Kimberlites and their Relation to the Mantle [and Discussion]

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Kimberlites and their relation to the mantle

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[Plate 1]

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Kimberlite is a rock-type that originates within the Earth's upper mantle, and which has sampled *en route* to the surface a variety of upper mantle rocks that now occur as xenoliths, or, in a fragmented form, xenocrysts in the kimberlite. Kimberlite is, in fact, a hybrid rock resulting from the incorporation of the mantle xenoliths and xenocrysts into a fine-grained matrix with which they may interact. This matrix, which must result from modification of primary mantle material, consists mineralogically mainly of calcite, serpentine, ilmenite, perovskite, magnetite, phlogopite and apatite; chemically, the matrix is rich (relative to garnet peridotite) in TiO_2, Al_2O_3, total iron, CaO, K_2O, Na_2O, H_2O, CO_2 and P_2O_5, and a large number of the so-called 'incompatible' trace elements. The kimberlite matrix focuses attention upon the presence of various elements the source of which in the upper mantle is not adequately explained by the currently popular garnet peridotite model. The source difficulties are to some extent resolved by accepting titaniferous phlogopite as an additional upper mantle phase, although the source of carbon, sulphur, nitrogen and phosphorus is still a matter for speculation.

1. Introduction

Kimberlite is one of the rarest rock-types known, occupying intrusive dykes, sills and diatremes of very small size. However, despite its volumetric insignificance, kimberlite is a rock-type of considerable interest as it is (together with some of its rarer type of xenoliths) the only known primary terrestrial source of diamond. In addition, it contains a variety of mantle-derived xenoliths that have in recent years received considerable attention from experimental petrologists in connexion with the source and formation of basaltic magma (see, for example, O'Hara 1967; Green 1968; O'Hara & Yoder 1967; Ito & Kennedy 1967).

It is the purpose of this paper to discuss the origin of kimberlite in the upper mantle, and to describe it as a rock type and the medium by which the deep-seated xenoliths and the diamonds are transported to the surface of the Earth from their site of origin in the upper mantle.

2. The constituents and depth of origin of kimberlite

(a) The xenoliths and xenocrysts

One of the most immediate features of any specimen of kimberlite is that it consists of relatively large rock-fragments or crystals set in a fine-grained matrix. Leaving aside the rock-

fragments and crystals of obvious crustal origin that were incorporated into the kimberlite during its final stages of ascent, the commonest xenoliths are of dunite, peridotite (olivine + enstatite), eclogite, spinel lherzolite and garnet lherzolite; of these, the garnet lherzolite xenoliths are generally the most common (figure 4a, plate 1). These rock-types may be regarded as samples of a series of depth-zones that, on the basis of seismic, density and experimental data, are believed to constitute the upper mantle (Clark & Ringwood 1964; Boyd & MacGregor 1964; MacGregor 1967; Green & Ringwood 1967). The distribution of these rock-types with depth is shown in figure 1. The main xenocrysts are of forsteritic olivine, enstatite, chrome-
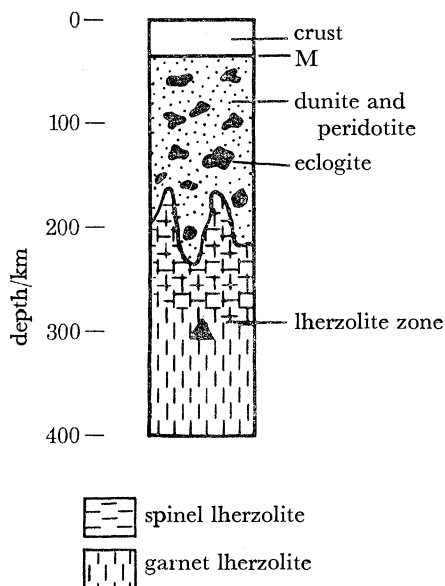

FIGURE 1. Schematic diagram showing the depth relationships of major rock types within the upper mantle. M, Mohorovicic discontinuity. The triangle indicates the depth of origin of the pyroxene-ilmenite intergrowths from the Monastery Mine. Modified after Clark & Ringwood (1964).

diopside, pyropic garnet, phlogopite and magnesian ilmenite. On the basis of comparison with the minerals in the xenoliths (see, for example, Boyd 1966; Carswell & Dawson 1970; Reid & Hanor 1970) it appears that the vast majority of the garnets and diopsides (and, by implication, the less diagnostic olivines and enstatites) are derived from the fragmentation of garnet lherzolite. This is particularly relevant since the regularity in the mineralogy and chemistry of garnet lherzolite xenoliths from kimberlite pipes, from localities as far apart as South Africa and Russia, strongly suggests a widespread source of such rock at depth in the upper mantle (O'Hara & Mercy 1963; Carswell & Dawson 1970). The exceptions are the magnesian ilmenite, and some olivines which may possibly be precipitation products of the matrix itself, and the mica (figure 4b), which will be discussed later.

The fact that these xenoliths and xenocrysts were derived from depths where the pressures and temperatures are consistent with those pertaining within the upper mantle may be inferred from the high pressure–temperature experiments that have been carried out over the past decade on ultramafic rocks and their constituent phases. The chrome-diopsides, that occur both in the lherzolite xenoliths and as xenocrysts in the kimberlite, for the most part equilibrated at depths of 100 to 150 km at temperatures of 1000 to 1200 °C (O'Hara 1967), though some higher temperature subcalcic diopsides (Nixon, von Knorring & Rooke 1963; Boyd 1967;

Boyd & Nixon 1970) appear to have equilibrated at depths around 200 km. The garnet in garnet lherzolite is stable over the pressure range 23 kbar (2.3 GPa) (1320 °C) to 49 kbar (4.9 GPa) (1600 °C) (Ito & Kennedy 1967) which is equivalent to depths of 80 to 170 km. Diamond itself is one of the most important indicators in that, in its stable form, it will not form at pressures less than 55 kbar (5.5 GPa) (Kennedy & Nordlie 1968)—equivalent to 160 to 180 km beneath the Precambrian shields where diamondiferous kimberlites are found. The deepest mineral type yet found is the diopside with exsolved ilmenite lamellae that occurs as nodules in the kimberlite of the Monastery Mine, South Africa (Dawson & Reid 1970; Ringwood & Lovering 1970). The experimental work of Ringwood & Lovering indicates that this mineral combination would have been a homogeneous, garnet-structured phase at pressures in excess of 100 kbar (10 GPa; 350 km) which would be well down within the garnet lherzolite depth zone (see figure 1). Since kimberlite contains blocks of these rock and mineral types, which it incorporated during its ascent towards the surface, it follows that the kimberlite itself must have risen from at least the depths where the deepest-known rock- or mineral-fragment originated. Kimberlite may, in effect, be regarded as containing a jumbled composite sample of the various mineral and rock-types from the depth-zones that it penetrated *en route* to the surface. A limit to the depth sampled may be deduced from the fact that the spinel-structured polymorph of olivine, which is believed to exist in place of olivine at depths of greater than 350 to 500 km (Ringwood & Major 1966; Ahrens & Syono 1967; Akimoto & Fujisawa 1968), has not yet been found in kimberlite or occurring as inclusions in diamond.

