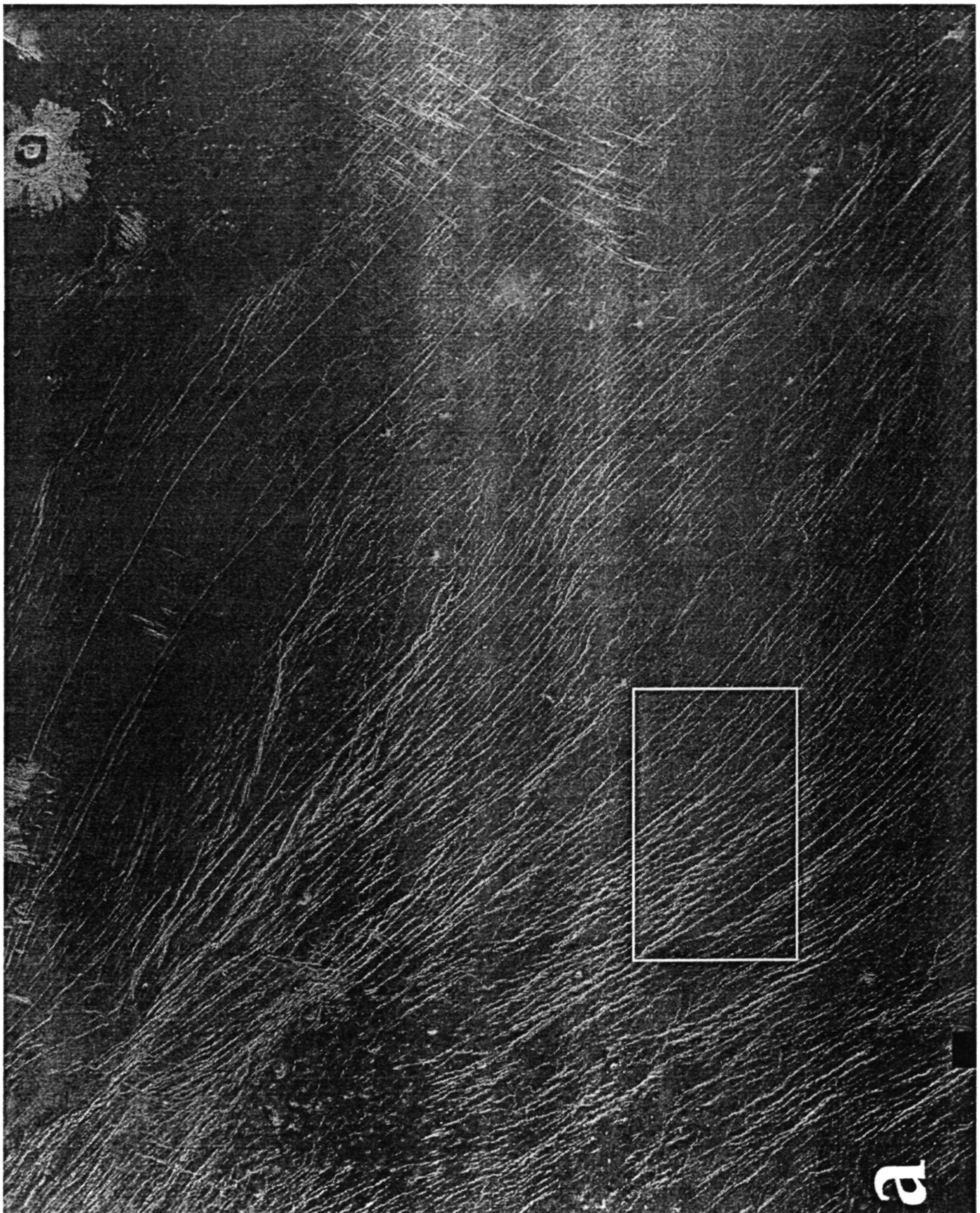


fig 1a

