PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A
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Fluid Inclusion Study of the Witwatersrand Gold-Uranium Ores

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Fluid inclusion study of the Witwatersrand gold–uranium ores

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[Plate 1]

Fluid inclusions, preserved in quartz pebbles of the uraniferous and auriferous Precambrian oligomictic conglomerates of the Witwatersrand Basin, provide a unique insight into the genesis of the ores. Using differences in inclusion characteristics in conjunction with intra- and inter-deformational textures for adjacent pebbles, a distinction is made between pre- and post-depositional inclusions. Excluding those related to subsequent brittle fracture, the former comprise five principal types; two of which are distinguished by the development of liquid carbon dioxide. Collectively they indicate a moderate to high pressure–temperature environment of vein quartz formation. Systematic variation in the relative abundance of these inclusion assemblages for different sections of the orefield demonstrates the importance of well-defined provenance areas or multiple entry points into the basins. A marked sympathetic relationship between uraniferous banket ores and the presence of vein quartz rich in liquid carbon dioxide inclusions, together with a corresponding antipathetic relationship for gold, strongly suggests separate sources for the metals. The temporal and spatial aspects of the association '$U\text{-}CO_2$' also imply a uranium influx into the basin from disrete areas of the hinterland contemporaneous with the sediments. Post-depositional inclusions are subordinate and offer no support for the alternative epigenetic model and show only a later interaction of relatively cool circulating groundwaters. A discussion is given of the probable nature and origin of uranium in the source rocks and its mode of transportation. In conclusion, a proposal is made for the use of applied fluid inclusion research in the evaluation of and exploration for similar deposits.

Introduction

In the southern part of the African Shield, thick sequences of relatively undisturbed Precambrian sediments are well preserved in a series of intercratonic basins. The sequence in the Witwatersrand Basin, considered to be the world's principal source of gold and uranium, comprises four Proterozoic super-groups; the Transvaal, Ventersdorp, Witwatersrand and Dominion Reef Systems (figure 1). Together they rest unconformably upon an extensive Archaean basement complex of granites and high-grade metamorphics. Economic concentrations of gold and uranium are characteristically, though not exclusively, confined to thin oligomictic quartz conglomerate beds which occur throughout the succession, particularly within the Upper Witwatersrand and Lower Dominion Reef formations.

The application of fluid inclusion studies to the genesis of these ores depends on the ability to differentiate between pre- and post-depositional inclusions. The latter refer to fluids active after the deposition of the enclosing sediments and are relevant to the epigenetic 'hydrothermal' model of mineralization, whereas the former refer exclusively to fluids which were circulating in the source area before erosion and thus relate more closely to the alternative syngenetic 'modified-placer' model.

Apart from a brief reference to South African uranium and gold-bearing conglomerates by Krendelev, Zozulenko & Orlova (1973) fluid inclusion data for the Witwatersrand ores is non-existent. In their paper they establish a distinction between pre- and post-depositional inclusions but are unable to apply it with any certainty. From an examination of only three samples they conclude 'The sulphide mineralization in the Witwatersrand conglomerates was formed by the reaction of rocks with solutions at temperatures from 220 °–400 °C'.

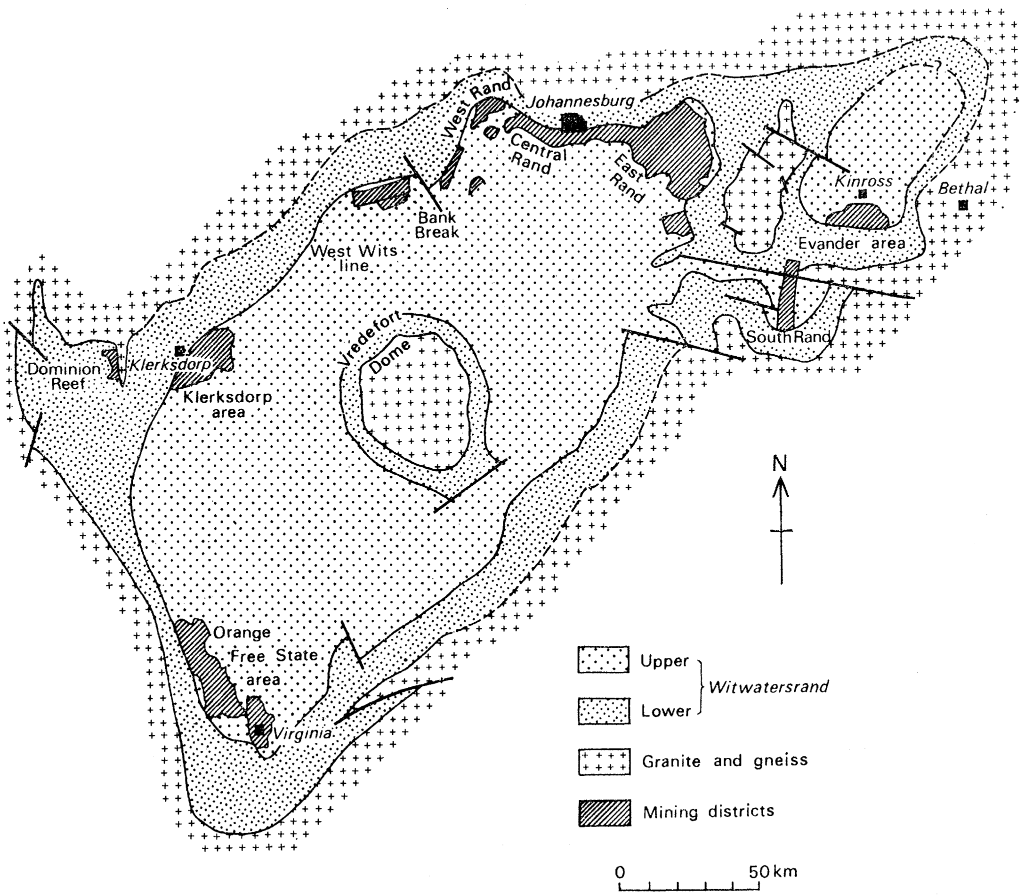

FIGURE 1. Simplified geological map of the Witwatersrand Basin beneath the Ventersdorp and younger cover (after R. Borchers 1961).

Preliminary work on the banket ores suggested that the ubiquitous pebbles of vein quartz provided the most suitable material for preserving the various generations of inclusions. Consequently a special study was made of the type and distribution of inclusions in vein quartz from 23 major mineralized conglomerate horizons in the Witwatersrand Basin.

INCLUSION CHRONOLOGY AND THE EFFECTS OF METAMORPHIC DEFORMATION

In conventional studies one is concerned with the distinction between primary, pseudo-secondary and secondary inclusions in minerals which are *in situ* and have undergone little or no deformation. As defined by Ermakov (1965), primary inclusions are those formed during the growth of the enclosing mineral due to irregularities in crystal growth or fluid inhomogeneity.

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Pseudosecondaries occupy fractures formed during crystal growth, while secondaries occur along fractures formed at some subsequent time. For the Witwatersrand pebbles this sequence, where preserved, represents only the first stage of their more complex history. Unlike the pre-depositional inclusions, formation of the post-depositional inclusions was due to the healing of fractures in the pebbles caused by later deformation. Morphologically such inclusions are not easily distinguishable from secondaries *sensu stricto*.

