PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A
MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Introduction

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Introduction

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The basis of this conference, which was something of an experiment, was the idea of bringing together two groups of people concerned with a similar problem, namely the mechanisms of slow deformation of solids at elevated temperatures, but who are differently motivated and so follow different disciplines in their study of the phenomena.

Both the structural geologist and the geophysicist clearly have an interest in the hot deformation of solids, since the increase in temperature within the Earth is considerable, even in quiet areas (i.e. those away from volcanic activity), ranging from 10 to 50 °C/km. This alone, if continued, would lead to temperatures of between 100 and 500 °C at the bottom of the crust under ocean floors. The variation in temperature gradient arises usually from variation of thermal conductivity, the product of the two being remarkably constant at a value around 60 mW/m^2 (1.5×10^{-6} cal cm^{-2} s^{-1}) (see, for example, Horai & Simmons 1969), leading to an observed outflow of heat from the Earth of some 2.5×10^{13} W. Movement of material within the mantle and crust occurs slowly except during earthquakes and these movements correspond to rates of strain and estimated stresses, which lead to values of the viscosity of the material of 10^{21} Pa s (10^{22} P) (see Anderson 1966).

The normal definition of a solid, used by the materials scientist based on experience with glass, is that it possesses a viscosity greater than 10^{14} Pa s (10^{15} P), so that the above rates of creep correspond to flow within the solid state.† A creep-resistant nickel alloy showing 2 % elongation in 1000 h under a stress of 61 MPa shows a viscosity of 3.7×10^{15} Pa s. Creep tests on engineering materials only very rarely correspond to viscosities greater than 10^{18} Pa s (10^{19} P) because the stresses used are those to produce strain rates of 3×10^{-10} s^{-1} (10^{-6} h^{-1}). However, components are designed for service lives of 20 years and if strains are to be less than say 0.1 % in this time under an operating stress of 75 MPa, then the engineer and materials scientist are interested in materials with nominal viscosities deduced from the equation

$$\sigma = 3\eta\dot{\epsilon}, \tag{1}$$

where σ is the tensile stress, η the coefficient of viscosity and $\dot{\epsilon}$ the tensile strain rate, of 1.5×10^{19} Pa s (1.5×10^{20} P).

The laws of creep deduced by the materials scientist are usually produced in the hope that they may help the engineer in the process of design, either to predict the rate of creep of engineering components, or else to defer the failure of these components. He knows the history of the synthesis of the material which is is studying.

The situation for the geologist is quite different. He attempts to explain physical features of the Earth and to account for motions in the Earth's crust and upper mantle. The history is, to a large extent, unknown. For instance, we know that the material at the top of the mantle (the

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† The strain point, a definition used in glass manufacture, corresponds to that temperature at which internal elastic strains in a piece of glass are removed in four hours in a conventional article and to an estimated coefficient of Newtonian viscosity of $10^{14.5}$ P.

mantle being defined as that below the Moho (Mohorovičić discontinuity)) is spreading laterally across the Earth's surface with an upswelling beneath the ocean ridges and subduction under the continental masses (Hess 1962). This is accompanied by fracture of the crust in many cases, with the attendant production of transcurrent faulting in the crust above the mid-ocean ridges (see, for example, Vacquier 1965), and with a pattern of cracking and faulting elsewhere (see references for example in the Royal Society Symposium on Continental Drift (Blackett, Bullard & Runcorn (eds) 1965)). The flow of the material of the upper mantle appears to be more akin to that of a creeping solid than of a Newtonian fluid (even though the motion may be driven by convection) because postulated viscosities become of somewhat obscure meaning with values of 10^{20} Pa s being necessary (Anderson 1966), and, in addition, there is evidence of the existence of differences between principal stresses of as much as $(1–2) \times 10^7$ Pa (Munk & MacDonald 1960).