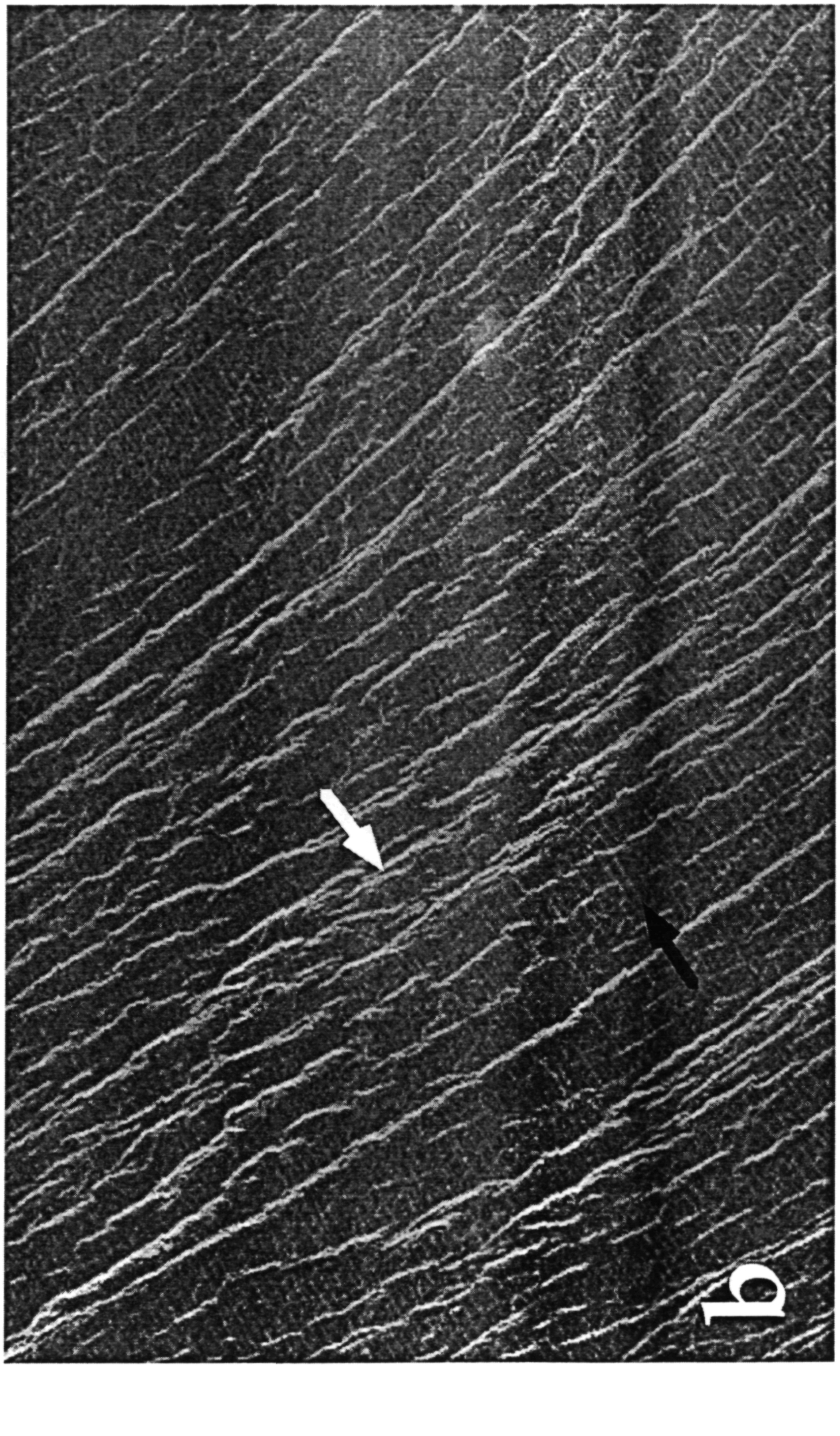


fig 1b