(b) The matrix

A feature of the xenoliths and xenocrysts is that, practically without exception, they show some degree of reaction with the kimberlite matrix; the interaction is particularly noticeable in diatreme kimberlite, but may be much less extensive in the kimberlites occurring in dykes or sills (Dawson 1967). Garnets and olivine xenocrysts in particular show strong signs of reaction with the kimberlite matrix, and may be completely replaced by their reaction products—kelyphite and serpentine respectively, and the ultrabasic and eclogitic xenoliths have usually been subjected to a certain amount of serpentinization, phlogopitization, silicification or calcitization. From the petrography, it is quite clear that kimberlite is a hybrid rock, resulting from incorporation of xenocrysts and xenoliths of mantle origin into a liquid or fluid, with subsequent interaction between the xenocrysts and the fluid, and consolidation of the fluid as the kimberlite matrix (Dawson 1962). As the genesis of kimberlite hinges upon the origin of this matrix, it is relevant to examine the nature of the matrix in some detail.

Physically, the matrix was, before its final consolidation, a magma in the sense that it was a high-temperature gas-charged liquid (containing suspended fragments of xenolithic material) capable of movement, and from which high-temperature phases could precipitate. A word of explanation is needed here, in view of the still prevalent concept that kimberlite is an essentially cold, fragmental material that has been emplaced explosively from the mantle without the intervention of a hot, liquid stage (Davidson 1964; Kennedy & Nordlie 1968). This concept arose as a result of the fact that most of the earlier observations upon the textures and field relationships of kimberlite were made within the major diamond-producing pipes of South Africa. Within the pipes, the kimberlite was, for the most part, a fragmental rock often re-sembling volcanic breccia or tuff. In addition, the kimberlite contained fragments of rock, derived from the walls of the pipe, that showed no sign of having been immersed in a hot fluid

Shales, that are normally very sensitive indicators of thermal metamorphism, were unaffected; fossil fragments were still perfectly recognizable, and hydrocarbons within the shales had not been driven off (Wagner 1914; Williams 1932). These phenomena completely overshadowed other less widespread, but none the less significant, observations. Wagner (1911) had observed thermal metamorphism of limestone fragments in the kimberlite of the Premier Mine, and similar features have since been noted in the kimberlites of Siberia (Bobrievich *et al.* 1959; Kharkiv 1967). In addition, high-temperature contact effects are found at the contacts of many kimberlite dykes and sills, within which kimberlite is massive (non-fragmental) and shows evidence of liquid, rather than fluidized, flow (Dawson & Hawthorne 1970). These two ap-
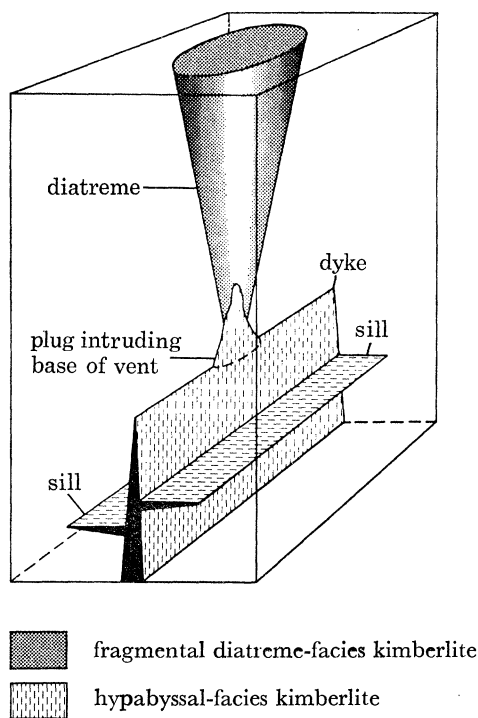

FIGURE 2. Schematic block diagram showing the depth relationships between kimberlite diatremes, dykes and sills, and between hypabyssal-facies kimberlite and diatreme-facies kimberlite.

parently conflicting sets of evidence can be reconciled if it is recognized that kimberlite may consolidate at different depths and under different conditions. Hot kimberlite, ascending along fractures and being injected into horizontal strata, consolidates as dykes and sills which impose thermal effects upon the wall rock and which exhibit liquid flow textures; this type of kimberlite may be referred to as *hypabyssal-facies kimberlite* since it is apparent that it consolidated at depth. In other instances, highly gas-charged kimberlite ascending along fractures broke through explosively to the surface, the explosion conduit then being enlarged and infilled by fluidized kimberlite to form a kimberlite diatreme or pipe (Dawson 1962). This *diatreme-facies kimberlite* will be fragmental, as a result of the explosion and fluidization processes, and the well-documented absence of thermal effects may be attributed to adiabatic cooling attendant upon the rapid expansion of the high-pressure gases (particularly CO_2), following the explosive break-through. In certain cases, later gas surges may emplace later distinctive columns of tuff or fragmental tuffisite dykes, while cavities in the lower part of the vent may be infilled

with quietly upwelling kimberlite which consolidates as hypabyssal-facies kimberlite plugs. The depth relationship between the kimberlite diatremes, dykes and sills, with the distribution of hypabbysal- and diatreme-facies kimberlite, is shown diagrammatically in figure 2.

Mineralogically, the matrix generally consists of calcite, apatite, olivine perovskite ($CaTiO_3$), magnetite, ilmenite, chromite and hydro-phlogopite. If the matrix contains abundant phlogopite, the kimberlite is termed 'micaceous'; if not, it is termed 'basaltic'. Rarer minerals found in the kimberlite matrix are potassic nepheline, monticellite, moissanite, periclase and pyrochlore. Lathlike carbonate pseudomorphs in the matrix have been interpreted as being after original melilite (Shand 1934; von Eckermann 1967), and the chemistry of kimberlite is consistent with this interpretation (Dawson 1967). (The above list excludes many of the secondary reaction minerals such as minerals of the serpentine, amphibole, zeolite and hydro-mica groups, as well as a wide variety of low-temperature sulphides, sulphates and carbonates.) In addition, in the case of diamondiferous kimberlite, the matrix contains diamond. It appears probable that most diamond originates in the matrix of kimberlite, as there is as yet little evidence for a widespread source of diamond in other rocks of upper mantle origin. Although a very few diamonds may be xenocrysts, having been derived from the breakup of rare diamondiferous eclogite, to the writer's knowledge there is only one indubitable record of diamond being found in an *ultrabasic* xenolith, the earlier occurrences reported by Williams (1932) being somewhat dubious. The one authentic case is reported from the Aykhal pipe in Siberia by Sobolev *et al.* (1969 *b*) where diamonds have been found in small fragments of garnet serpentinite; the authors assume that the serpentine is a secondary alteration product after olivine, so the rock might be termed a serpentinized garnet dunite. Even this garnet 'peridotite' must be regarded as unusual since: (i) it contains neither enstatite nor diopside; (ii) the garnet is specifically mentioned as having euhedral faces, in contradistinction to the rounded, kelyphite-rimmed garnets in 'normal' garnet peridotites; and (iii) the garnet is unusually high in chromium compared with 'normal' garnet peridotite garnets, being more similar to the high-chrome pyrope garnet inclusions in diamond recently described by Meyer (1968), Meyer & Boyd (1969) and Sobolev, Lavrentyev, Pospelova & Sobolev (1969 *a*).