We also know from geodetic, tidal data, and tilted and raised beaches, that where ice sheets have melted, what is called isostatic rebound is occurring, decaying at a rate approximately exponential with time (Farrand 1962), so that crustal features are being elevated due to the release of the pressure due to the ice sheets. Superficial measurements may be made of the vertical movements in this case, which are of the order of centimetres per year, and of the horizontal movements in the case of continental drift. The rates in the latter case are again of the order of 1 cm/a and may be up to 10 cm/a in parts of the Pacific Ocean. Creep is clearly involved, but the question of what material is undergoing these rates of slow creep is not, of course, entirely clear. If an input can be obtained, either from the science of materials or from other sciences, concerning possible lower and upper limits to the rates of creep for known materials, then some rational deductions may be made concerning the type of material involved in the creep processes in the mantle. The constitution of the mantle rocks is not subject to direct experimental verification, although very plausible arguments suggest that they may be identified close to the mid-ocean ridges and when overriding occurs during mountain building (Jacobs, Russell & Wilson 1974, pp. 87 and 469).

There has, apparently, been some success achieved in interpreting rates of creep involved in geological processes in terms of laws deduced from materials science (see, for example, Gordon 1965). In addition, Orowan (1965) has considered the whole question of continental drift from the point of view of the science of materials and theory of plasticity.

The theories which have been used to understand creep of the upper mantle of the earth have nearly all, as far as I am aware, been concerned with so called 'steady-state' creep, in which the strain varies linearly with time. However, other forms of creep – often referred to as transient creep (see, for example, Garofalo 1965) may be important over a geological time scale (see Murrell (1976); Weertman, this volume, p. 9).

The type of creep involved in the flow of the mantle has been postulated to be either that called Nabarro-Herring creep (Nabarro 1948), Coble (1963) creep, or Nabarro's modification of the former for coarse grained materials in which dislocations form the principal sources and sinks for vacancies (Nabarro 1967). The general theory for volume conserving diffusion creep in a polycrystal of a one component solid (Raj & Ashby 1971) yields for the tensile strain rate an equation of the form

$$\dot{\epsilon} = \frac{14\sigma\Omega}{kT}\frac{1}{d^2}D_{\mathrm{V}}\left(1+\frac{\pi\delta}{d}\frac{D_{\mathrm{B}}}{D_{\mathrm{V}}}\right), \tag{2}$$

where σ is the stress, Ω the atomic volume, k and T have their usual meanings, d is the grain diameter and δ the effective cross section of a grain boundary. D is the diffusion coefficient with subscript B for boundary and V for volume diffusion. There is a linear dependence of strain rate upon stress and so an effective Newtonian viscosity can be identified with an effective temperature dependence of the form $(1/T)\exp(-Q/kT)$. Nabarro's volume diffusion predominates at very large grain sizes and at very high temperatures (where D_B/D_V becomes reduced). When diffusion creep in compounds is considered, attention must be paid to the nature of the diffusing unit and to the effects of departures from stoichiometry, as well as the effects of specific impurities upon the value of the diffusion coefficient. The simple use of tracer diffusion coefficients is inappropriate (Pascoe & Hay 1973; Stocker & Ashby 1973).

When dislocations become involved as sources and sinks for vacancies, then the strain rate depends upon a higher power of the stress and this is so for all processes of dislocation creep. For instance, for many coarse-grained face-centred cubic and body-centred cubic metals, the secondary creep rates are given by an equation of the form

$$\dot{\epsilon} = KDGb(\sigma/G)^n/kT, \tag{3}$$

where G is the shear modulus, b the Burgers vector and K is a constant. The exponent n varies between a value of 3 and 7, consistently with shear modulus and stacking fault energy for the face centred cubic metals. The constant K can vary widely over a factor of 10^6 depending upon the exact dislocation process involved (Bird, Mukherjee & Dorn 1969).

A dependence of strain rate upon stress to a high power is generally true for many materials (see Finnie & Heller 1959; Lubahn & Felgar 1961). We have, as yet, no fundamental theories of creep under other than uniaxial stress.

There are clear phenomena in the deformation of rocks and minerals which are not dealt with in the conventional discipline called Materials Science. In the régime of cold deformation, we have the process of cataclasis, where the material is effectively fragmented along a plane and relative movement of the fracture faces occurs. At elevated temperatures there is also the recently recognized importance of the phenomenon of pressure solution (Ramsay 1967; Rutter 1976). In this, diffusion is assisted by the presence of water at grain boundaries and it has some geometrical similarities to the diffusion creep described above.

