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Heat Flow and Magmatic Activity in the Proterozoic

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Heat flow and magmatic activity in the Proterozoic

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[Plate 14]

Proterozoic tectonics are considered to reflect the changes from the small mantle convection cells of the Archaean to the giant cells of the present. Approach to the 'modern' regime is considered to be evident about one billion years ago. Metamorphic patterns from Brazil provide evidence for a substantial reduction in thermal gradients over the Proterozoic period. It is suggested that reduction of radioactive heat production near the Archaean–Proterozoic boundary led to thickening of stable granitoid crust and sweeping together of a very extensive granitoid veneer into super continents. Fundamental to the view presented, is the concept of large scale crust mantle mixing caused by subduction, crustal basement uplift, and weathering processes.

Introduction

Almost one year before this discussion meeting on Proterozoic Tectonics, Professor Sutton invited me to take part and talk on heat flow and magmatic activity. It was not difficult to accept the invitation but I was well aware that the subject I had accepted, involving a time span of half of Earth history, is one where we are only beginning to collect the data necessary to form any definite conclusions. But this is the period of the International Geodynamics Programme and it is perhaps a fitting time to examine the problem.

Practically every tectonic phenomenon we observe at or from the Earth's surface, is related to the way in which heat escapes from the Earth. Magmatic events are involved in almost every major tectonic process and may even be the dominant primary phenomena driving tectonic events. At the outset, one need not apologize for the present state of ignorance or even confusion for it is only during the last three decades that we have developed a rational approach to the last 200 Ma of Earth history. At this time too, we are beginning to have a reasonable comprehension of the small remnants of the pre-3000 Ma crust. Thus before approaching the topic of this paper, I consider it necessary to reflect on what is becoming well understood.

Certain constraints on our knowledge of the past and our approach must be clearly recognized. First, we have only parts of the present continental crust to observe. The ocean floor crust is new and in its formation by magma injection and subduction much of our evidence is swept away. What happened to the other 80 % of Proterozoic crust, or for that matter Archaean crust; what was its nature? Can we use the preserved sample as a guide to the larger part that has been removed? All we have is on the continents.

Secondly, we can be sure, that radioactive heat production has dropped in intensity by the exponential laws of decay (see Windley 1973; Mason 1966). How this has influenced heat flow depends on our models of the distribution of the radioactive elements and such models are not perfect. But most geochemists would agree that the hot elements tend to be concentrated near the surface, but they may also be mixed by the subduction process (e.g. subducted spilites, probably contain more potassium than their parent basalts). Estimates of the fall off in radioactive heat production vary, but starting from 4500 Ma ago, it seems reasonable that by 3000 Ma heat production might have decayed to one half its original value, and by 1000 Ma ago to a value less than double the present. If tectonic processes reflect heat production, then the drastic changes must be in the early crust while during the Proterozoic, and particularly Late Proterozoic, we may anticipate a regime tending to that of the present. In the present stable continental crust, heat production, heat flow and thermal gradient are in a close approach to balance. The 30 km crust, the 20–30 °C km^{-1} gradient, are also in accord with data on the melting behaviour of crustal materials. If temperatures at 30 km depth are near 600 °C, then any significant increase will lead to melting and production of quartz rich melts of the granite family.

I would stress that igneous processes lead to surface spreading. Magmatic processes tend to increase surface elevation which in turn leads to spreading via the erosional processes of particle transport and solution. Solution processes (let us remember that river water and ground waters contain about 100 p.p.m. dissolved rock constituents) which are vast in quantity and extent, rapidly lead to spreading through the entire hydrosphere and bring 'continental' elements into interaction (mixing) with 'mantle' elements of the sea floor. The oceanic residence times of elements (U, 0.5 Ma; K, 10 Ma; Rb, 0.3 Ma; Sr, 19 Ma) are short. The sea floor crust may later remix with the mantle. And the subduction process must return water to the mantle and back to the crust via mantle motions. At the present time the oceans are subducted about every 300 Ma.