Excluding samples which exhibit localized post-depositional tectonism, the quartz shows a wide range of deformational textures. This is most readily explained by its derivation from a variety of metamorphic and deformational environments equivalent to or of higher grade than the host sediments. Confirmation is provided by the coexistence of strongly contrasting deformational textures in pebbles from the same sample (see figure 3*a*, plate 1). According to White & Treagus (1975) quartz veins deform naturally by a dislocation creep mechanism analogous to that produced in metals and ceramics. The associated optical strain features are continuous and discontinuous undulatory extinction, deformation bands, deformation lamellae, narrow sub-grains and Boehm lamellae. With increasing strain the intercrystalline dislocation structures are replaced by misorientated sub-grains, leading ultimately to a complete recrystallization of the quartz. Without exception, the Witwatersrand pebbles display varying degrees of the above features making it necessary to allow for the effects of later deformation on the pre-depositional inclusions. No systematic study of inclusions during progressive deformation has yet been carried out but the present observations agree closely with those recorded by R. Kerrich (personal communication 1975). The development of undulatory extinction and deformational bands appears to have had little effect on pre-existing inclusions and caused only a 'necking' of the more irregular shaped inclusions. With the establishment of advanced sub-grain development the smaller inclusions (< 10 μm) become disrupted and driven to sub-grain boundaries. The current consensus of opinion is that inclusions in deformed crystals are unreliable geothermometers and give anomalous homogenization temperatures. Synmetamorphic intercrystalline deformation is often succeeded by a period of brittle fracture, accompanying tectonic uplift, and capable of generating further sets of secondary inclusions. However, the task of differentiating between pre- and post-deformational secondaries is beyond the scope of the present work. For the Witwatersrand quartz pebbles the chronology of events may be summarized as follows:

Stage I: Crystal growth in the source area.
1. Formation of primary, pseudosecondary and secondary inclusions.

Stage II: Metamorphic and tectonic deformation in the source area.
1. Intercrystalline deformation and modification of pre-existing inclusions.
2. Brittle fracture and the formation of a second generation of secondary inclusions.

Stage III: Post-depositional tectonic deformation.
1. Minor modifications due to inter-pebble pressure solution phenomena for conglomerates with a high packing index.
2. Brittle fracture and the formation of a third generation of secondary inclusions.

Stage IV: Post-depositional contact thermal metamorphism (probably overlaps with stage III)
1. Thermal rupture of inclusions adjacent to minor intrusives.

Had the Witwatersrand and Dominion Reef Systems suffered a higher grade of regional metamorphism it is doubtful whether many source area inclusions would have survived.

Because of the difficulty in distinguishing between stage I and II secondaries, only the primary and pseudosecondary inclusions were selected for study. Even so the data probably still contains a small component of secondaries.

The comb texture produced by nucleation at a surface followed by growth perpendicular to the surface with mutual impingement is notably lacking in the quartz pebbles. This arrangement is generally taken to imply low-temperature deposition. Instead, the quartz consists of single crystals or interlocking anhedra, typical of higher temperature hydrothermal or synmetamorphic veins, greisens and pegmatite zones. The apparent granular appearance is considered therefore to be a primary growth texture unrelated to the strain mosaics produced by later deformation.

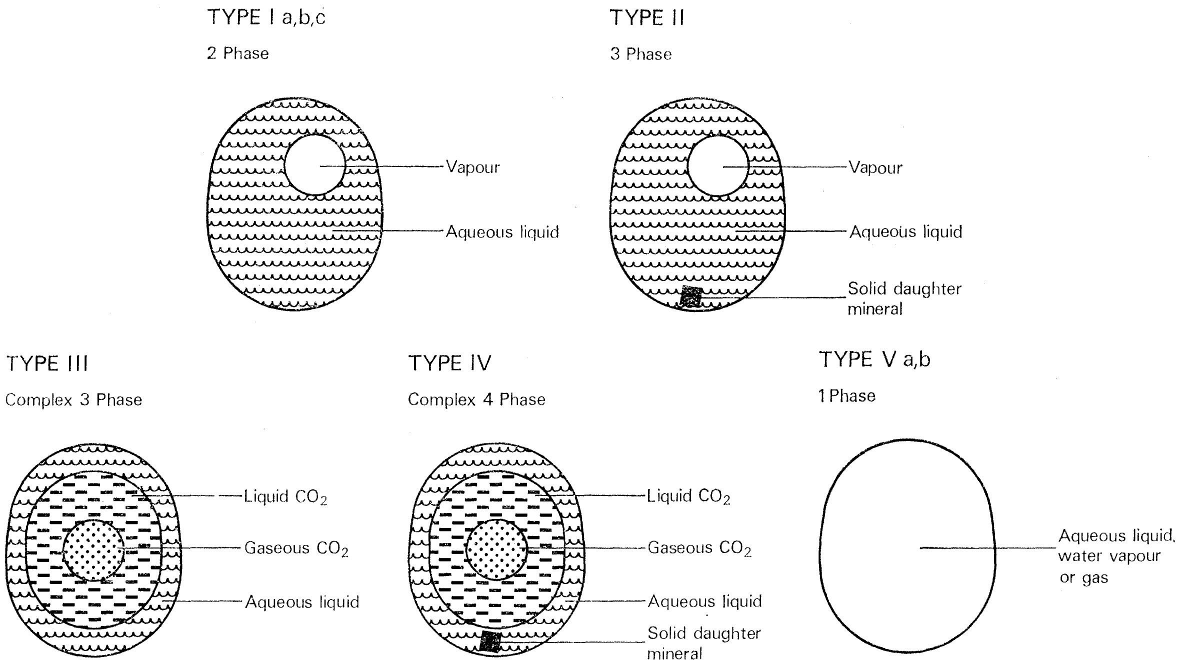

FIGURE 2. Diagrammatic representation of the principal types of fluid inclusion.

DESCRIPTION OF PLATE 1

FIGURE 3. (*a*) Photomicrograph of typical uranium–gold banket ore showing contrasting deformational textures in adjacent vein quartz pebbles (p.t.s. 1940, transmitted light, crossed nicols, bar = 0.25 cm). *Locality:* Main Reef, West Driefontein, West Wits area.

(*b*)–(*f*) Photomicrographs of selected inclusions in pebbles of vein quartz.

(*b*) Group of pre-depositional type I two-phase inclusions (p.t.s. 2006, bar = 50 μm). *Locality:* Dominion Reef, Dominion Reefs, Dominion Reef area.

(*c*) Large pre-depositional type II three-phase inclusion showing rhombic anisotropic daughter mineral (p.t.s. 2050, bar = 100 μm). *Locality:* Vaal Reef, Vaal Reefs, Klerksdorp area.

(*d*) Multifaceted pre-depositional type III three-phase inclusion containing liquid and gaseous carbon dioxide; as arrowed (p.t.s. 2006, 18 °C, bar = 50 μm). *Locality:* Dominion Reef, Dominion Reefs, Dominion Reef area.

(*e*) Plane of pre-depositional type I inclusions growing onto and enveloping solid rutile needles; as arrowed. (p.t.s. 1969, bar = 50 μm). *Locality:* Main Reef, Daggafontein, East Rand area.