If, as a result of this meeting, the materials scientist recognizes some additional modes of deformation, or if superplasticity (see Gittus (1975) for a review) be seen to be important in geological processes, the organizers will feel gratified. The constitutive equation describing superplastic flow shows a dependence of strain rate on stress to a higher power than in equation (2), and the microstructural characteristics of a material undergoing superplastic flow, characterized by a fine and stable grain size, are different from those of a material deforming by Nabarro creep or dislocation motion.

Another point worth making at the outset is that the materials scientist and engineer is usually able to distinguish quite clearly between structures produced by the process of slow deformation at elevated temperatures, whether or not accompanied by fracture, and those produced during recrystallization in which the microstructure is totally reconstituted. Creep under conditions of periodic recrystallization has been studied by Gilbert & Munson (1965). Of course, low melting point metals are well known to recrystallize during deformation at room temperature or slightly above, so that the microstructure progressively changes with deformation and then shows a discontinuous change when recrystallization occurs (see, for example, Gay & Kelly 1953). With the hot creep of engineering materials or of ceramics, whether or not recrystallization has intervened, is usually known from X-ray or microscopical observation. In the case of deformation

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of subsurface rocks, of course, it will not be known how far recrystallization may have altered the microstructures and how far not. When metals are subject to heavy deformation and subsequently allowed to recrystallize, sharp textures are produced and these sharp textures can be related to the preceding texture produced by the deformation (R. W. Cahn, this volume, p. 159). I do not know whether or not discussion of this topic could illuminate some riddles of geological structure.

The engineer, when considering creep, usually likes to ignore the microstructure and to deduce constitutive equations describing the material's behaviour. F. A. Leckie, in the second paper, calls this the 'black box' approach. It often fails, and, when a material shows wide deviations in creep ductility, leads to a very conservative design. It leaves out of account methods of examining a component part-way through its life in order to assess the damage accompanying creep. However, it has the great advantage of considering multiaxial stress states.

At a meeting such as this where creep is to be considered under widely different conditions, the stress system is very important. In materials science it is clearly recognized that there is a difference between the effects of tensile and shear stresses, and the different effects on the microstructure can be identified. For instance, shear strains produce voids at grain boundaries, but a tensile stress is needed in order for these to grow (Dyson, Loveday & Rodgers 1976). The terrestrial creep, which we shall be considering at this meeting, occurs under conditions of moderate pressure, e.g. at a depth of 7 km under the ocean, the pressure at the top of the mantle is about 6×10^7 Pa, and at 50 km directly below the stable platforms of a continent some 15×10^8 Pa. If we consider that flow can occur in the soft upper mantle – the asthenosphere ('ασθενεία, lack of strength) – at depths of 100 km, then the pressures attain 3×10^9 Pa, or a small percentage of the bulk modulus at atmospheric pressure.

Creep and fast slip also occur at what geologists call transform faults, and there appears to be some similarity in this to grain boundary sliding. The differences in scale are enormous, e.g. that between 10 μm and 100 km, or a factor of 10^{10}. However, the geometrical similarities are so striking that I would like to believe they cannot be ignored and may be helpful in arriving at possible modes of relative motion.

In an alloy at temperatures above one half of the melting temperature, the grain boundaries deform easily and the grains themselves are relatively, but not completely, rigid. The grains slide past one another and there is some deformation within the grains. This deformation may be accomplished either by diffusional flow or by some type of dislocation motion; the dislocation motion often results in kinks and folds. The driving force is the ability of the applied stress to do work upon the specimen. The analogy is between this process and that in which relatively rigid lithospheric plates are pushed apart by upswelling of magma at an inconformity between the plates – compare Figures 1 and 2 of Bhattacharji & Koide (1975) describing motions in the Red Sea area (see also figure 1) and the illustration of a fold near a triple-point grain junction in Chang & Grant's (1956) work on the slow deformation of an aluminium–zinc alloy at a temperature of 260 °C, where the grain boundaries are weak and their sliding produces a deformation band within the grains (see figure 2).