The present thermal regime

The heat flow-magmatic situation of the present Earth is dominated by

(*a*) Magma rise at ocean ridges leading to large values of heat flow. Absorption of heat by the melting process in the mantle must involve a significant fraction of mantle heat production and must buffer the mantle thermal gradient.

(*b*) Cooling of intrusive ridge magmas by fluid convection (Lister 1972) leading to low values of heat flow and intense chemical modification of the primary materials. Metamorphic processes reflect steep thermal gradients at low pressures.

(*c*) Conductive cooling of the new crust associated with spreading from the ridge coupled to chemical heating by seawater interaction processes (Fyfe 1974*a*; Salisbury & Christensen 1973).

(*d*) Low heat flow at trench subduction regions associated with descent of cool crust. This is the environment of blue schist metamorphism and intense metasomatism associated with return flow of subducted water.

(*e*) High heat flow associated with regions above subduction zones where a small part of the descending slab melts producing basaltic andesites (Fyfe 1975; Fyfe & McBirney 1975) whose composition reflects the continent–sea floor mixing.

(*f*) Magma rise above the subducted plate moves water back to the crust, loads the crust and promotes the granite cycle coming from deep crustal levels. Again this is a spreading process with the strong possibility of deep mixing of crust and mantle fusion products.

Thus, overall, heat flow and magma patterns and tectonic motions are sympathetic allowing for modifications caused by hydrosphere interaction. The patterns of magma and crust motion control the thermal regime and modify the pattern expected from radioactive heat production alone (cf. the stable regions). Magma motions, intensity of magma production, and metamorphic regimes are intimately related; their various influences cannot be separated. Thus the

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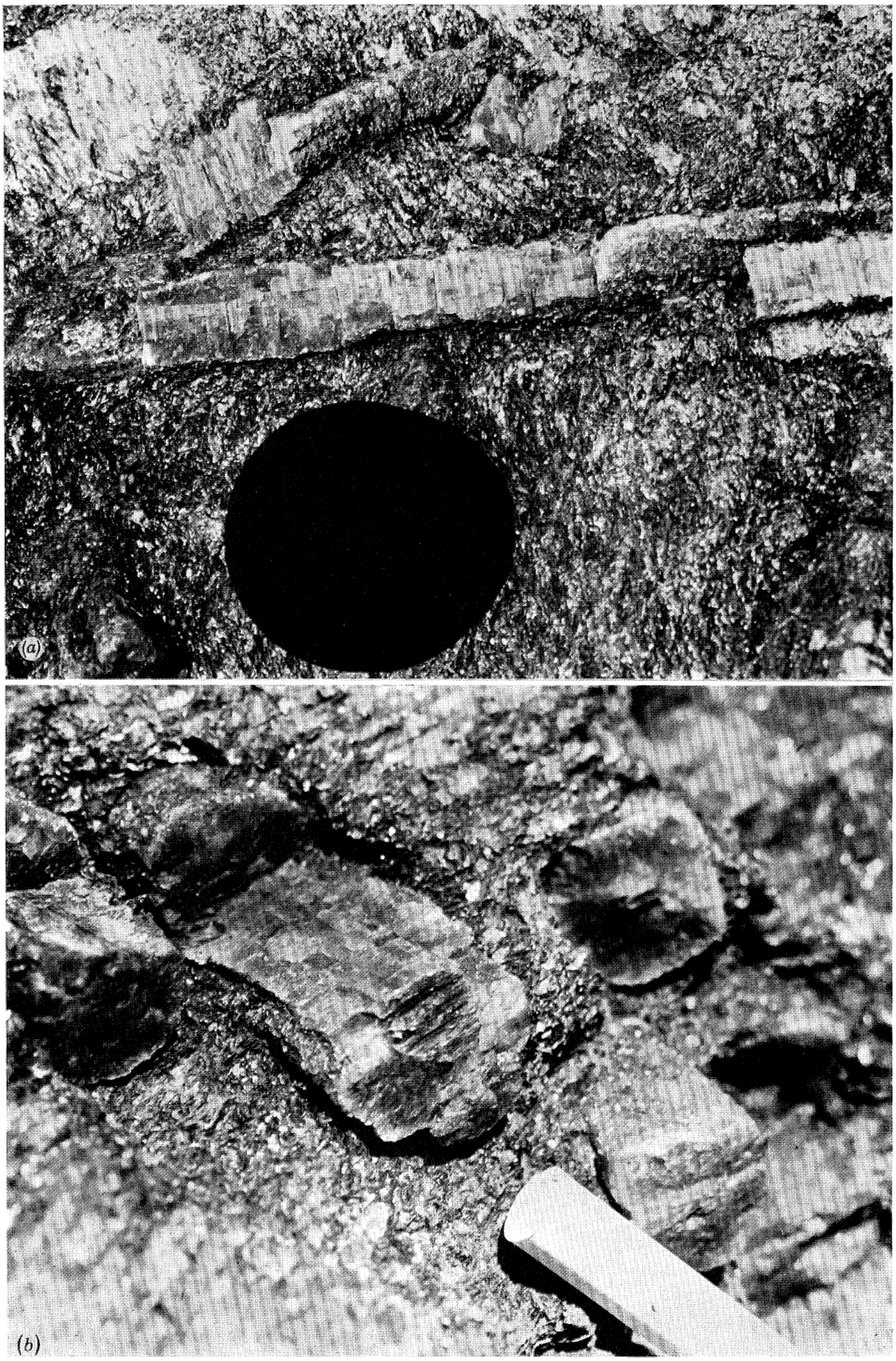