The chemistry of the matrix is more difficult to define in precise terms due, in most cases, to the inherent difficulties of obtaining a clean separation of the matrix from the xenocrysts, but a general qualitative assessment of it may be obtained by comparing the composition of mantle garnet peridotite with the analyses of average micaceous and basaltic kimberlites which are, broadly speaking, garnet peridotite diluted with matrix (table 1). Relative to peridotite, kimberlite is enriched in the following major oxides that are concentrated in the matrix: TiO_2, Al_2O_3, Fe_2O_3, Cr_2O_3, MnO, CaO, K_2O, P_2O_5, H_2O and CO_2; it is, however, poor in SiO_2 and MgO; in addition it has $K_2O > Na_2O$ and differences in Mg:Fe. Extreme enrichment in some of the 'matrix' oxides may be seen in the case of some hypabyssal-facies kimberlite where, in dykes or sills, more complete separation of matrix from the xenocrystal or xenolithic components may have taken place; considerable enrichment in potassium, calcium, iron titanium and carbon dioxide is apparent in these examples (table 2). In addition, kimberlite, and hence its matrix, is relatively enriched in the following minor elements: Li, B, F, Sc, V, Cu, Ga, Rb, Sr, Y, Zr, Nb, Cs, Ba, La, Ta, Pb, Th, U (Dawson 1960, 1962, 1967; Holmes & Paneth 1936; Litinski 1961), the relative enrichment being underlined by low Al/Ga, K/Rb, Nb/Ta and Ca/Sr ratios (Dawson 1967). Diamond is characterized also by δ ^{13}C values of -3.0 to $-8\%_0$ which compare closely with those of carbonatites (range -4.5 to $7.8\%_0$: Vinogradov,

Kropotova & Gerasimovsky 1970), and the $^{87/86}$Sr values of 0.7038 to 0.7040 for the main strontium-bearing phase of the kimberlite groundmass—calcite—is also within the range of carbonatites (Brookins 1967; Brookins & Watson 1969). However, $^{87/86}$Sr values of from 0.705

TABLE 1. MAJOR ELEMENT CONTENT OF GARNET PERIDOTITE AND KIMBERLITE

	(1)	(2)	(3)
SiO_2	46.53	35.2	31.1
TiO_2	0.10	2.32	2.03
Al_2O_3	1.84	4.4	4.9
FeO (total)	6.10	9.8	10.5
MnO	0.11	0.11	0.10
MgO	41.98	27.9	23.9
CaO	1.47	7.6	10.6
Na_2O	0.16	0.32	0.31
K_2O	0.15	0.98	2.1
H_2O^+	2.90	7.4	5.9
P_2O_5	0.02	0.72	0.66
CO_2	0.20	3.3	7.1
K/Na	1.0	3.4	7.5
Mg/Fe	4.8	2.2	1.8

(1) Average of nine garnet peridotite xenoliths in South African kimberlites. Calculated from data in Carswell & Dawson (1970). It should be noted that the small amounts of K_2O, H_2O, P_2O_5 and CO_2 are probably derived from secondary minerals caused by percolation of solutions from the host kimberlite.
(2) Average basaltic kimberlite (Dawson 1960).
(3) Average micaceous kimberlite (Dawson 1960).

TABLE 2. CHEMICALLY EXTREME VARIETIES OF KIMBERLITE

	(1)	(2)	(3)
SiO_2	36.12	0.52	3.17
TiO_2	1.45	0.10	10.98
Al_2O_3	4.38	0.48	9.21
Fe_2O_3	6.80	1.30	18.78
FeO	2.68	0.61	11.04
MnO	0.22	0.19	0.22
MgO	22.82	8.87	14.99
CaO	8.33	44.07	16.49
Na_2O	0.29	0.41	0.04
K_2O	5.04	—	—
H_2O^+	4.89	0.36	1.90
H_2O^-	1.28	0.03	0.23
P_2O_5	1.46	1.42	1.67
CO_2	3.80	41.24	10.91
S	0.02	n.d.	n.d.
F	0.29	n.d.	n.d.
	99.75	99.60	99.63

(1) High potassium, high fluorine kimberlite (BD 1089B), New Elands Mine, Kimberley area, South Africa. Analyst: J. R. Baldwin (total includes —O≡F 0.12 %).
(2) Calcite-rich fraction of kimberlite, Benfontein sill, Kimberley area, South Africa (Dawson & Hawthorne 1970).
(3) High titanium, iron and aluminium kimberlite (rich in opaque minerals) (Dawson & Hawthorne 1970).

to 0.716 for bulk specimens of kimberlite (Powell 1964; Mitchell & Crockett 1969) indicate that kimberlite must contain some other phase or material rich in radiogenic strontium. To summarize, kimberlite as a whole reflects its mixed or hybrid origin in its bulk chemistry, consisting of two main groups of elements: (i) an 'ultrabasic' group inherited from the garnet

peridotite xenocrysts; and (ii) the matrix group, which possibly find their closest match in the carbonatites and alnöites.

It is apparent that, since it originates in the part of the upper mantle where garnet peridotite appears to be the dominant material, the kimberlite matrix must largely result from some modification of garnet peridotite (or some variant of it), the changes of chemistry being a result of the modification.

3. The genesis of kimberlite

Before considering some of the more modern hypotheses for the genesis of kimberlite, some of the older ideas will be briefly reviewed. In 1914, Wagner (p. 117) in a cautious, though remarkably perceptive statement, proposed that 'kimberlite magma was generated by the liquification, consequent upon the relief of pressure, of potentially fluid portions of a universal zone or *couche* of holocrystalline peridotite...' of which the peridotite blocks were representative. A more elaborate theory was put forward some time later by Williams (1932, p. 236) who envisaged that at depths within the Earth 'there existed a reservoir of molten magma which, owing to a change of temperature or pressure, or both, had already started to crystallise and solidify in certain portions of the reservoir into peridotite, pyroxenite and eclogite rocks.... The crystallization of these ultrabasic rocks must have continued over a very long period during which time the composition of the original magma was undergoing changes until it eventually assumed the composition of kimberlite magma'. In this hypothesis (which in certain respects resembles the modern 'residual' hypothesis which will be discussed later) Williams regarded the peridotite and eclogite blocks as being comagmatic or 'cognate' with the host kimberlite. The whole concept of 'cognate' xenoliths in kimberlite has recently been thrown into disrepute (see Dawson 1968) since radiometric datings indicate a much older age for the xenoliths than for the kimberlite matrix (Sarsadkikh, Blagulkina & Silin 1966) and the pyroxenes from eclogite xenoliths have quite different strontium isotope ratios from kimberlite (Allsopp, Nicolaysen & Hahn-Weinheimer 1969). Although Williams had recognized the essential two-component nature of kimberlite (i.e. fragments + matrix), the 'foreign-ness' of the xenoliths and xenocrysts had escaped his notice. This was a feature that had been noted earlier by Du Toit (1907) who had concluded that kimberlite had been produced by the shattering of various basic and ultrabasic rock types and the incorporation of this material into a magma of ultrabasic character. This view was endorsed by Holmes (1936) who defined this groundmass magma more specifically as melilite basalt (a rock that is often intimately associated with kimberlite and which consists of olivine, augite pyroxene, melilite, and nepheline or analcime) diluted with 'emanations' consisting mainly of CO_2, P_2O_5 and H_2O. The Holmes hypothesis was reiterated recently by O'Hara & Mercy (1963) and by Nixon *et al.* (1963), although Taljaard (1936) believed kimberlite to be no more than hydrothermally altered melilite basalt. It is of interest to note that in their earlier monographs on the kimberlites of Yakutia, Russian geologists believed that, like Williams, the peridotites were comagmatic with kimberlite (Bobrievich *et al.* 1959) having been precipitated from an ultrabasic, alkaline magma that is formed exclusively under the shield areas; more recent Russian work favours a xenolithic origin for the peridotite nodules and fragments.