The similarity between the work of the materials scientist and that of the structural geologist or geophysicist is that each has been concerned with a deduction of properties, and in the geologist's case also a deduction of history, from a knowledge of crystal structure and microstructure. The engineer uses this knowledge to derive constitutive equations, indicating rates of flow under prescribed conditions of temperature, pressure, strain rate, stress state, etc. Now that crustal blocks of the Earth are seen to be in constant motion, the science of geology may be able to predict

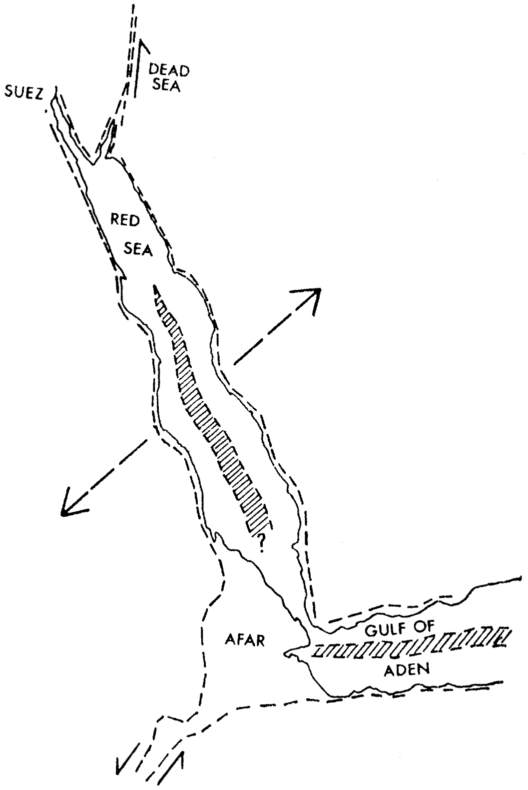

FIGURE 1

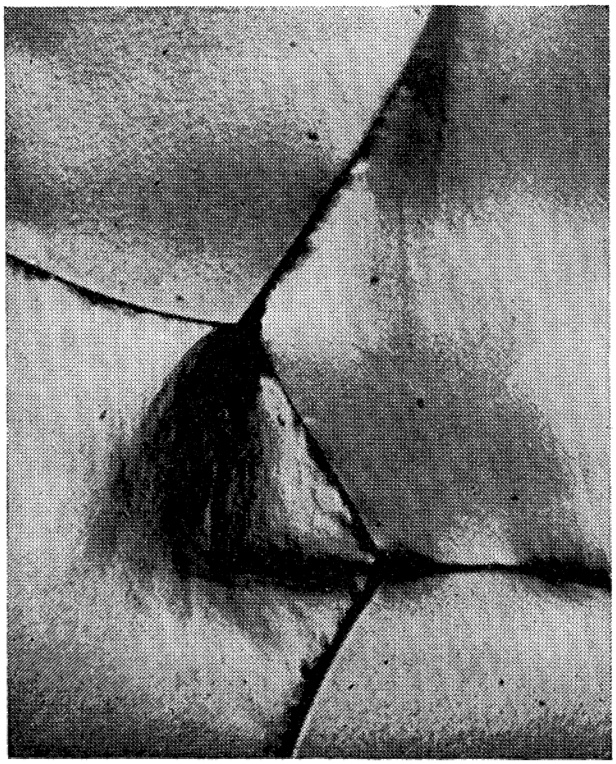

FIGURE 2

FIGURE 1. The formation of the Red Sea by extension (scale 1:28600000). (Reproduced from Girdler 1965.)

FIGURE 2. Fold formation in an aluminium–zinc alloy at 260 °C and 15.9 MPa (magn. × 92). (Reproduced by permission of the copyright owner, American Institute of Mining, Metallurgical and Petroleum Engineers, from Chang & Grant (1956).)

triumphantly the expected changes in geography and knowledge of the constitutive equations will be necessary for this. In figure 3 I have illustrated the conventional flow of information, which has usually been vertical, between the materials scientist and engineer and between the geologist and geophysicist. By placing one above the other, I am *not* emphasizing a hierarchy.