FIGURE 1. (*a*) Well developed kyanite from an Archaean schist belt near Holalkere, Mysore, India. (*b*) Another aspect of the same rocks showing that kyanite is secondary after andalusite and is itself being replaced by hydrated phases (cigarette for scale).

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topic of my discussion involves an understanding of crustal and mantle motions in the Proterozoic as well as heat production. To unravel this problem we must have a detailed understanding of structural patterns, rates of motion (coupled with magma volumes) and this must be achieved without the aid of modern seismic or paleomagnetic observations.

The Archaean regime

When we turn to the ancient (3000 Ma) residual fragments of ancient crust many differences are apparent. The general situation has been summarized by Bridgwater & Fyfe (1974). Features which seem characteristic of the most ancient crust include

(*a*) The dominance by granitic rocks.

(*b*) The granitic rocks appear to be high level and merge into rocks of rhyolitic character.

(*c*) Most processes appear to be subaqueous or submarine.

(*d*) Metamorphic patterns are dominated by low pressure regimes (but not always high temperature (Jolly 1974). Rocks such as eclogite, blue schists, kyanite schists are rare or absent. In some cases where kyanite is present, it may be replacing earlier sillimanite or andalusite (figure 1, plate 14).

(*e*) The scale of sedimentary basins is small and basins tend to be highly arcuate. The MacGregor (1951) Rhodesian model seems typical.

(*f*) Special magma types such as komatiites may indicate a greater degree of melting in the mantle and perhaps small distances of motion.

(*g*) There is no evidence as yet for extensive ocean floor crust of the present type. The crust appears to be granitic to granulitic and mantle-derived volcanism is widespread with penetration centres closely spaced.

We shall return to an interpretation of such phenomena below, but here it should be stressed that there is little evidence not supporting the concept of a highly mobile, high heat flow regime.

The Proterozoic

I must turn to this vast stretch of time which is the subject of this meeting and I would like to briefly mention certain crustal regions which appear to indicate changes in the tectonic regime.