(*f*) Planar arrays of post-depositional type I inclusions along fractures having a common orientation with respect to adjacent pebbles (p.t.s. 2011, bar = 20 μm). *Locality:* Dominion Reef, Dominion Reefs, Dominion Reef area.

(*g*) Photomicrograph of flame-like Boehm lamellae in vein quartz pebble. (p.t.s. 1969, bar = 50 μm). *Locality:* Main Reef, Daggafontein, East Rand area.

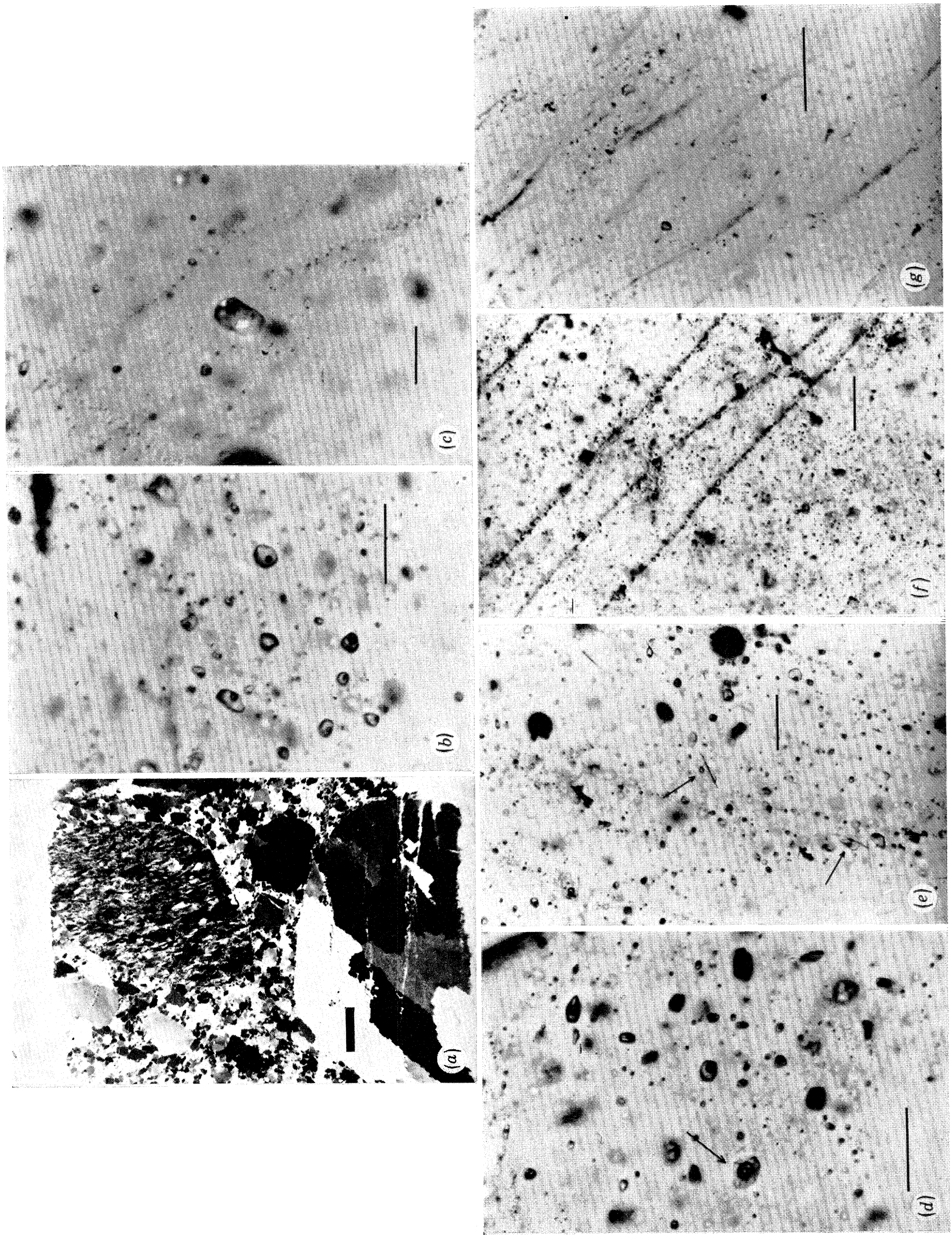

FIGURE 3. For description see opposite.

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Types of inclusion

The quartz pebbles contain five principal types of inclusion, varying from < 1 μm to 80 μm in diameter but normally < 20 μm (figure 2).

Type I: Simple two-phase inclusions (aqueous liquid + vapour) (figure 3*b*). These are by far the most abundant and may be divided into three sub-groups according to their vapour/total volume ratio: (*a*) < 0.05, (*b*) ~ 0.1 to 0.15, (*c*) ~ 0.2 to 0.4. For a 10 % (by mass) NaCl solution this is equivalent to homogenization temperatures of (*a*) < 110 °C, (*b*) ~ 170–225 °C, (*c*) ~ 275–400 °C.

Type II: Simple three-phase inclusions (aqueous liquid, vapour + solid daughter minerals) (figure 3*c*). Though less abundant they show considerable variation in daughter mineral content, suggesting a wide range of fluid compositions. Isotropic, anisotropic, euhedral, anhedral, cubic and rhombic phases are well developed. The vapour/total volume ratio for this group ranges from 0.05 to 0.2 but never less than 0.05.

Type III: Complex three-phase inclusions (aqueous liquid, liquid CO_2 + gaseous CO_2) (figure 3*d*).

Type IV: Complex four-phase inclusions (aqueous liquid, liquid CO_2, gaseous CO_2 + solid daughter minerals).

Types III and IV are highly distinctive and contain appreciable quantities of liquid CO_2. Depending upon the temperature at which the CO_2-rich phase homogenizes to the liquid state they contain either liquid CO_2 or liquid CO_2 + gaseous CO_2 at room temperature. The ratio of aqueous liquid/liquid CO_2 varies from about 1.5 to 5.0 for the type III inclusions but generally < 2.5 for the type IV group. Numerically the complex four-phase inclusions are the least important and show little variation in daughter minerals. Inclusions containing liquid CO_2 respond violently to thermal overprinting and frequently explode due to a massive build-up in internal pressure. The black inclusions surrounded by haloes of tiny satellite inclusions commonly associated with the type III inclusions are thought to be the remains of disrupted inclusions with a high initial liquid CO_2 content.

Type V: Single phase inclusions (*a*) aqueous liquid or (*b*) wholly gaseous. The sub-types V*a* and V*b* are mutually exclusive and correspond to different conditions of formation. The aqueous variety is interpreted as a metastable low temperature type I inclusion which has failed to nucleate a small vapour bubble (Roedder 1967). By contrast the gaseous variety though superficially similar to the disrupted type III inclusion is without a debris halo. Where proved coeval with type II, III or IV inclusions it is considered to be diagnostic of fluid boiling; representing the vapour phase of a heterogeneous two-phase liquid–vapour system.

In addition to fluid inclusions, some of the quartz crystals contain solid rutile inclusions, especially in pebbles < 4 mm diameter. The degree of rutilation, shape, dimension and orientation of the needles is variable. An unusual association noted in certain grains is the growth of secondary inclusions on contact with or enveloping the rutile (figure 3*e*).

Pre-depositional inclusions 'primaries'

With the exception of type V*a*, the 'primaries' are represented by all five inclusion types. For any one pebble the number of different types rarely exceeds three, but in a normal specimen of banket ore there may be several pebbles with different assemblages of inclusions.