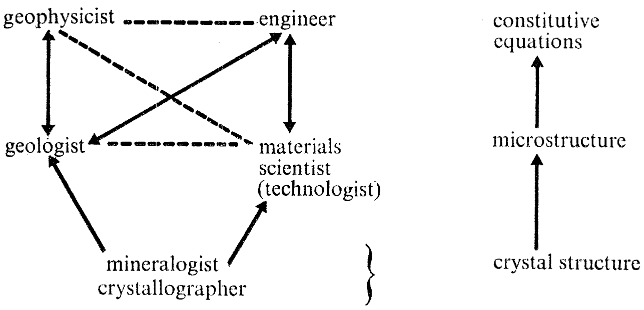

FIGURE 3

There has been some contact, of course, between the geologist and the engineer, via soil mechanics and structural phenomena. The aim of this conference is to bring about a better horizontal flow of information and also a better diagonal flow of information, e.g. between the geophysicist and materials scientist.

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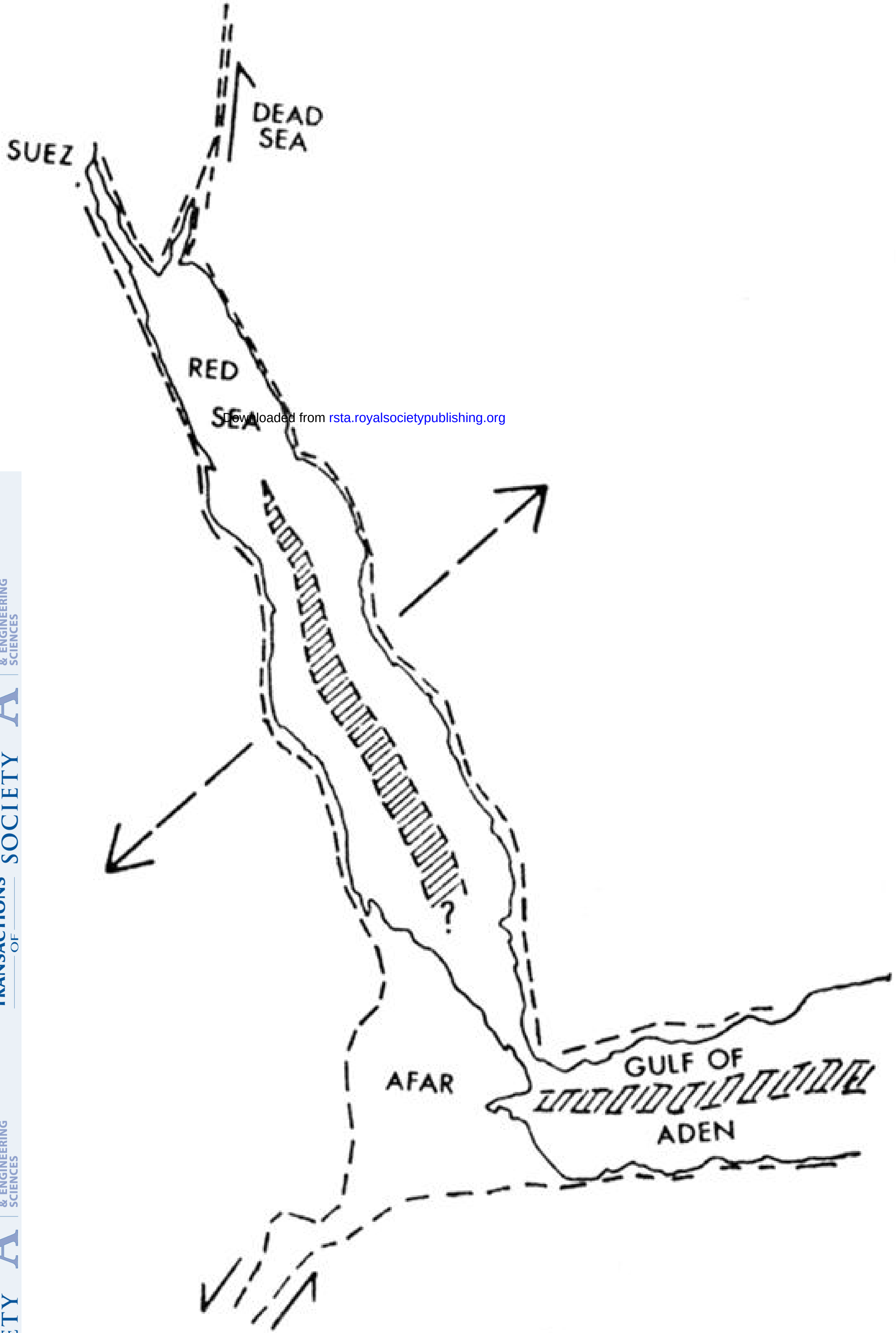