There now appear to be many regions of the crust where Late Proterozoic phenomena are similar to the present. The shield region of Saudi Arabia (see Greenwood *et al.* this volume) seems a particularly good example. This well exposed shield is dominated by rocks in the series andesite-dacite, diorite-granite, spanning ages 800–600 Ma. The depth of erosion is moderate with many rocks being metamorphosed in the greenschist facies. The entire igneous array seems very similar to an Andean subduction situation. It seems possible that when present work on the shield reaches a more advanced stage, some estimate of the rate of andesitic magma production may be possible and this in turn may reflect the intensity of subduction. If one considers the area of this shield, it is certain that these rates were at least the equivalent of those in the more recent andesite provinces. Such an observation carries with it implications concerning rates of crustal motion.

Recent work by research students at the Centre of Applied Geology in Jeddah is also showing further analogies with the modern situation. In particular, the work of M. E. Thekair (unpublished M.Sc. thesis, C.A.G. 1975) shows that the Al-Amar Idsas fault in the eastern section of the shield may well be a thrust fault involving a suture and that fragments of an ophiolitic succession indicating the closing of an ocean may be present.

Similarly, work in the Anti-Atlas region of Morocco (see Church 1975) indicates that modern-type oceanic crust was present during the Late Proterozoic and observations from the Urals again indicates blue schist-eclogite subduction metamorphism in the same time period. It thus seems that clear evidence is appearing for modern tectonics about one billion years ago It is also impressive, that while this ancient record may be fragmentary, it can be deciphered and the lack of such evidence at earlier times must be taken seriously. Thus I think we must be critical of approximations on partial evidence (cf. 'pseudo-ophiolites' of Burke & Dewey 1973).

As we move deeper into the Proterozoic of say Africa, Brazil or Canada, it is clear that there are large changes from the Archaean. Large scale sedimentary regimes are present (perhaps resting on acidic crust). These scales are large, but still much smaller than the modern regimes (e.g. the circum-Pacific belt). Hoffman's (1973) description of the Coronation geosyncline is typical. Continental sediments appear in the record on a larger scale. Of great significance are the larger areas of sediments lacking major volcanic components. This indicates that centres of mantle magma rise are more widely spaced and the same can be said for zones of subduction.

In Brazil (see Leonardos & Fyfe 1974) the Proterozoic mobile belts show changes between the Atlantic Belt (2000 Ma) and the later Brasilia–Espinhaco São Roque belts (younger than 1400 Ma) in that metamorphic patterns change from high temperature low pressure facies to those of moderate pressure developing kyanite. Phase relations in the Atlantic belt indicate thermal gradients of near 60 °C km^{-1} while those in the Brasilia belt nearer 30 °C km^{-1}. More data and experiment are needed to confirm such figures but if they are of the correct order of magnitude then there is the corollary that Archaean gradients of at least 100 °C km^{-1} are possible.

Recent work of Dr G. P. Sighinolfi of the University of Modena (private communication) on proterozoic acid volcanism in Brazil is also of significance. Sighinolfi has found evidence for very widespread rhyolitic volcanism at periods of 1800, 1500 and 1000 Ma. Such volcanism also occurs in Guiana and Venezuela. The rhyolitic activity is not associated with major contributions from other igneous types and does not appear to fit a subduction model. Sighinolfi considers the magmas to originate in the deep crust. This writer might suggest that such magmatism could result by crustal thickening processes associated with thrusting. The writer has seen direct evidence for major thrusts in parts of the Brasilia belt. Thrust processes inter-leaving mantle and crust could also lead to the alkaline rocks of such regions.

Conclusions and a model for crustal evolution

From the contributions presented at this meeting certain tentative conclusions perhaps begin to appear

(*a*) There is increasing evidence that the 'modern' tectonic situation was appearing about one billion years ago.

(*b*) In the Archaean and Early Proterozoic, the continental masses we have available to sample now, show good evidence for having been in close proximity or welded into a single mass; the supercontinent of Piper (this volume). If there were ocean basins of modern type with opening and closing, the motions were not on as large a scale as the present motions.

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(*c*) There is good evidence for motion of the crust in large units, perhaps motions of the 'toroidal' type discussed by Runcorn (1973).

(*d*) The spacing of mantle derived volcanic penetration was larger than in the Archaean but smaller than the present.