Theoretically this allows a large number of permissible combinations. The fact that this is not observed demonstrates a restricted *P–T–X* environment for the veins, which limits the range of possible source areas for the quartz pebbles. The occurrence of different inclusion assemblages and deformational textures in adjacent pebbles provides a useful guide to the recognition of pre- and post-depositional inclusions and supplements the general recognition of primary, pseudosecondary and secondary inclusions. While types I and II generally conform to the Ermakov criteria, types III and IV often occur in curving zones or discontinuous irregular planar arrays. This is quite distinct from the more continuous regular arrays of unequivocal secondaries decorating well-defined healed fractures. Unlike a large euhedral crystal which records the whole *P–T–X* history of a mineralizing event, an interlocking aggregate of anhedral crystals cannot be expected to respond in the same manner. Thus within the context of a smaller crystal, fundamental changes in fluid chemistry during the main phase of quartz deposition may only be recorded in the secondaries. The CO_2-rich inclusions are therefore regarded as pseudosecondaries with secondary inclusion characteristics. This relationship is probably equivalent to the complex refilling mechanism and development of secondary inclusions described by Kalyuzhnyy & Voznyak (1969) for Zanorysh-type pegmatites. The correct recognition of 'primaries' related to quartz deposition is confirmed by the relative exclusion from the data of incompatible combinations of inclusions as might be expected by superimposing pre-depositional secondaries unrelated to vein formation.

Since dissolved salts are known to suppress the onset of critical phenomena in the system H_2O–CO_2 (Takenouchi & Kennedy 1965) type IV inclusions represent the trapping of supercritical fluids at temperatures higher than those for the corresponding type III variety. Where the liquid CO_2 content of the latter inclusions is greatest they are sometimes accompanied by coexisting type II inclusions suggesting sub-critical immiscibility and the simultaneous trapping of two-fluid phases (a CO_2-rich phase and a H_2O-rich phase). Many intermediate conditions exist, as shown by the range of H_2O/liquid CO_2 ratios, but all suggesting elevated *P–T* conditions.

Post-depositional inclusions 'secondaries'

The only unambiguous 'secondaries' are those occurring along fractures traversing both pebble and matrix, or as planar arrays with a common orientation in pebbles of different crystallographic orientation (figure 3*f*). For specimens showing no apparent fracture fabric, the occurrence of 'secondaries' along planes of weakness due to crystal anisotropy can not be discounted. Even so, compared to the 'primaries', the post-depositional inclusions are poorly developed and represented almost exclusively by types I*a* or V*b*; more rarely by I*b*. Without a petrofabric analysis of the host rocks it is impossible to assign even a relative age to the 'secondaries'.

Inclusions of uncertain origin

Occupying a position between the two main classes are a group of inclusions whose origin is less certain. By virtue of their occurrence they are clearly secondaries *sensu stricto*. Of these the least problematical are the minute inclusions decorating Boehm lamellae, which impart a reddish-brown colour to the quartz as a result of Tyndall light scattering (figure 3*g*). Closely associated are the arrays of small inclusions (< 5 μm) orientated at 90° to the deformation bands and elongated sub-grains. Both appear to have originated during the pre-depositional deformation of the quartz veins but are not necessarily contemporaneous.

Regional variation in inclusion assemblages

When considered regionally the fluid inclusion data for individual goldfields or sections of the Witwatersrand basin suggests a marked variation in the nature and origin of the vein quartz. This is most clearly illustrated by differences in the pre-depositional inclusion assemblages for separate geographical areas (figure 4). Quartz pebbles from the Klerksdorp–Dominion Reef area are significantly different from those of the East Rand and probably also from those of the O.F.S. and West Wits areas. Collectively, the evidence would appear to support a sedimentological model of multiple entry points into the basin (Brock & Pretorius 1964). A further observation not wholly reflected in the bulk mineral composition of the sediments is the persistence of a rather distinctive source for the vein quartz in the Klerksdorp region throughout the Dominion Reef and Upper Witwatersrand periods. Similarly, the dominance of type I*b* inclusions and presence of rutilated quartz implies a unique source for the East Rand quartz pebbles.

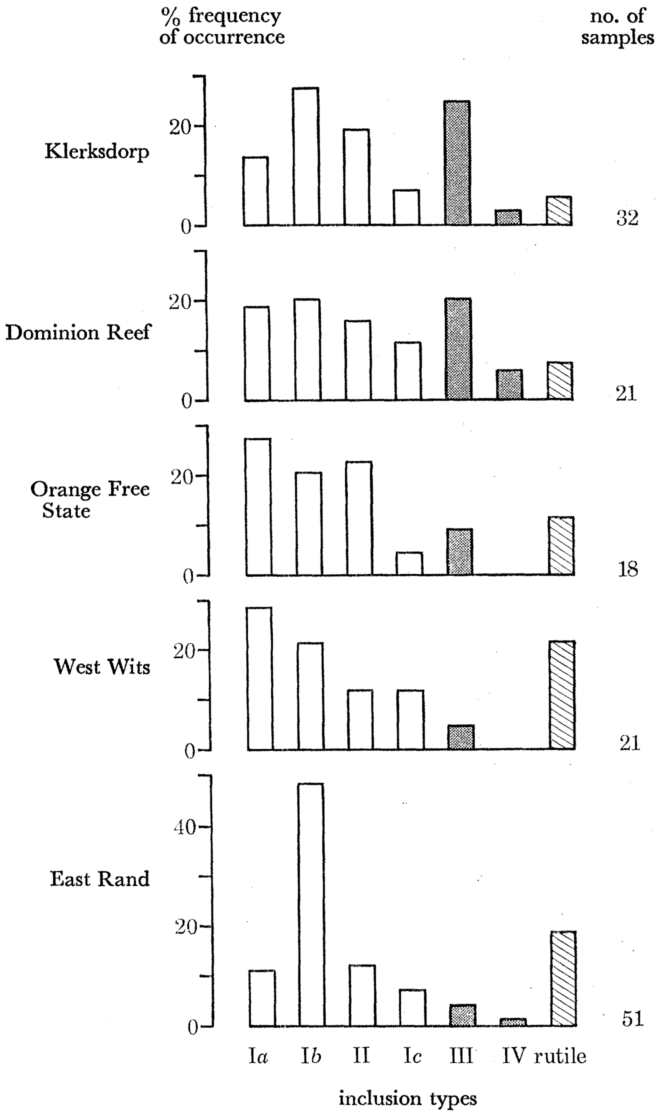

FIGURE 4. Regional variation in inclusion assemblages for the Witwatersrand orefield.