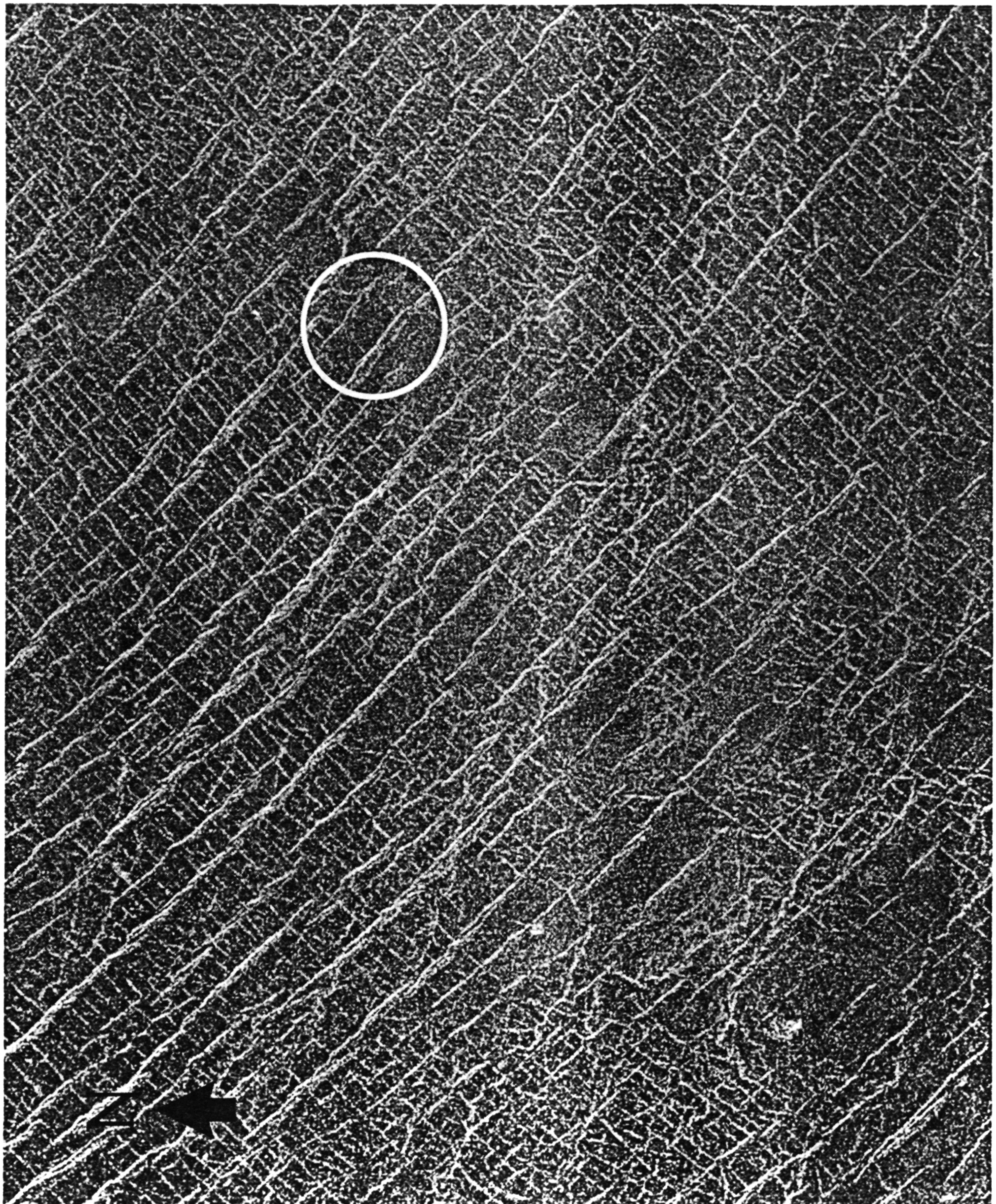


Fig 2