It will be seen from the above hypotheses that, as stated earlier, it is the nature and origin of the kimberlite matrix that are the essential problems. The nature of the matrix has been outlined in an earlier section and further comment is unnecessary save to note that the melilite

basalt matrix, postulated by some of the workers mentioned above, has a major problem in that it contains more Na_2O than K_2O, whereas the reverse is found in the kimberlite matrix (Dawson 1962, 1967). This feature, combined with the high amounts of 'carbonatitic' trace elements, caused Dawson (1964, 1967) to propose that the ultramafic xenoliths resulted from the assimilation of crustal granite into carbonatite magma, but the gross time difference between the age of the xenoliths and the host kimberlite has invalidated this proposal (see Dawson 1968). Three more modern hypotheses, all of which attempt to explain the high potassium content of these ultrabasic rocks, are discussed below. In all these hypotheses a rise in temperature is involked to initiate the process of mantle melting; the temperature rise may be tentatively attributed to some convective process in the mantle.

(1) The first process, which may be referred to as the 'residual' hypothesis, is currently very popular (e.g. O'Hara & Yoder 1967). Starting with a garnet peridotite parent (pyropic garnet + chrome-diopside + enstatite + olivine), partial melting involving the garnet-diopside fraction at depths of 80 to 100 km is believed to produce a liquid with the composition of picrite basalt; the more refractory olivine-enstatite portion remains as dunite or peridotite. Fractional crystallization at high pressures of the picrite basalt is believed to give rise to bi-mineralic eclogite cumulates, and a series of silica-poor alkalic residual liquids that have the geochemical characteristics of kimberlite and some rare, ultrabasic potassic lavas. The genetic association of xenoliths of garnet peridotite (a source rock believed to be widespread in the mantle) with xenoliths of eclogite (possible high-pressure cumulates from the garnet peridotite partial melt liquid) in the kimberlite groundmass (a possible residual fluid of the high-pressure fractionation) makes this an extremely attractive hypothesis. One major problem is that the assemblage garnet–diopside–enstatite–olivine is 'barren', or contains only insignificant amounts, of oxides such as K_2O, TiO_2, CO_2, P_2O_5, and H_2O, that are so obviously concentrated in the kimberlite matrix, and hence it cannot be regarded as an ideal starting material. Another problem is that, whereas the garnet peridotite in this scheme may be regarded as an older material (and therefore xenolithic when incorporated into the kimberlite), the eclogite is regarded as forming contemporaneously with the residual fluid and, being 'cognate', meets with the same disparate age problems as the scheme proposed earlier by Williams (1932).

(2) A second process to explain the genesis of kimberlite is the 'zone-refining' hypothesis originally proposed by Harris (1957) and reiterated more recently by Harris & Middlemost (1970). The hypothesis envisages that a liquid (the composition of which is not predicted) is generated at a depth of some 600 km. The liquid, being dynamically unstable in the Earth's gravitational field, moves upwards by a process of 'solution stoping' or a zone refining process similar to that used in metallurgical refining. During the upward movement of such a magma body, the major components remain more or less in equilibrium between the liquid and the solid phases, so that at each successive depth the liquid composition corresponds to that of an initial melt at that pressure. However, the residual elements (i.e. those elements that are unable to substitute readily in the major minerals of ultrabasic rocks), will undergo continuous enrich-ment during this process. As the melt ascends, it will eventually enter a lower temperature region where it partially crystallizes and decreases in volume, with attendant fractionation and increasing concentration of the residual elements such as K, Rb, Cs, Ba, La, Pb, Th, and U; the effect of concentrations of volatiles of H_2O, CO_2 and F is to lower the solidification tempera-ture. This residuum, in which it is envisaged that 'the major elements and their diadochs are at concentrations near those of picritic or ultramafic rocks' (Harris & Middlemost 1970, p. 83)

while at the same time containing large concentrations of residual elements, water and carbon dioxide, is regarded as kimberlite. The high volatile content is believed to make it capable of being explosively injected from great depth.

The arguments against explosive injection from great depth have been outlined earlier, but more specific objections can be made to the process outlined above. (i) This hypothesis takes no account of the actual, physical two-component make-up of kimberlite, although acknowledging it from the chemical aspect, and the proposal that the major elements and their diadochs are at concentrations near those of picritic or ultramafic rocks is contrary to the data on kimberlites. Neither in the absolute concentrations of the major elements, nor in the relative proportions of the elements, do kimberlites resemble other ultrabasic rocks; indeed it is their relatively high concentrations of Al, Ti, Fe, Ca and K, and their high Fe/Mg and K/Na ratios that set kimberlites apart (Dawson 1967). (ii) In addition, the zone refining process as a method of producing potassium-rich basaltic rocks (the genesis of which has problems similar to those of kimberlite) has been found to be incompatible with strontium isotope data for rocks of this type from southwest Uganda (Bell & Powell 1969). (iii) In a wider context it has been pointed out by Turner & Verhoogen (1960) that the products of zone-refining of the mantle might be expected to be abundant and widespread, which is at variance with the insignificant amounts of kimberlite and the other rare potassic lava types. However, despite these objections, the zone refining process does propose a mechanism for the transfer from depth of elements whose origin is not readily explained by melting of rock types known to exist in the upper mantle. We will return to this point later.

(3) Another process, that favoured by the writer, may be termed the 'incipient melting' hypothesis; among the older concepts it is closest to that of Wagner (1914). In this instance, it is envisaged that the parental material is a garnet peridotite containing small amounts of a phlogopite mica rich in titanium. This proposed starting material has recently received support from the finding of primary phlogopite in unaltered garnet peridotite blocks ejected from the small volcano Lashaine in northern Tanzania (figure 4c, plate 1) (Dawson 1964; Dawson & Powell 1969; Dawson, Powell & Reid 1970). It should be stated that although there are numerous recordings of mica in the garnet peridotite and eclogite xenoliths found in kimberlite pipes (Wagner 1914; Williams 1932; Holmes 1936; Kushiro & Aoki 1968), many are undoubtedly secondary, resulting from potassium- and water-rich fluids percolating through the xenoliths from the host kimberlite (Dawson & Powell 1969). Other examples of mica in peridotite xenoliths in kimberlite do indeed appear to be primary, but extreme caution has to be exercised in interpreting them as primary when accompanied by even the slightest trace of serpentinization or granulation of the associated olivine, or kelyphization of the reaction coronae surrounding the garnet. The Lashaine mica-garnet peridotite occurs in ankaramitic scoria, a comparatively 'dry' magma type, that has imposed no metasomatic effects upon the xenoliths, and the mica is in equilibrium with fresh olivine, and the garnet reaction coronae are not hydrated (figure 4d). The mica is a variety, containing high amounts of TiO_2 and Cr_2O_3 and very small amounts of FeO (table 3). It is also high in Rb, Sr and Ba, and has an extraordinarily high $^{87/86}$Sr ratio -0.817 (table 4).