Correlation between uraniferous ores and CO_2 inclusions

After allowing for differences in the stratigraphic range of samples, several patterns emerge concerning the spatial and temporal distribution of uranium not discernible in the regional evaluation. Figure 5 shows the data re-plotted using a geological succession for the reefs suggested by Whiteside (1970). Of the six most economically important uraniferous reefs in the O.F.S., Klerksdorp, Dominion Reef, West Wits and East Rand areas, five are characterized by the presence of vein quartz pebbles containing type III or IV liquid CO_2 inclusions (i.e. the Intermediate, Leader, Vaal, Dominion and Kimberley UK9 reefs). The only exception is the Carbon Leader Reef of the West Wits which differs from the others in representing the best example of ore associated with hydrocarbon in the Witwatersrand Basin. Of the 19 major auriferous reefs studied, including the Afrikander Reef of the Rietkuil Syncline, vein quartz containing liquid CO_2 inclusions is present in only four cases (i.e. the Leader Reef of the O.F.S., the Black Reef, Ventersdorp Contact Reef and Vaal Reef of the Klerksdorp area). Both the Leader and Vaal Reefs are uranium producers and hence do not constitute real exceptions. Since the Black Reef and Ventersdorp Contact Reef represent a reworking of the underlying Upper Witwatersrand sediments it is conceivable that the quartz pebbles containing liquid CO_2 inclusions have been derived from the Vaal Reef.

The positive correlation between uraniferous banket ores and associated quartz pebbles containing type III and IV inclusions strongly supports the contemporaneous deposition of metal and associated sediments. Though favouring a syngenetic origin, the evidence offers no criteria for distinguishing between detrital uraninite and uranium precipitated chemically from the water in which the sediments were being laid down. In view of the work of Coetzee (1965), Hiemstra (1968), Liebenberg (1955) and Minter (1976), and the successful application of the 'placer' model, one must conclude that some uraninite, free from carbonaceous matter, is a primary detrital component. If this is correct, then the occurrence of vein quartz rich in liquid CO_2 inclusions reflects the presence or proximity of detrital uraninite. With regard to uranium in solution, a clue to the importance of this component may lie in our understanding of the hydrocarbon-rich ores and their relation to the banket ores. Brock & Pretorius (1964), De Kock (1964) and others have for many years advocated an algal origin for the 'carbon', implying growth and accumulation in a low-energy environment. Recent work by Hallbauer (1975) now appears to confirm this suggestion and demonstrates that simple organisms are capable of extracting Au and U from pre-existing minerals and depositing the elements inter- and intracellularly. Occupying the distal parts of alluvial fans, the hydrocarbon-rich ores probably represent the efficient biogenic extraction of U from solution in areas beyond the zone of active fan accretion.

Unfortunately, samples were not available from the eastern part of the West Wits area and hence it was not possible to test the concept of a distal to proximal facies change eastwards over the Bank Break from the Carbon Leader of the Blyvooruitzicht section to the more typical banket deposits of the Libanon section. However, unless the area was located at the confluence of two alluvial fans one should expect some detrital uraninite together with diagnostic vein quartz in the adjacent Libanon section. Further south, in the O.F.S. and Klerksdorp areas, hydrocarbon-rich ores in the Basal and Vaal Reefs share their horizons with typical banket type ores. In describing the geology of the O.F.S. (central section), McKinney (1964) notes

supergroup/group	formation	Orange Free State section	Klerksdorp section	Dominion Reef section	West Wits section	East Rand section
Transvaal			***Au.** Black Reef			
Ventersdorp			***Au**+(**U**). V.C.R.		**Au.** V.C.R.	
Upper Witwatersrand	Elsburg	**Au.** Elsburg	**Au.** Elsburg			**Au.** Elsburg
	Kimberley	**Au.** ‘A’ Reef				**Au.** Kimberley UK7 ***U**+**Au.** Kimberley UK9
	Bird	***U**+**Au.** Leader Basal	***U**+**Au.** Vaal			
	Main	***U**+(**Au**). Intermediate	**Au.** Ada May		**Au.** M.R.L. **U**+**Au.**C.L. **Au.** N.L.	**Au.** M.R.L.
Lower Witwatersrand	Jeppestown			**Au.** Afrikander		**Au.** Footwall
	Government Reef					
	Hospital Hill					
Dominion Reef				***U**+(**Au**). Dominion		

KEY: * Vein Quartz containing type III or IV liquid CO_2 inclusions. **Au**, Gold; **U**, Uranium; V.C.R., Ventersdorp Contact Reef; M.R.L., Main Reef Leader; C.L., Carbon Leader; N.L., North leader.

FIGURE 5. Correlation between uraniferous reefs and the presence of vein quartz containing liquid carbon dioxide-type inclusions.

that economic amounts of uranium are only found in the centre of the basin where carbon is more abundant. The present data suggests a predominance of quartz pebbles containing type III and IV inclusions in the southern section (Virginia) and their absence in the northern section (Freddies). This is in keeping with a southerly proximal facies related to a movement of sediment from south to north as inferred from palaeocurrent direction. In the Klerksdorp area, Minter's work (1976) confirms the importance of the association 'uranium-hydrocarbon' in the Vaal reef orebody but from an exhaustive treatment of sedimentological and mine data he derives a close relationship between reef isopachs and uranium values, which combined with the observed hydraulic equivalence of uraninite with other heavy minerals, strongly supports the case for a major detrital component. The alluvial fan complexes of the O.F.S. and Klerksdorp areas may therefore represent situations where both the detrital and solution components of syngenetic uranium are developed at the same stratigraphic horizon.

Origin of the uranium

Concerning the significance of the association U-CO_2, the spatial relationship for the basin does not prove a genetic affinity in the source area. Inclusion data for the 'primaries' does suggest, however, that P–T–X conditions during vein formation were typical of those for hydrothermal uranium mineralization. Tugarinov & Naumov (1969) in describing various uranium deposits in the U.S.S.R. report a temperature range of 350 to 50 °C and pressure range of 2000 to 400 bar. This agrees closely with the temperature range for intergranitic uranium veins in the Massif Central, given by Poty, Leroy & Cuney (1974). Both groups record a pronounced enrichment of CO_2 in the orefluids; a feature interpreted as indicating uranium transport as uranyl carbonate complexes. Tugarinov & Naumov also note that whereas uraninite is the most stable mineral above 250 °C, pitchblende is characteristic of the lower temperature deposits. Opinions differ as to the distinction between these two phases, but whatever terminology is used the less resistate 'pitchblende' would be more susceptible to solution during weathering. Furthermore, since the 'secondaries' were of a low temperature type it is unlikely that post-depositional fluids were responsible for the development of the allogenic uraninite phase.

The marked contrast in gross mineralogy of the Dominion Reef and Upper Witwatersrand systems has promoted several workers to advocate separate origins for the uraninites. The abundance of accessory garnet, monazite, columbite and zircon in the older sediments is taken as evidence for a pegmatitic source whereas the relative absence of these minerals in the younger sediments is indicative of a non-pegmatitic source. If, however, one assumes the diagnostic quartz pebbles reflect the depositional environment of quartz-rich uraniferous bodies in the hinterland, then the similarity in inclusion assemblages for the Dominion Reef and Klerksdorp areas implies that the uraninites were formed under similar conditions (figure 4). This apparent contradiction can best be explained by considering the uranium to have been derived from a suite of uraniferous veins emplaced in a terrain of variable metamorphic and granitic rocks, the heavy mineral content of the reefs being determined by the mineralogy of the eroded country rocks. Furthermore the discrete distribution of uranium in the basin also implies a restricted distribution in the source areas such that the influx of uranium was controlled by the occurrence and erosion of these veins. With the exception of the Black Reef and Ventersdorp Contact Reef it is doubtful whether a reworking of older mineralized sediments, as proposed by Vos (1975) for the gold ores, could produce conglomerates uniquely defined by the presence of one particular type of vein quartz.