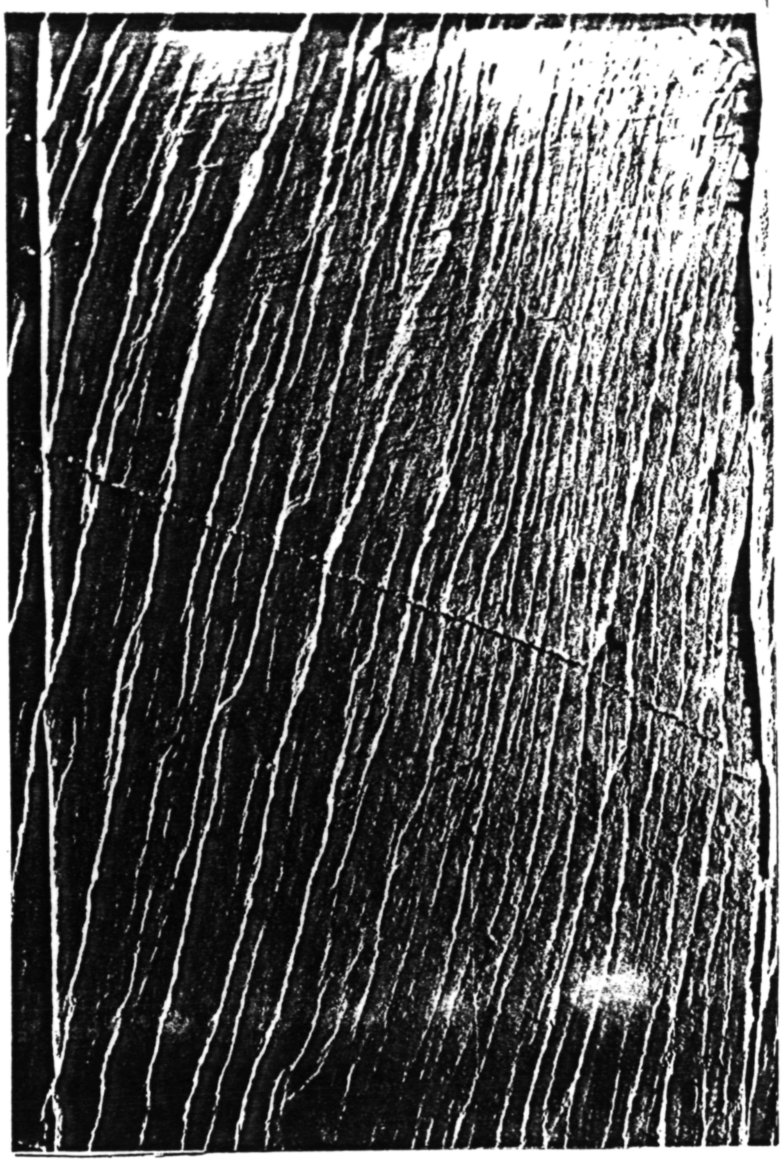


fig 3

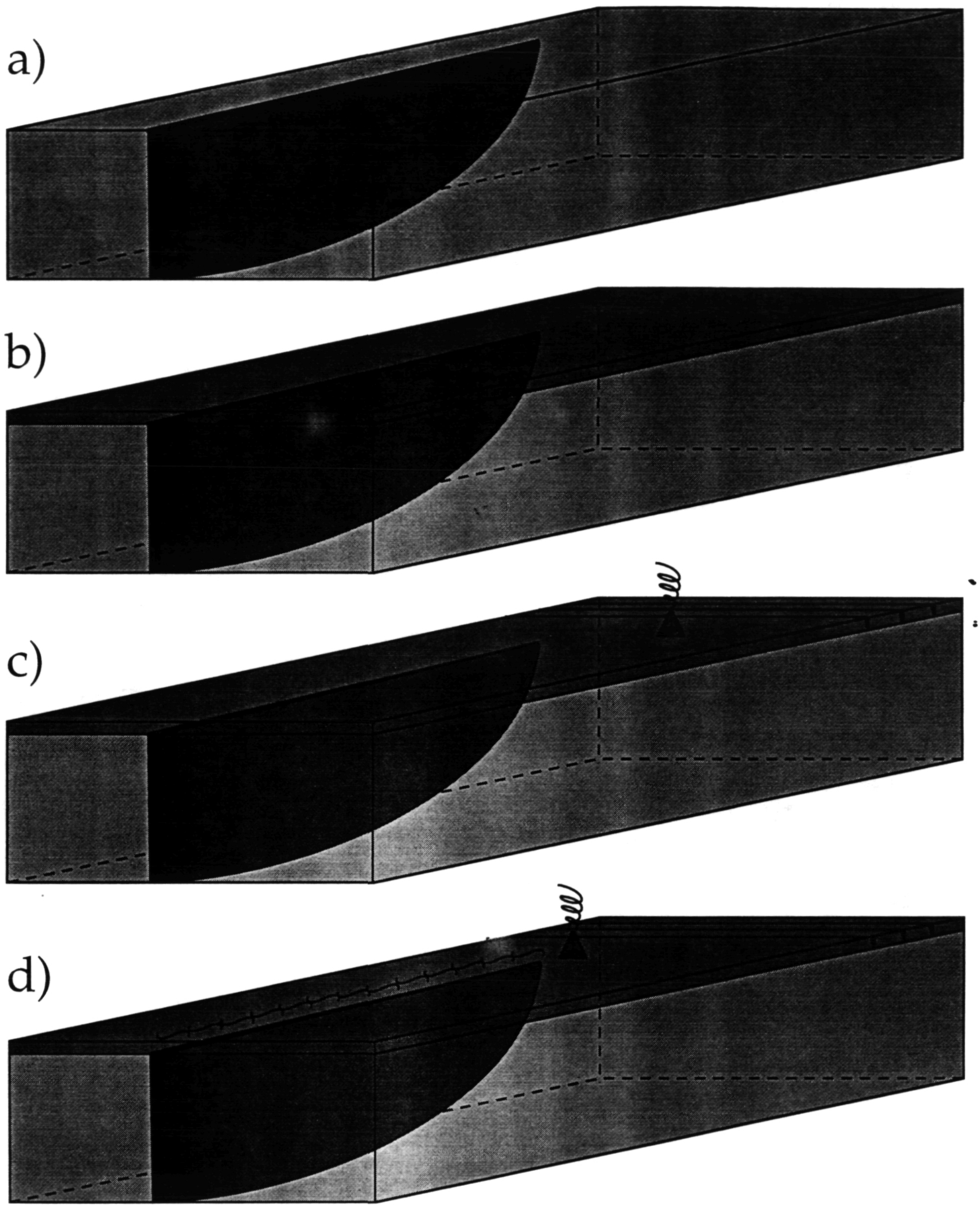