(*e*) The concept of continental accretion and cratonization requires modification. As stated by Kröner (this volume) there is good evidence for an extensive Archaean granitoid crust that was progressively destroyed or reworked. This writer would only add that if the continents are not growing, there is good evidence that they are becoming smaller (and thicker). Most continental margins contain ancient rocks.

The model for crustal evolution this writer would like to propose rests on certain postulates. First, we assume that the granitoid crust has a thickness controlled by heat production in the crust. Thus at the earliest times it must have been thinner. In fact, by simple proportion, if heat production three billion years ago was three times the present, granitoid crust would cover most of the Earth. With time, and lower heat production, all motions such as subduction and collision with folding or thrusting, would tend to leave a thicker crust after the processes relaxed. It seems logical, that near the Archaean–Proterozoic boundary, ocean floor crust would appear.

If an extensive acid crust was present, heat transfer from the mantle might involve magma transfer from the mantle to the base of the crust (with some extrusion) and then crustal convection. The system would be analogous to a system of convecting water overlain by a thin layer of oil, also convecting. With such a model, continental drift or ocean floor spreading is not a necessary consequence of intense mantle activity, or subcrustal basic igneous activity. The latter would produce anorthosites associated with granulites.

As Runcorn has repeatedly emphasized, there is evidence for changes in the convection pattern of the mantle. It is suggested here that the pattern is from small cells to larger cells with time; from the small Archaean mobile belts to the large ones of the present. Such changes would be in accord with Elder and Ramberg models of motion in a cooling Earth with the melting zone descending into the mantle through time (see Fyfe 1974*b*).

One of the major problems confronting us is to explain the nature of the crust under the very high-grade mobile belts (such as Limpopo, Grenville, Atlantic of Brazil, etc.) where high grade crustal metamorphic rocks which have undergone partial melting are brought to the surface. Such belts seem to be preferred sites for continental separation, perhaps because of their refractory nature (Fyfe & Leonardos 1973). They may be sites of collisions, with folding or thrusting and subduction or they may represent as Shackleton (1973) states 'upwelling currents in the mantle'. The problem with this latter view involves that of dispersing heat and mantle fusion products. But our knowledge of structure beneath the ancient mobile belts is inadequate. And evidence based on lack of sediments from thick cover ignores the fact that some major river systems of the world erode dominantly by solution and not mechanical transport. At present the evidence is not conclusive but such features should be capable of resolution. All that appears certain is that motions of stable blocks across such belts may be rather small. It is also suggested that remarkable phenomena like the Pan-African Orogeny may represent thermally 'noisy' periods interposed between more stable steady convection patterns of the modern type.

Finally, one must acknowledge that there are great gaps in our present knowledge. Dr Moorbath of Oxford has pointed out to me some of the problems with the reworking hypothesis associated with observations on strontium and lead isotopes. The confusion and ambiguities in this aspect of petrogenetic theory is well illustrated in Carmichael, Turner & Verhoogen (1974). Much depends on present views of mixing of crust and mantle, views which are probably inadequate. Vast mixing is occurring via the continent-weathering-subduction process (Gilluly, Reed & Cady 1970). If the earth grows cooler and mixing continues, more potassium and water may reside in the mantle as phlogopite, more sodium in pyroxenes, more silica in pyroxene derived from olivine. There must be a tendency to put the crust back into cooler mantle. The hydrosphere and typical 'granitoid' elements may be slowly returning to form compounds in the mantle which are fundamentally thermodynamically stable; they come to the top because of melting. It should also be stressed, that where old basement granulites are now at the surface in many mobile belts, they are now undergoing mixing with high level crustal materials and mantle materials. We do not yet appreciate the immense influence of the hydrosphere chemical bridge in petrogenesis.

I wish to acknowledge the stimulation I have received from students and faculty at the Centre for Applied Geology, Jeddah, Saudi Arabia and from my many friends in Brazil and in particular Professor O. H. Leonardos, Jr.