Recent work by Touret (1971), Hoefs & Touret (1975), and Hollister & Burruss (1976) has demonstrated the important rôle of supercritical H_2O–CO_2 fluids during high-grade metamorphism and migmatization. Lambert & Heier (1968) have also shown that increasing metamorphism is accompanied by a progressive loss of U and Th from the system. Given the extreme mobility of uranium in carbonated fluids, a situation where both processes were operating simultaneously would create the optimum conditions for uranium remobilization. Such a situation may have existed in the granite–greenstone belts of the Kapvaal craton surrounding the Witwatersrand Basin. In the Barberton area, Hunter (1968) and Viljoen, Saager & Viljoen (1970) describe the intrusion of volatile-rich metasomatic granites and migmatitic granite complexes along the margins of older low-volatile tonalitic gneiss domes. A concomitant expulsion of CO_2-rich fluids, enriched in uranium may have triggered an additional remobilization of uranium from the metavolcanic/sedimentary cover to be redeposited at higher levels as uraniferous quartz veins. Depending upon the source of the metal and conditions during its extraction and precipitation, one would expect the Th/U ratio of the resultant uraninite to vary accordingly.

As a corollary, it is suggested that the relative proportions of detrital uraninite and uranium in solution entering the Witwatersrand Basin were governed by the mineralogical character of the uraniferous veins; a high solution component reflecting a predominance of pitchblende in that part of the source area.

Conclusions

The pebbles of vein quartz, characteristic of the mineralized oligomictic conglomerates, show considerable variation in the degree of intercrystalline deformation and the development of fluid inclusions, both within and between samples. These features indicate the heterogeneous origin of the quartz, not always apparent in hand specimens. According to differences in morphology, mode of occurrence and relative phase proportions, the inclusions may be classified into five main types. Using these differences together with the associated dislocation creep phenomena and crystallographic orientation of adjacent pebbles it is possible to distinguish between pre- and post-depositional events.

As shown by the progressive modification of pre-existing inclusions corresponding to changes in the intensity of deformation, the inclusions also record the pre-depositional metamorphism of the parent quartz veins. The effects, though variable, cannot be discounted entirely and must be considered when assessing the phase relations for primary and pseudosecondary inclusions.

The 'primaries' or pre-depositional inclusions are represented by all five types, of which those containing liquid CO_2 are the most distinctive. Their presence, especially where coexistent with high vapour two phase inclusions, indicates formation at elevated temperatures and pressures. P–T–X data for this group provides direct information on physico-chemical conditions in the source area.

The 'secondaries' or post-depositional inclusions are less well developed and represented by only the lowest temperature types. The temperature régime as defined by these inclusions appears too low to account for the deposition of uraninite but is adequate to account for a later secondary remobilization of uranium by circulating groundwaters.

Regional variation in pre-depositional inclusion assemblages follows a coherent geographical pattern, implying a systematic variation in the source areas for individual sections of the Witwatersrand basin. Within each section there is a positive correlation between uraniferous banket ores and the presence of vein quartz containing liquid CO_2 inclusions. This suggests a syngenetic origin for the uranium and though the hydrocarbon-rich ores appear at first to contradict this model it is thought they represent the precipitation of uranium from solution by organic matter in areas beyond the zone of active fan accretion; and hence beyond the areas of significant detrital uraninite.

Data for the 'primaries' demonstrates that conditions during vein formation in areas supplying uranium to the basin were typical of those for hydrothermal uraninite/pitchblende deposits, especially with regard to the enrichment of CO_2 in the fluids.

The marked similarity in inclusion assemblages for the Klerksdorp and Dominion Reef areas suggests that the contrasting bulk mineral composition of the Dominion Reef and Upper Witwatersrand Systems may not have a direct bearing on the origin of the associated uraninite, but more a reflection of the country rocks adjacent to the uraniferous quartz bodies. The discrete distribution of uranium in the basin implies a restricted distribution in the hinterland such that the influx of uranium was controlled by the occurrence and erosion of these uranium enrichments.

Given the important rôle of supercritical H_2O–CO_2 fluids during high grade metamorphism and migmatization, it is proposed that the intrusion of migmatitic granite complexes into the granite–greenstone belts of the Kapvaal craton was responsible for the remobilization of uranium and its subsequent deposition in contiguous quartz veins.

Future research

The obvious exploration potential given by the ability to recognize uraniferous horizons from a study of inclusions in pebbles of vein quartz needs to be developed more fully. If integrated with routine pebble counts, as practised by several mining companies, fluid inclusion studies may provide a much better understanding of the distribution of U and Au within particular reefs. An important extension of the present work should be the sampling of areas as yet untested (i.e. the West Rand, South Rand and Evander goldfields). Satisfactory confirmation of this model for the Witwatersrand Basin opens up the possibility of using this technique to evaluate similar uranium prospects in the eastern Transvaal, northern Natal and ultimately other oligomictic quartz conglomerate sequences in Brazil, Australia, Canada and Algeria.

Equally, a more detailed characterization of inclusions for the auriferous reefs may provide criteria for differentiating between barren and mineralized conglomerates. The important rôle of uranium-bearing quartz veins would be greatly substantiated if it could be demonstrated that CO_2-rich inclusion fluids were uraniferous.

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Appendix I

Tables 1–5: Tables of samples used for fluid inclusion studies according to geographical areas described in the text

Table 1. East Rand area

polished thin section no.	sample no.	mine property	stratigraphic horizon	material
1968	1	Daggafontein	Main Reef	conglomerate
1969	2	Daggafontein	Main Reef	conglomerate
1970	3	Daggafontein	Main Reef	conglomerate
1971	4	Daggafontein	Main Reef	conglomerate
1972	4	Daggafontein	Main Reef	conglomerate
1973	5	Daggafontein	Main Reef	conglomerate
1974	6	Daggafontein	Main Reef	conglomerate
1975	7	Daggafontein	Main Reef	conglomerate
1976	8	Daggafontein	Main Reef	conglomerate
1978	10	Daggafontein	Main Reef	conglomerate
1979	11	Daggafontein	Main Reef	conglomerate
1980	12	Daggafontein	Main Reef	conglomerate
1981	13	Daggafontein	Main Reef	conglomerate
1982	14	Daggafontein	Main Reef	conglomerate
1983	15	Daggafontein	Main Reef	conglomerate
1984	16	Daggafontein	Main Reef	conglomerate
1985	17	Daggafontein	Main Reef	conglomerate
1986	18	Daggafontein	Main Reef	conglomerate
1987	19	Daggafontein	Main Reef	conglomerate
1988	20	Daggafontein	Main Reef	conglomerate
1989	21	Daggafontein	Main Reef	conglomerate
1990	21	Daggafontein	Main Reef	conglomerate
1991	22	Daggafontein	Main Reef	conglomerate
1992	23	Daggafontein	Main Reef	conglomerate
1993	24	Daggafontein	Main Reef	conglomerate
1994	25	Daggafontein	Main Reef	conglomerate
1995	26	Daggafontein	Main Reef	conglomerate
2029	MK 1A	Daggafontein	Kimberley Reef	conglomerate
2030	MK 1B	Daggafontein	Kimberley Reef	conglomerate
2031	MK 2	Daggafontein	Kimberley Reef	conglomerate
2061	UG 9145	East Geduld	Main Bird	quartzite
2062	UG 9146	East Geduld	Main Reef	conglomerate
2063	UG 9147	East Geduld	Main Reef	conglomerate
2064	UG 9148	East Geduld	Main Reef	conglomerate
2065	UG 9149	East Geduld	Main Reef	conglomerate
2066	UG 9150	East Geduld	Main Reef	conglomerate
2067	UG 9151	East Geduld	Main Bird	quartzite
2068	UG 9152	East Geduld	Kimberley Reef (UK3)	conglomerate
2069	UG 9153	East Geduld	Kimberley Reef (UK3)	conglomerate
2070	UG 9154	East Geduld	Kimberley Reef (UK4)	quartzite
2071	UG 9155	East Geduld	Kimberley Reef (UK5)	conglomerate
2072	UG 9156	East Geduld	Kimberley Reef (UK7)	conglomerate
2073	UG 9157	East Geduld	Kimberley Reef (UK8)	quartzite
2074	UG 9158	East Geduld	Kimberley Reef (UK9)	conglomerate
2076	UG 9160	East Geduld	Kimberley Reef	conglomerate
2077	UG 9161	East Geduld	Kimberley Reef	quartzite
2078	UG 9162	East Geduld	Kimberley Reef	conglomerate
2099	A 232	East Geduld	Main Reef Leader	conglomerate
2100	A 233	East Geduld	Kimberley Reef	conglomerate
2108	MR 1	Springs	Main Reef Leader	conglomerate
2109	FR 1	Sallies	Footwall Reef	conglomerate
2110	VC 1	Sallies	Ventersdorp Contact Reef	conglomerate
2111	EC 1	Sallies	Elsburg Conglomerate	conglomerate