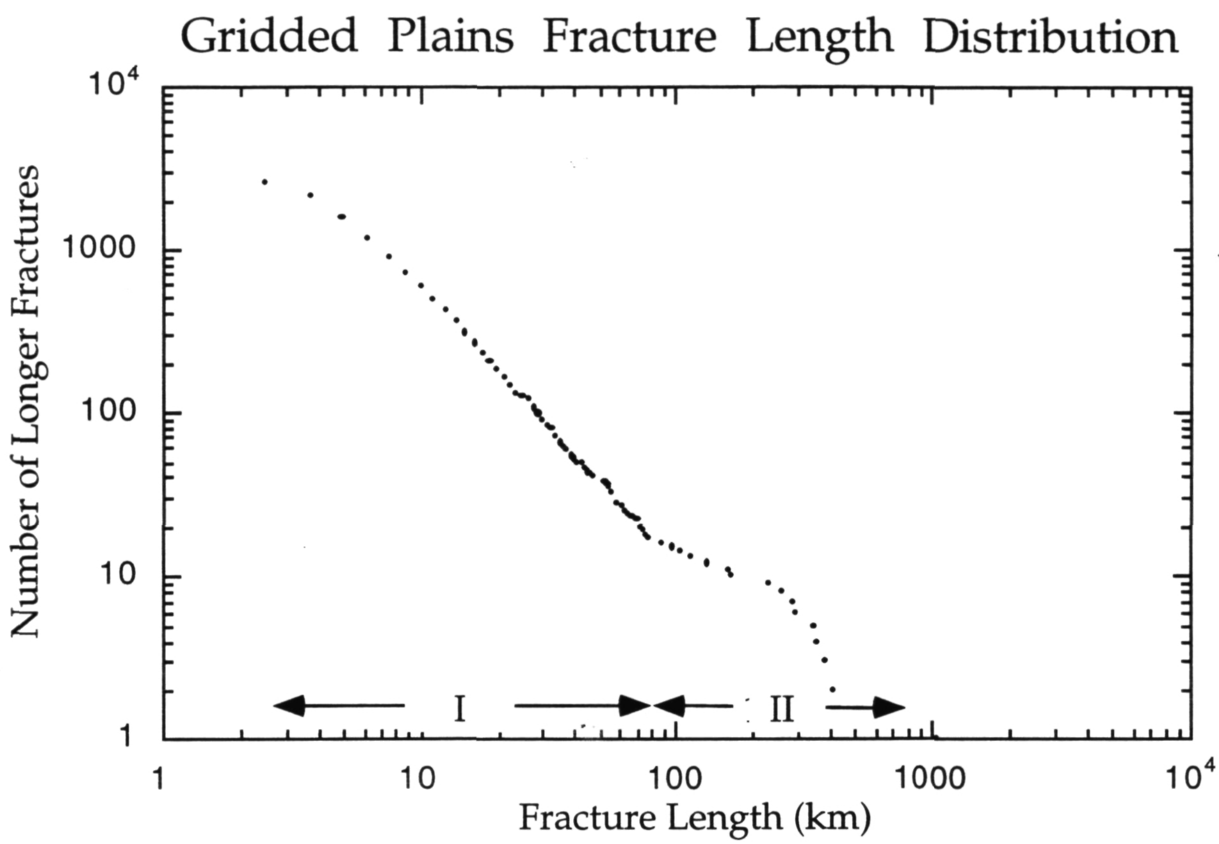