FIGURE 1

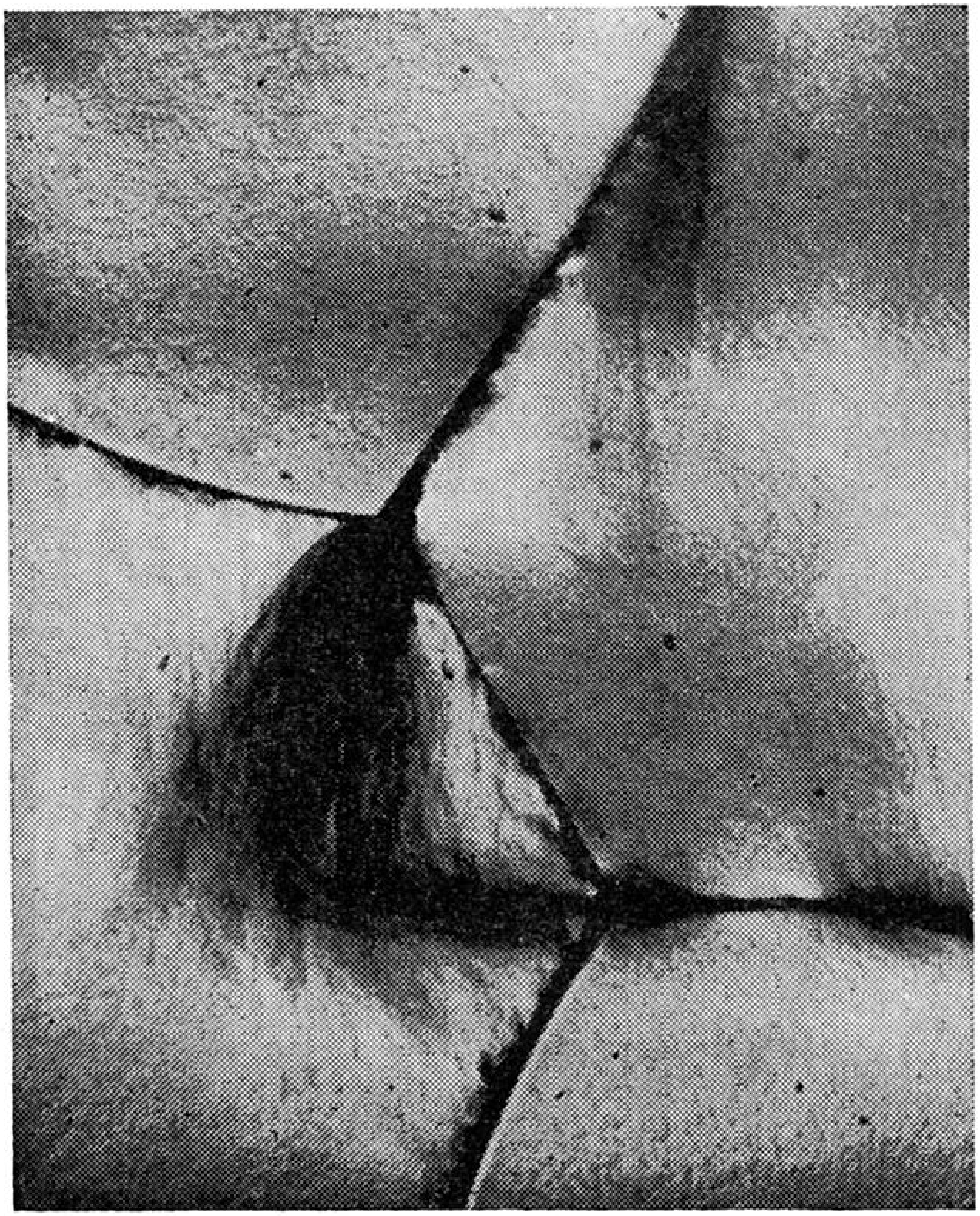

FIGURE 2

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