The advantages of having a mica of this type within the mantle model are considerable, as its presence can account for a number of petrologic and geochemical features that are otherwise not readily explained. It is a source of potassium, titanium, water (and possibly numerous trace elements) all of which cannot be provided by the normal 'barren' garnet peridotite model; in

addition the potassium is a source of radiogenic heat. Furthermore, breakup of blocks of mica-bearing garnet peridotite provides a logical origin for the xenocrysts of mica in kimberlite (which are truly as xenocrystal as the garnet, olivine and oyroxenes), a feature also not explained by the garnet peridotite model. In addition, the presence in kimberlite of xenocrysts of this type of mica, containing, as it does, a large proportion of radiogenic strontium, adequately explains

TABLE 3. ANALYSIS OF MANTLE PHLOGOPITE

	(1)
SiO_2	39.98
TiO_2	9.13
Al_2O_3	13.45
Cr_2O_3	0.71
FeO (total)	3.57
MnO	0.04
MgO	18.73
Na_2O	0.06
K_2O	9.64
H_2O	not determined
F	not determined
	95.31

(1) Titanium-rich phlogopite, from garnet peridotite xenolith, Lashaine volcano, Tanzania (Dawson, Powell & Reid 1970).

TABLE 4. MINOR ELEMENT AND ISOTOPIC DATA FOR LASHAINE PHLOGOPITE

K	82038 parts/10^6
Rb (total)	665.1 parts/10^6
Sr (total)	66.46 parts/10^6
$^{87/86}Sr$	0.817 (3) $\pm$ 0.0014
K/Rb	123.35
$^{87}Rb/^{86}Sr$	29.21
Analyst: D. Barrett	
Ba	ca. 4500 parts/10^6
Analyst: I. Ridley	

the enhanced $^{87/86}Sr$ ratio of 0.706–0.712 of the bulk kimberlites over the typical 0.703–0.704 'carbonatitic' ratio of the kimberlite matrix, assuming that the strontium has not re-equilibrated with that of the matrix. A further and wider implication is in connexion with the genesis of other potassic ultramafic rock-types, such as fitzroyites, jumillites, orendites and wyomingites. The overall geochemical coherence of K_2O, TiO_2, SrO and BaO in these unusual rock-types, together with unusually high $^{87/86}Sr$ ratios, may be logically explained if a mantle mica of the Lashaine type was involved in their formation.

In the 'incipient melting' hypothesis, it is envisaged that the mica first melts followed by a small amount of the chrome-diopside. The liquid formed by the incipient fusion will be rich in K_2O, Na_2O, TiO_2, Al_2O_3, CaO, FeO, Cr_2O_3 and H_2O compared with the bulk parental peridotite, but will, of course, still contain considerable amounts of MgO and SiO_2; it would be a medium from which chromite, magnesian ilmenite, chromite and the chrome-rich pyrope found in kimberlite (Nixon & Hornung 1968) and in diamond (Meyer 1968; Sobolev *et al.* 1969*a*) could precipitate. This melt, probably modified by precipitation of these phases, would approximate to the kimberlite matrix. Under the 'incipient melting' scheme, the rock-types olivine melilitite, olivine nephelinite and alnöite, which are so often intimately related to kimberlite (see, for example, Taljaard 1936), are envisaged as resulting from the fusion of a

higher proportion of diopside relative to mica (hence accounting for their relatively high Ca and Na content), combined with a lower content or proportions of mantle xenocrysts and xenoliths. In addition, melting of the phlogopite-diopside fraction, with the mica being rich in radiogenic strontium could explain the strontium isotope ratios and other geochemical features of the potassic lavas of southwest Uganda (Bell & Powell 1969).
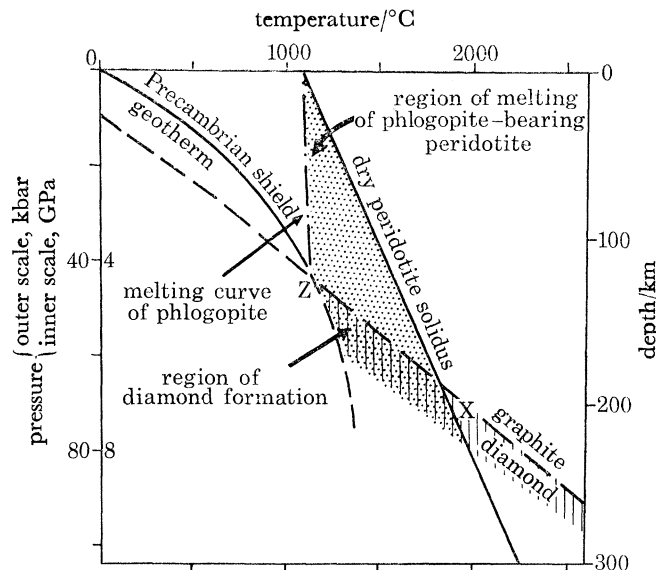

FIGURE 3. Diagram showing the effect of mica upon mantle melting and the formation of diamond. Continental geotherm is from Clark & Ringwood (1964); melting curve of phlogopite from Yoder & Kushiro (1969); the dry peridotite solidus from Ito & Kennedy (1967); the diamond–graphite equilibrium curve from Berman & Simon (1955). The points X and Z are explained in the text.

A further advantage of the 'incipient melting' hypothesis is that its products may be expected to be volumetrically small, as is the case with kimberlite, and they may appear completely independently of any major cycle of volcanic activity, again as is the case with kimberlite activity.

One consequence of having a mica-bearing garnet peridotite as the model for at least part of the upper mantle is the lowering of the melting-point of the upper mantle, which carries certain implications for the formation of diamond. Mica-bearing garnet peridotite will start to melt at a lower temperature than ordinary garnet peridotite, and there will be a large field below the 'dry' garnet peridotite solidus where melting of phlogopite-bearing peridotite will take place (figure 3). This is of considerable interest when considering the minimum pressures and temperatures at which diamond can form, if it is assumed that diamond can only form in molten or partially molten ultrabasic rock on the high-pressure side of the diamond–graphite equilibrium curve (Kennedy & Nordlie 1968). In the case of a 'dry' peridotite, the minimum point (where the diamond–graphite equilibrium curve intersects the dry peridotite solidus) is at approximately 1800 °C and 68 kbar (6.8 GPa)—point X on figure 3. In the case of mica-bearing peridotite, the melting curve of phlogopite intersects the diamond–graphite equilibrium curve at approximately 1200 °C and 45 kbar (4.5 GPa)—point Z in figure 3. The implication is that the minimum depth at which diamond may theoretically form is reduced from 200 to about 135 km. It may also be regarded as significant that the intersection of the melting curve of

phlogopite with the diamond–graphite equilibrium curve virtually forms a triple-point inter-section with the Precambrian shield geotherm; the inference is that only a small rise in tempera-ture above the Precambrian geotherm is required to initiate melting of mantle phlogopite peridotite, and that the initial melting will take place at, or very close to, a depth at which diamond is the stable carbon polymorph.