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

TABLE 2. WEST WITS AREA

polished thin section no.	sample no.	mine property	stratigraphic horizon	material
1940	1 A	West Driefontein	Main Reef	conglomerate
1941	1 B	West Driefontein	Carbon Leader	conglomerate
1942	2 A	West Driefontein	Main Reef	conglomerate
1943	2 B	West Driefontein	Main Reef	conglomerate
1944	3 A	West Driefontein	Carbon Leader	conglomerate
1945	3 B	West Driefontein	Main Reef	conglomerate
1946	3 C	West Driefontein	Main Reef	conglomerate
1947	3 D	West Driefontein	Main Reef	conglomerate
1948	3 D	West Driefontein	Main Reef	conglomerate
1949	4 A	West Driefontein	Main Reef	conglomerate
1950	4 B	West Driefontein	Carbon Leader	conglomerate
1951	5	West Driefontein	Carbon Leader	conglomerate
1952	6 A	West Driefontein	Carbon Leader	conglomerate
1953	6 B	West Driefontein	Carbon Leader	conglomerate
1954	6 C	West Driefontein	Carbon Leader	conglomerate
1955	6 C	West Driefontein	Carbon Leader	conglomerate
1956	7 A	West Driefontein	Carbon Leader	conglomerate
1957	7 A	West Driefontein	Carbon Leader	conglomerate
1958	7 B	West Driefontein	Carbon Leader	conglomerate
1959	8 A	West Driefontein	Main Reef	conglomerate
1960	8 B	West Driefontein	Main Reef	conglomerate
1961	8 B	West Driefontein	Main Reef	conglomerate
1962	9 A	West Driefontein	Carbon Leader	conglomerate
1963	9 A	West Driefontein	Carbon Leader	conglomerate
1964	9 A	West Driefontein	Carbon Leader	conglomerate
1965	9 B	West Driefontein	Main Reef	conglomerate
1966	9 B	West Driefontein	Main Reef	conglomerate
1967	9 B	West Driefontein	Main Reef	conglomerate
2084	A 217	Western Deep levels	Ventersdorp Contact Reef	conglomerate
2085	A 218	Western Deep levels	Carbon Leader	conglomerate
2086	A 219	Western Deep levels	North Leader	conglomerate
2087	A 220	Western Deep levels	Carbon Leader	conglomerate

TABLE 3. ORANGE FREE STATE AREA

polished thin section no.	sample no.	mine property	stratigraphic horizon	material
2052	V 1	Virginia	Basal Reef	conglomerate
2053	V 3	Virginia	Leader Reef	conglomerate
2058	V 2	Virginia	Basal Reef	conglomerate
2059	V 4	Virginia	Leader Reef	conglomerate
2093	A 226	Freddies	Elsburg Reef	conglomerate
2094	A 227	Free State Saaiplaas	Leader Reef	conglomerate
2095	A 228	President Steyn	Intermediate Reef	conglomerate
2096	A 229	President Steyn	'A' Reef	conglomerate
2097	A 230	Free State Saaiplaas	Basal Reef	conglomerate
2098	A 231	President Brand	Basal Reef	conglomerate
2102	FW 1	Freddies	Basal Reef	conglomerate
2103	FW 2	Freddies	Basal Reef	conglomerate
2104	FW 3	Freddies	Basal Reef	conglomerate
2105	FW 4	Freddies	Basal Reef	conglomerate
2106	FW 5	Freddies	Basal Reef	conglomerate
2107	FW 6	Freddies	Basal Reef	conglomerate
2112	FW 7	Freddies	Basal Reef	conglomerate
2113	T 1	Freddies	Basal Reef	conglomerate

TABLE 4. KLERISDORP AREA

polished thin section no.	sample no.	mine property	stratigraphic horizon	material
2032	VR 1	Vaal Reefs	Vaal Reef	conglomerate
2033	VR 2	Vaal Reefs	Vaal Reef	conglomerate
2034	VR 3	Vaal Reefs	Vaal Reef	conglomerate
2035	VR 4	Vaal Reefs	Vaal Reef	conglomerate
2036	VR 6A	Vaal Reefs	Vaal Reef	conglomerate
2037	VR 6B	Vaal Reefs	Vaal Reef	conglomerate
2038	VR 6C	Vaal Reefs	Vaal Reef	conglomerate
2039	VR 5	Vaal Reefs	Vaal Reef	conglomerate
2040	VR 7	Vaal Reefs	Vaal Reef	conglomerate
2041	VR 8	Vaal Reefs	Vaal Reef	conglomerate
2042	VR 9	Vaal Reefs	Vaal Reef	conglomerate
2043	VR 10	Vaal Reefs	Vaal Reef	conglomerate
2044	VR 11	Vaal Reefs	Vaal Reef	conglomerate
2045	VR 12	Vaal Reefs	Vaal Reef	conglomerate
2046	VR 13	Vaal Reefs	Vaal Reef	conglomerate
2047	VR 14	Vaal Reefs	Vaal Reef	conglomerate
2048	VR 15	Vaal Reefs	Vaal Reef	conglomerate
2049	VR 16	Vaal Reefs	Vaal Reef	conglomerate
2050	VR 17	Vaal Reefs	Vaal Reef	conglomerate
2054	VR 20	Vaal Reefs	Vaal Reef	conglomerate
2055	VR 21A	Vaal Reefs	Vaal Reef	conglomerate
2056	VR 21B	Vaal Reefs	Vaal Reef	conglomerate
2057	VR 22	Vaal Reefs	Vaal Reef	conglomerate
2060	VR 19	Vaal Reefs	Vaal Reef	conglomerate
2079	A 212	Western Reefs	Black Reef	conglomerate
2080	A 213	Western Reefs	MB 10 Reef	conglomerate
2082	A 215	Western Reefs	Ada May Reef	conglomerate
2083	A 216	Western Reefs	Ventersdorp Contact Reef	conglomerate
2088	A 221	Western Reefs	Vaal Reef	conglomerate
2089	A 222	Western Reefs	Ventersdorp Contact Reef	conglomerate
2090	A 223	Western Reefs	Elsburg No. 5 Reef	conglomerate
2091	A 224	Western Reefs	Dennys Conglomerate	conglomerate