fig 4



Gridded Plains Fracture Length Distribution
Number of Longer Fractures
Fracture Length (km)
I
II

fig 5

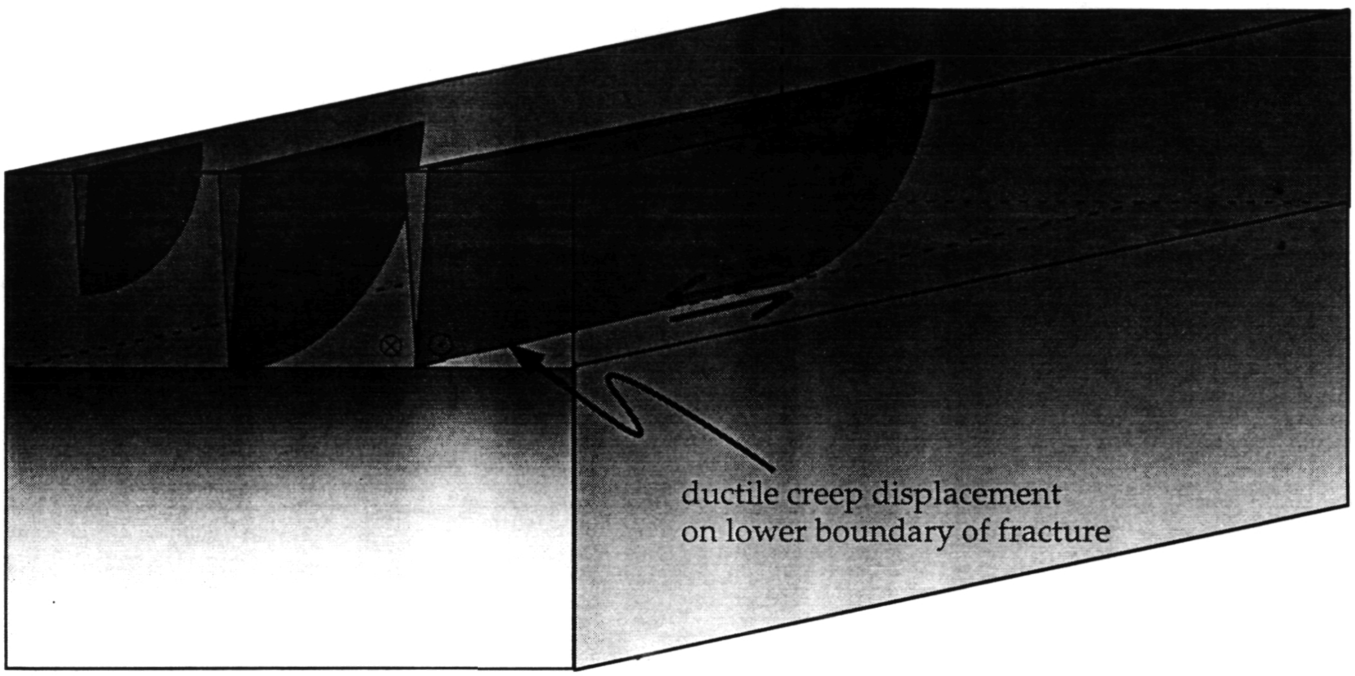


fig 6