The melting curve of phlogopite shown on figure 3 is the upper stability limit of synthetic phlogopite (composition K_2O, $6MgO$, Al_2O_3, $6SiO_2$, H_2O) in the presence of excess of gas. The melting curve of the same phlogopite in the water deficient region as determined to 10 kbar (1 GPa) (Yoder & Kushiro 1969) lies on the high-temperature side of the first curve. The inference is that the initial melting of phlogopite in nature would take place at higher tempera-tures than suggested on figure 3 which would place the minimum thermal gap between the Precambrian shield geotherm and the melting curve of natural phlogopite within the diamond stability field.

4. Outstanding problems

Although, in the writer's opinion, the 'incipient melting' hypothesis explains the genesis of the kimberlite matrix more adequately than the 'residual' hypothesis, it also shares with it some features that cannot be explained at present. To be more accurate, it is the source of various elements, rather than their concentration processes, that requires explanation. These elements are carbon, phosphorus, nitrogen and sulphur which are not present or present only in minute amounts in phases in the garnet peridotite or mica garnet peridotite mantle models. Even water, the presence of which is partially explained by the existence of mica, presents some problems. In mica the $K_2O:H_2O$ ratio is approximately 3:1, whereas in the average basaltic kimberlite this ratio is 1:7; hence it must be assumed that not all the water in kimberlite comes from the mantle mica. In addition, there must be at depth a source for nitrogen, which is found in small quantities in diamond, and which is also released in considerable quantities during volcanic eruptions.

When looking for a source for these elements, it must be borne in mind that they may originate at depths within the mantle that are not sampled during kimberlite magmatism. In this context it is relevant in some cases to draw inferences from the mineralogy of certain types of meteorites that may be chemically similar to the lower parts of the mantle.

In the case of carbon, its source is a matter for speculation, though there are several possi-bilities:

(*a*) Carbon may exist in the form of a primary reservoir of diamond, as suggested by Lang

Description of plate 1

Figure 4 (*a*). Garnet lherzolite xenolith from the Letseng Le Terai kimberlite, Lesotho; representative of the most abundant xenolithic rock-type found in kimberlite.

Figure 4 (*b*). Xenocryst of phlogopite in kimberlite from the Monastery Mine, South Africa. Note the buckling and fracture pattern, most probably caused by deformation before the incorporation of the xenocryst into the kimberlite. Compare with the strained mica in the Lashaine garnet lherzolite (*d*).

Figure 4 (*c*). Garnet lherzolite xenolith containing high-titanium phlogopite (black mineral), from the Lashaine volcano, Monduli district, northern Tanzania.

Figure 4 (*d*). Photomicrograph of high-titanium phlogopite in garnet lherzolite, Lashaine, Tanzania. Note the absence of reaction between mica and contiguous olivine; (ii) the extreme freshness of the olivine; (iii) the anhydrous mineral assemblage (pyroxene + spinel) of the reaction corona surrounding the garnet. (Magn. × 5, plane–polarized light.)

Dawson

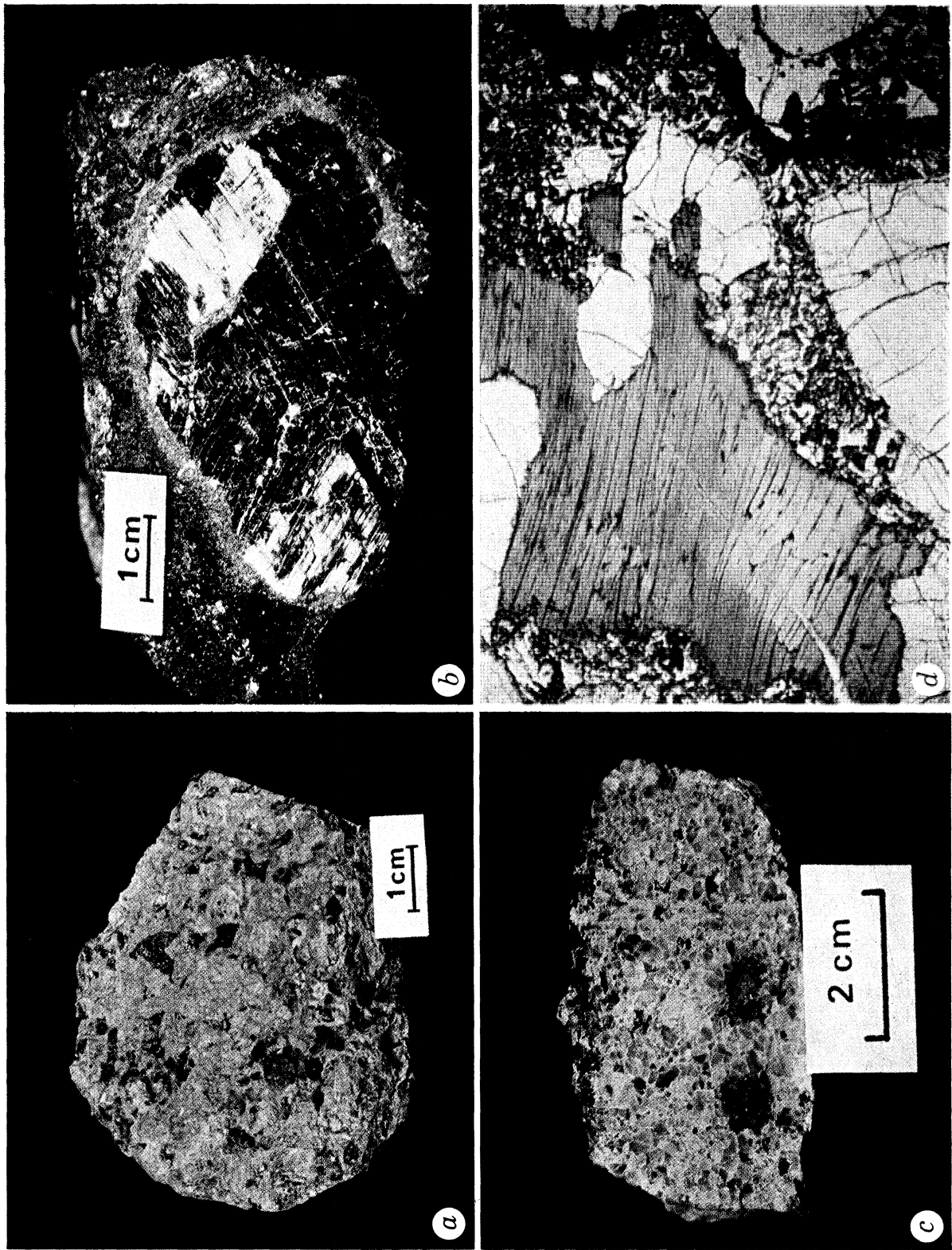*Phil. Trans. R. Soc. Lond. A*, *volume* 271, *plate* 1

FIGURE 4. For legend see facing page

(1970). This suggestion appears at present to be at variance with the evidence that diamond has not yet been found in unmodified primary mantle material, but the possibility must not be ruled out that diamond may be a primary phase in the deeper parts of the mantle which are not sampled by kimberlite.