TABLE 5. DOMINION REEF AREA

polished thin section no.	sample no.	mine property	stratigraphic horizon	material
1997	BR7 N1 A	Dominion Reefs	Dominion Reef	conglomerate
1998	BR7 N1 B	Dominion Reefs	Dominion Reef	conglomerate
1999	BR5 N2 A	Dominion Reefs	Dominion Reef	conglomerate
2000	BR5 N2 B	Dominion Reefs	Dominion Reef	conglomerate
2001	BR7 N2 A	Dominion Reefs	Dominion Reef	conglomerate
2002	BR7 N2 B	Dominion Reefs	Dominion Reef	conglomerate
2003	BR8 N2 A	Dominion Reefs	Dominion Reef	conglomerate
2004	BR8 N2 B	Dominion Reefs	Dominion Reef	conglomerate
2005	UG 9187	Dominion Reefs	Dominion Reef	quartzite
2006	BR8 N5 A	Dominion Reefs	Dominion Reef	conglomerate
2007	BR8 N5 B	Dominion Reefs	Dominion Reef	conglomerate
2008	BR9 52 A	Dominion Reefs	Dominion Reef	conglomerate
2009	BR6 N3 A	Dominion Reefs	Dominion Reef	conglomerate
2010	BR6 N3 A	Dominion Reefs	Dominion Reef	conglomerate
2011	BR10 N2 A	Dominion Reefs	Dominion Reef	conglomerate
2012	BR10 N2 B	Dominion Reefs	Dominion Reef	conglomerate
2013	UG 9184	Dominion Reefs	Dominion Reef	conglomerate
2014	BR8 N6	Dominion Reefs	Dominion Reef	conglomerate
2015	BR8 S2 A	Dominion Reefs	Dominion Reef	conglomerate
2016	BR8 S2 B	Dominion Reefs	Dominion Reef	conglomerate
2017	BR6 N4 A	Dominion Reefs	Dominion Reef	conglomerate
2018	BR6 N4 B	Dominion Reefs	Dominion Reef	conglomerate
2019	BR5 N3 A	Dominion Reefs	Dominion Reef	conglomerate
2020	BR5 N3 B	Dominion Reefs	Dominion Reef	conglomerate
2021	BR 952 B	Dominion Reefs	Dominion Reef	conglomerate
2022	UG 9181	Dominion Reefs	Dominion Reef	quartzite
2024	UG 9183	Dominion Reefs	Dominion Reef	conglomerate
2025	UG 9184	Dominion Reefs	Dominion Reef	conglomerate
2026	UG 9185 A	Dominion Reefs	Dominion Reef	conglomerate
2027	UG 9185 B	Dominion Reefs	Dominion Reef	conglomerate
2028	UG 9186	Dominion Reefs	Dominion Reef	conglomerate
2081	A 214	Afrikander Lease	Afrikander Reef	conglomerate
2101	A 234	Dominion Reefs	Dominion Reef	conglomerate

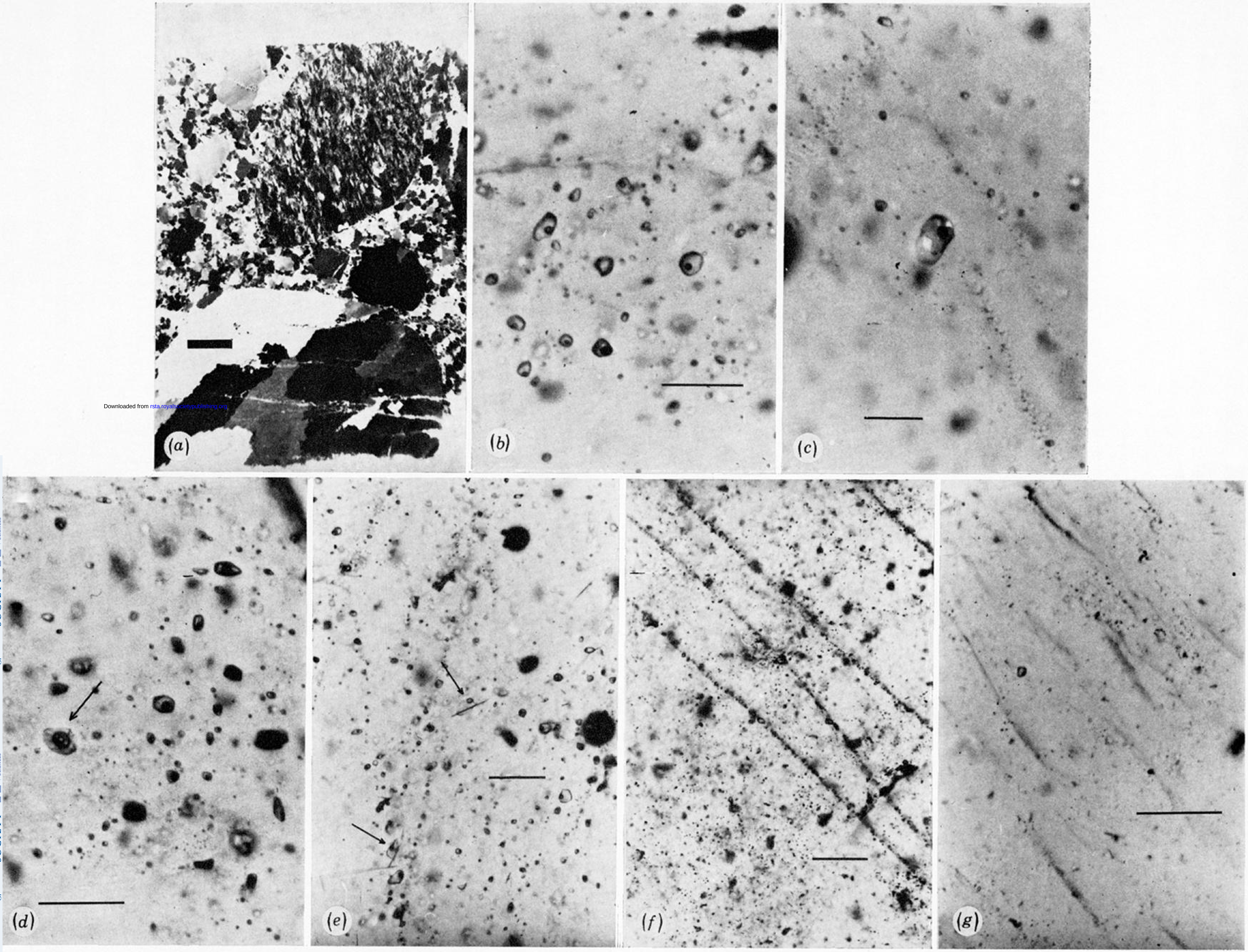

FIGURE 3. For description see opposite.