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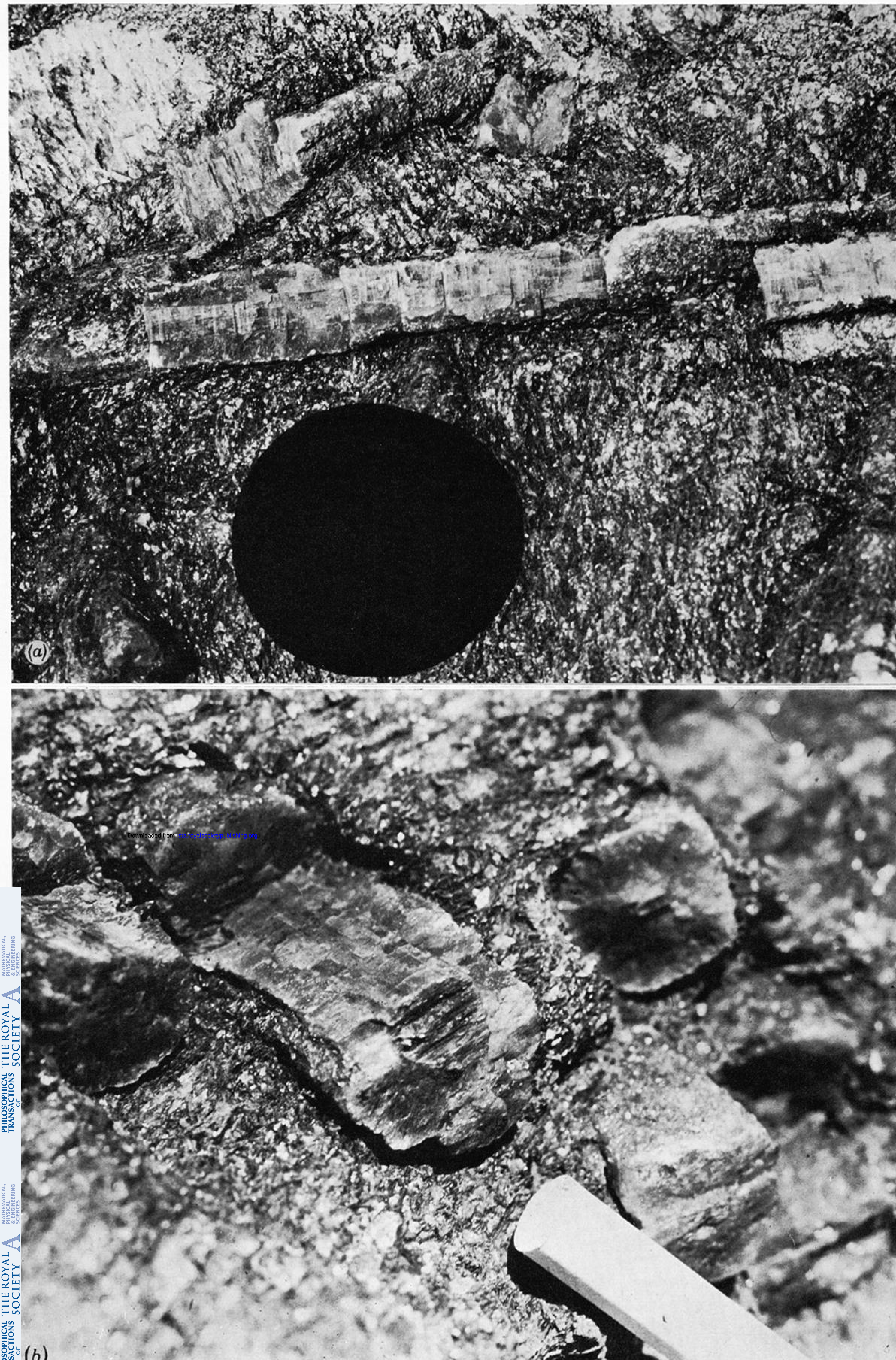

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