(b) The carbon may be combined at depth with some metal to form a carbide. Cohenite (Fe_3C) is a reasonably common mineral in meteorites, and moissanite (SiC) has been recorded in kimberlite from Russia (Marshintsev, Schelkova & Zolnikov 1967).

(c) The carbon may occur as inclusions or interstitial patches of gas or liquid CO or CO_2. Roedder (1965) has reported liquid CO_2 inclusions in mantle olivines.

(d) The carbon could exist as a primary hydrocarbon such as that found in the pegmatites of Kola peninsula (Petersilie 1964), or the gases escaping from boreholes in the Udachnaya pipe, Yakutia (Davidson 1967). The idea of such a hydrocarbon is attractive in that it would provide, when oxidised, a source of both CO_2 and H_2O.

Regarding sulphur, small amounts of chalcopyrite and pentlandite have been found rarely in garnet peridotite xenoliths in the Obnaznannaya pipe, Yakutia (Sobolev & Vakhushrev 1967), though the amount of sulphide in garnet peridotite appears to be far too small to account for the amount of sulphur produced during volcanism.

Whereas some evidence, albeit scanty, exists for carbon, sulphur and hydrogen in rocks and minerals known to have originated in the mantle, no such evidence as yet exists for nitrogen and phosphorus. However, since phosphorus (in the form of schreibersite, apatite, merrillite and farringtonite) and sulphur also (in the form of numerous sulphides) are known in meteorites there is a possibility that these volatile elements may originate at depths greater than those normally sampled by kimberlite and that they may migrate from depth with the convective heat that initiated the kimberlite magmatism possibly in a manner similar to that proposed by Harris & Middlemost (1969). Another strong possibility is that meteoritic-like minerals from depth containing phosphorus and sulphur may actually exist as xenocrysts in kimberlite but have so far gone undetected. The source of these two elements in particular is a problem that kimberlite shares with most other igneous rocks, and one that warrants continued research, particularly into the chemistry of the opaque phases in kimberlite and its associated xenoliths.

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Discussion

Dr J. R. Andrews (*Department of Geology, University of Newcastle on Tyne*). Commenting on the presence of possible primary phlogopite in garnet-peridotite inclusions Dr J. R. Andrews said that he had been fortunate enough to observe very fresh garnet, spinel and phlogopite peridotite xenoliths from kimberlite dykes and sills in southwest Greenland. The garnets in four phase garnet peridotites were invariably surrounded by a reaction corona consisting of orthopyroxene, spinel, serpentine and carbonate. Large flakes of primary looking fresh phlogopite were commonly found in or adjacent to these coronas. In view of the constant association with partly broken down garnets it seemed unwise to regard them as primary minerals equilibrated with the garnets as suggested for some similar micas observed by Dr Dawson. Complete replacement of garnet is indicated in phlogopite peridotites where 4 mm circular areas are filled with 0.5 to 1.0 mm xenoblastic laths of phlogopite intergrown with orthopyroxene and a very dark spinel.
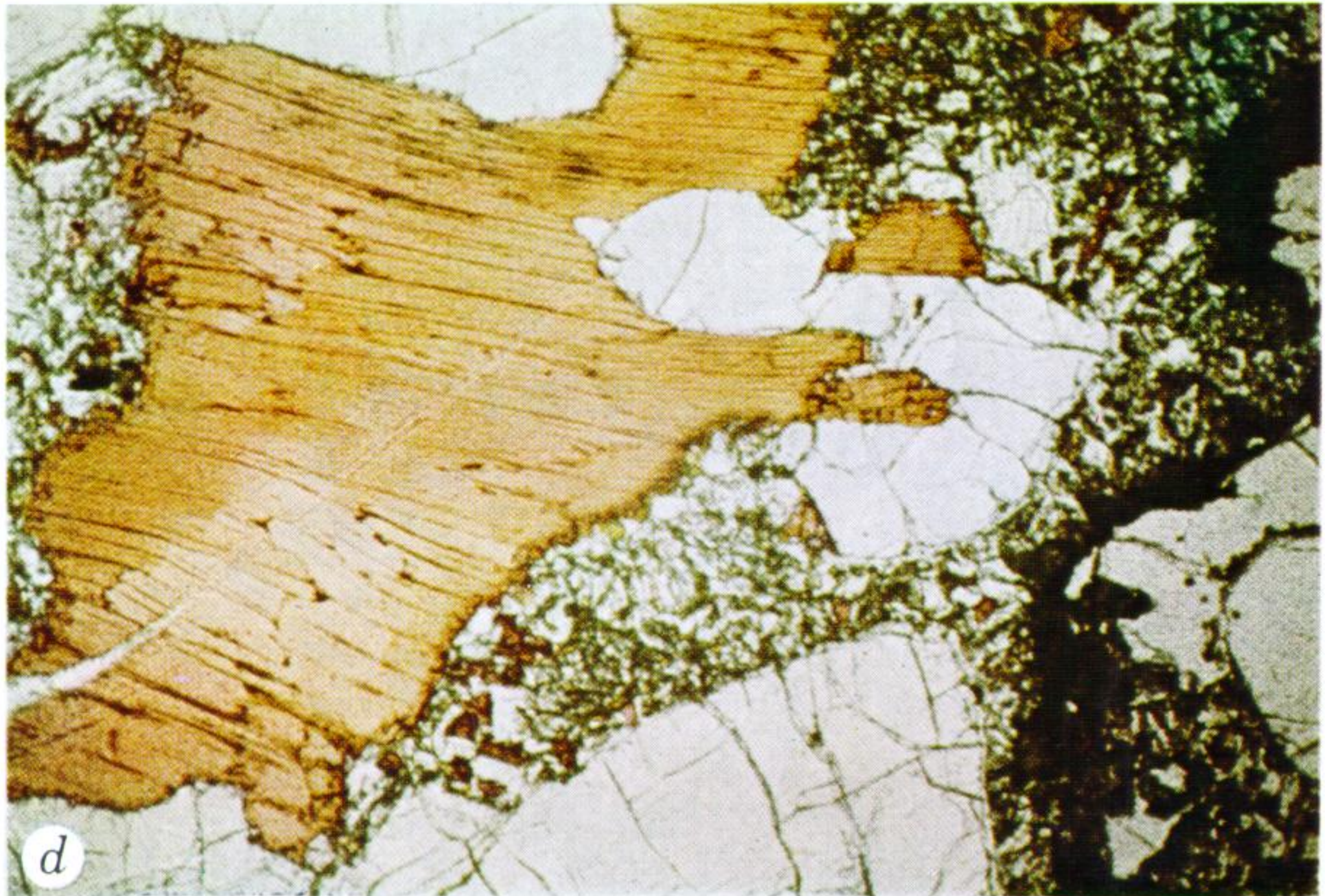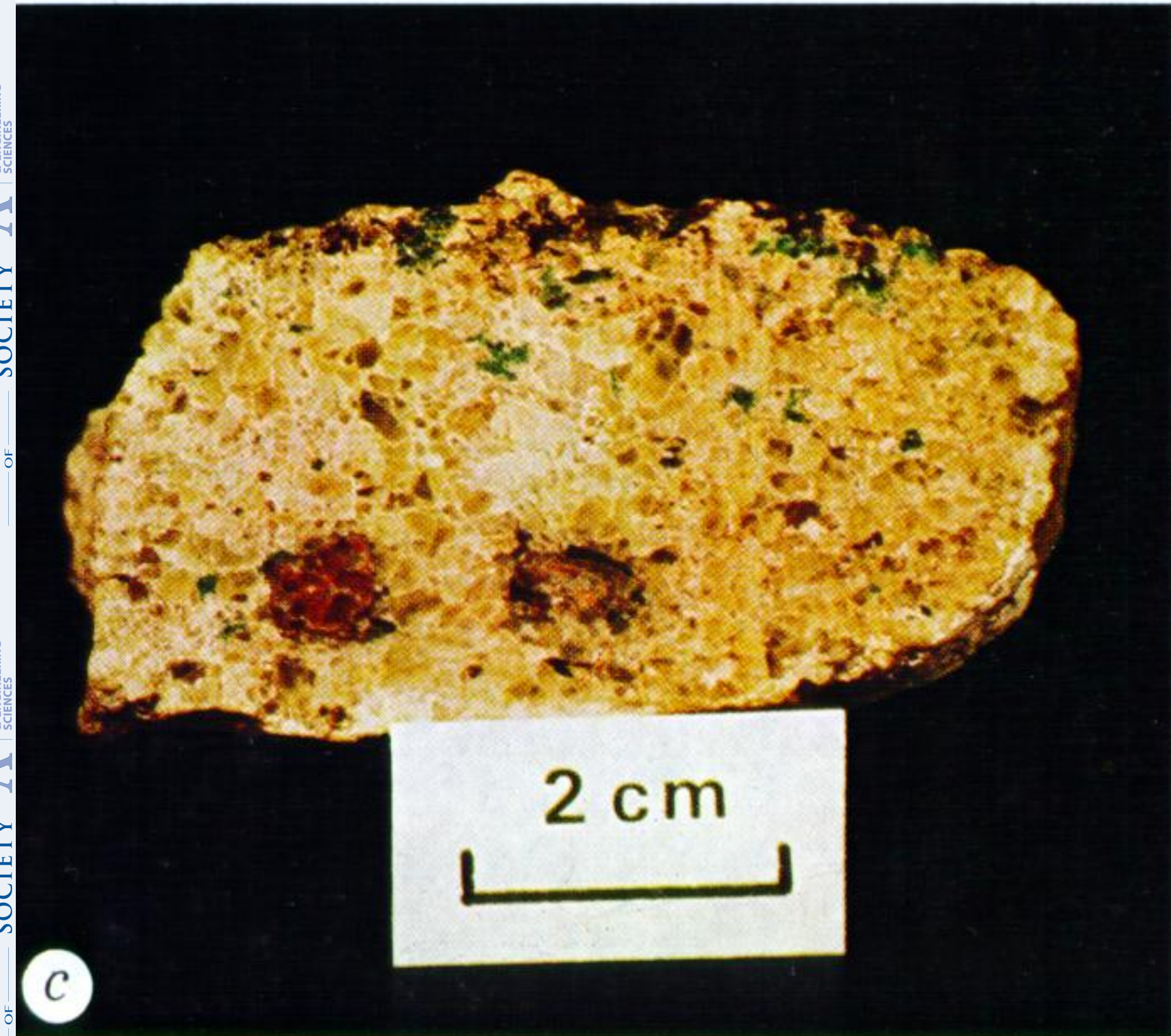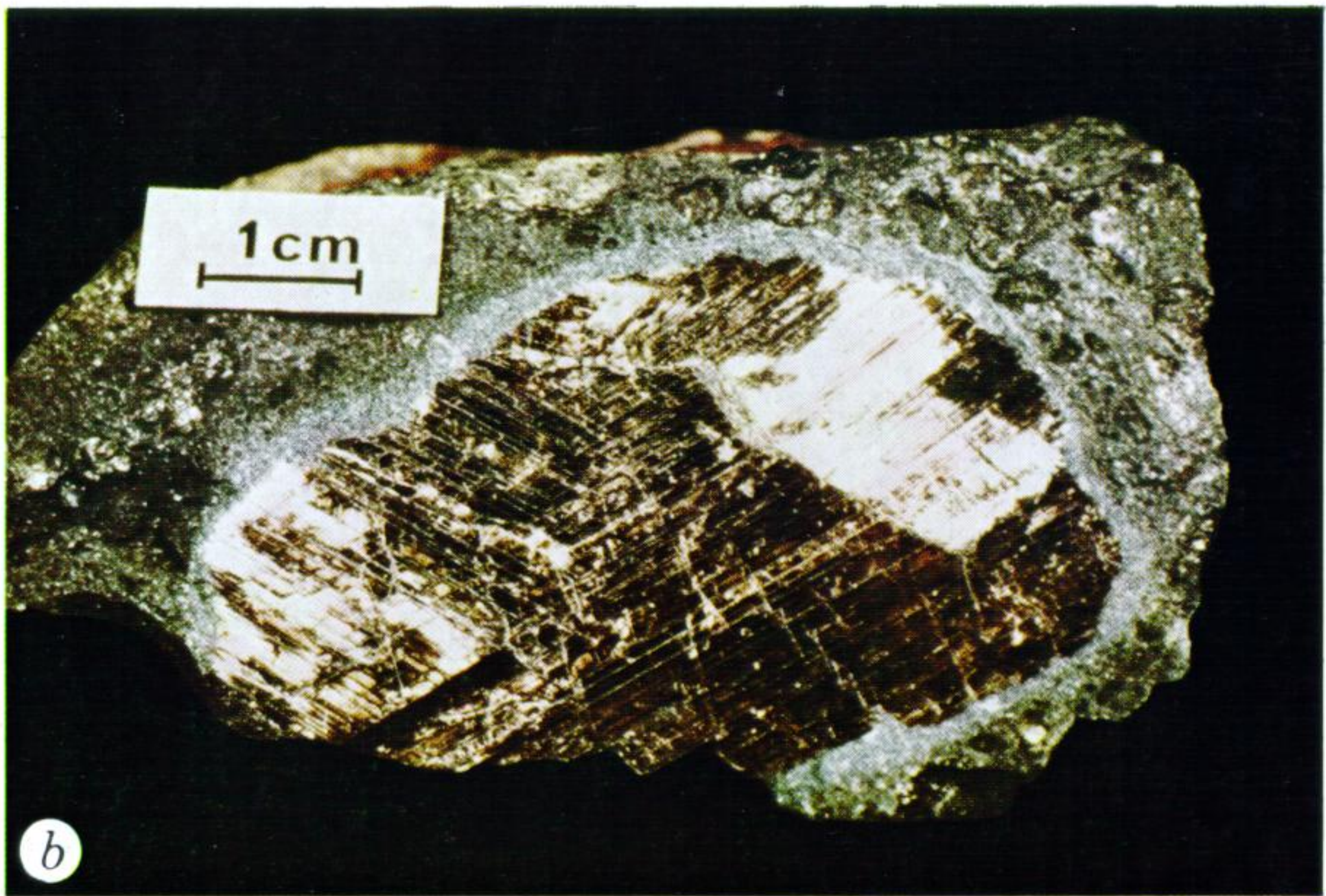
FIGURE 4. For legend see facing page