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PSEUDOTACHYLITES OF THE VREDEFORT DOME AND THE SURROUNDING WITWATERSRAND BASIN, SOUTH AFRICA

W.U. REIMOLD and W.P. COLLISTON

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by

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ABSTRACT

The Vredefort Structure is the type locality for pseudotachylite, a type of clast-laden melt breccia often observed in tectonic zones of brittle or brittle-ductile deformation and generally believed to be the result of frictional melting. Pseudotachylitic breccia is also particularly abundant in the Sudbury Structure and the Roter Kamm impact crater, as well as in the northern part of the Witwatersrand Basin surrounding the Vredefort Dome. In order to facilitate comparison between the pseudotachylite from the Vredefort Structure, of widely, but not universally accepted impact origin, with those from impact structures and tectonic settings, the existing data base is reviewed and recent field and laboratory observations summarised. Modes of breccia occurrences, petrographic appearance, the distribution and orientation data for Vredefort pseudotachylite, and the complex temporal relationships between breccias and other deformation phenomena are reviewed. Differences observed in the breccias of the Sudbury Structure and those from Vredefort, as well as the structural and chemical trends that are similar to those recognised for pseudotachylite formations in tectonic settings are also discussed. The Ar chronological record for Vredefort and Witwatersrand pseudotachylite strongly suggests multiple breccia-forming events in the Vredefort Dome.

It is concluded that a need exists for further quantitative mineralogical, chronological and structural studies, in order to allow full comparison of - and perhaps discrimination between - pseudotachylites from different geological environments, and to fully understand the role that pseudotachylite formation played during the extended evolution of the region of the Witwatersrand Basin.

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INTRODUCTION

Pseudotachylites, glassy or microcrystalline melt breccias, are known from numerous tectonic settings worldwide (e.g. Maglaughlin and Spray, 1992a and references cited therein). They commonly occur in the form of thin veins, rarely a few millimeters or even centimeters wide, in shear zones or along faults. Large-scale exposures are only known from three sites: 1. the Sudbury Structure in Ontario of probable impact origin (Dressler, 1984 and references therein; Grieve et al., 1991); 2. the Roter Kamm impact crater in Namibia (Reimold and Miller, 1989); and 3. the Vredefort Structure (also termed Vredefort Dome or Vredefort Ring) in South Africa, that is also widely regarded as an impact structure. Pseudotachylite is also known from a few other, confirmed impact structures, but these occurrences are rare and generally limited to narrow (mm-wide) veinlets (e.g. in the Rochechouart Structure, France - Reimold et al., 1987; the Nördlinger Ries crater, Germany - Dressler and Graup, 1969; and the Manicouagan Structure, Canada - Dressler, 1970).

Ever since Shand (1916) coined the term 'pseudotachylyte' (in most recent literature the here preferred spelling 'pseudotachylite' has been adapted) for the abundant breccia in the basement to the Vredefort Dome, many workers (e.g. Bisschoff, 1962; Dietz, 1964; Wilshire, 1971; Schwarzman et al., 1983) believed such breccia to be the result of 'shock' processes. Schwarzman et al. (1983) suggested that Vredefort pseudotachylite was formed by shock brecciation (cataclasis) followed by thermal metamorphism leading to partial melting of cataclastic breccia. Structural geologists, however, tend to agree that tectonically produced pseudotachylite is generated by frictional melting due to seismic slip events (Sibson, 1975; and various papers in Maglaughlin and Spray, 1992a) or even landslides (Masch et al., 1985). In some cases evidence for cataclasis preceding the melting process could be observed, too (Wenk, 1978; Maglaughlin, 1992; Swanson, 1992). Other fault rock types, such as mylonitic rocks or cataclasite, may also occur in intimate association with pseudotachylite (Brandl and Reimold, 1990; Killick et al., 1988; Passchier, 1982, 1984).

It is quite conceivable that, as a consequence of impact cratering, frictional fusion could be achieved by rapid block movement in the initially strongly compressed, then later, on rebound, extended crater basement (Martini, 1991). It is therefore possible that pseudotachylite-like breccia may be generated by several geological processes. Consequently, much detailed work, including thorough characterisations of pseudotachylites from different geological settings, is needed to identify distinctive criteria for pseudotachylites of different origin. A further complicating factor lies in the similarity between pseudotachylite and certain impact melt rock types (such as the A1 impact melt described by Lambert, 1981 from the Rochechouart crater; Reimold et al., 1987).

In the case of the Vredefort Structure detailed contributions on the nature and occurrence of pseudotachylite were published by Shand (1916), Hall and Molengraaff (1925), Nel (1927), Willemse (1937), Bisschoff (1962), Wilshire (1971), Schwarzman et al. (1983), Fletcher and Reimold (1989), and Killick and Reimold (1990). Killick et al. (1986) and Reimold et al. (1986a) first noticed that pseudotachylite is not restricted to the Vredefort

Dome, but also occurs in abundance in parts of the Witwatersrand Basin in the environs of the Dome.

Many earlier workers (e.g. Dietz, 1961) stressed the likelihood that the origin of the pseudotachylites of the Vredefort Dome is directly related to some catastrophic event, either a large impact or an internally triggered (cryptoexplosion or tectonics) event, the nature of which has been hotly debated in the past. Together with the occurrence of shatter cones, certain microdeformation features in quartz, and the presence of coesite and stishovite in narrow pseudotachylite veinlets, the pseudotachylites from Vredefort are now widely believed to be consistent with an impact origin of this structure.

Since an earlier review by Killick and Reimold (1990) new detailed field and laboratory studies have been undertaken. Internationally, studies of tectonically produced pseudotachylites have increased, following the need to understand high-strain-rate processes related to earthquake mechanisms. In South Africa the mining community has recognised the necessity to study the Vredefort Structure as an integral part of the economically important Witwatersrand basin.

This paper summarises the main features of the Vredefort and Witwatersrand pseudotachylites and indicates where follow-up studies are warranted. No attempt is made here to discuss in detail the definition of the term 'pseudotachylite', a topic that has been treated, for example, by Maglaughlin and Spray (1992b). Here the term 'pseudotachylite' is used descriptively, as follows, to characterise melt-bearing breccia: "Pseudotachylite is a fragment-laden breccia with either aphanitic or crystalline melt matrix" (Reimold et al., 1987). The terms 'Sudbury Breccia' or 'impact melt breccia', by contrast, are used to distinguish tectonically produced pseudotachylites (sensu strictu) from melt breccias* formed in other geological settings (e.g. in impact structures). Should it be fully agreed that the Vredefort Structure is of impact origin, the term 'Vredefort Breccia' could be introduced to replace 'Vredefort pseudotachylite'.

REGIONAL GEOLOGICAL SETTING OF THE VREDEFORT DOME

From approximately 60 km east of Johannesburg to the gold fields of the Orange Free State around Welkom (Figure 1) lies the gold and uranium province of the Witwatersrand Basin. The basin margins are partially outlined by basement highs (domal structures; Brock and Pretorius, 1964), with the Vredefort Dome forming a basement high near the geographical centre of the Basin. According to Corner et al. (1990), this position is near the intersection of the northeast-southwest trending axis of symmetry of the Basin with the so-called Vredefort Axis, interpreted as the crest of a crustal upwarp defined by geophysical data.

Footnote: Several types of clastic and melt breccias from the Sudbury Structure are collectively named 'Sudbury Breccia'. Comparison with Vredefort pseudotachylite and comparable melt breccias from other sites should therefore be carried out very cautiously.

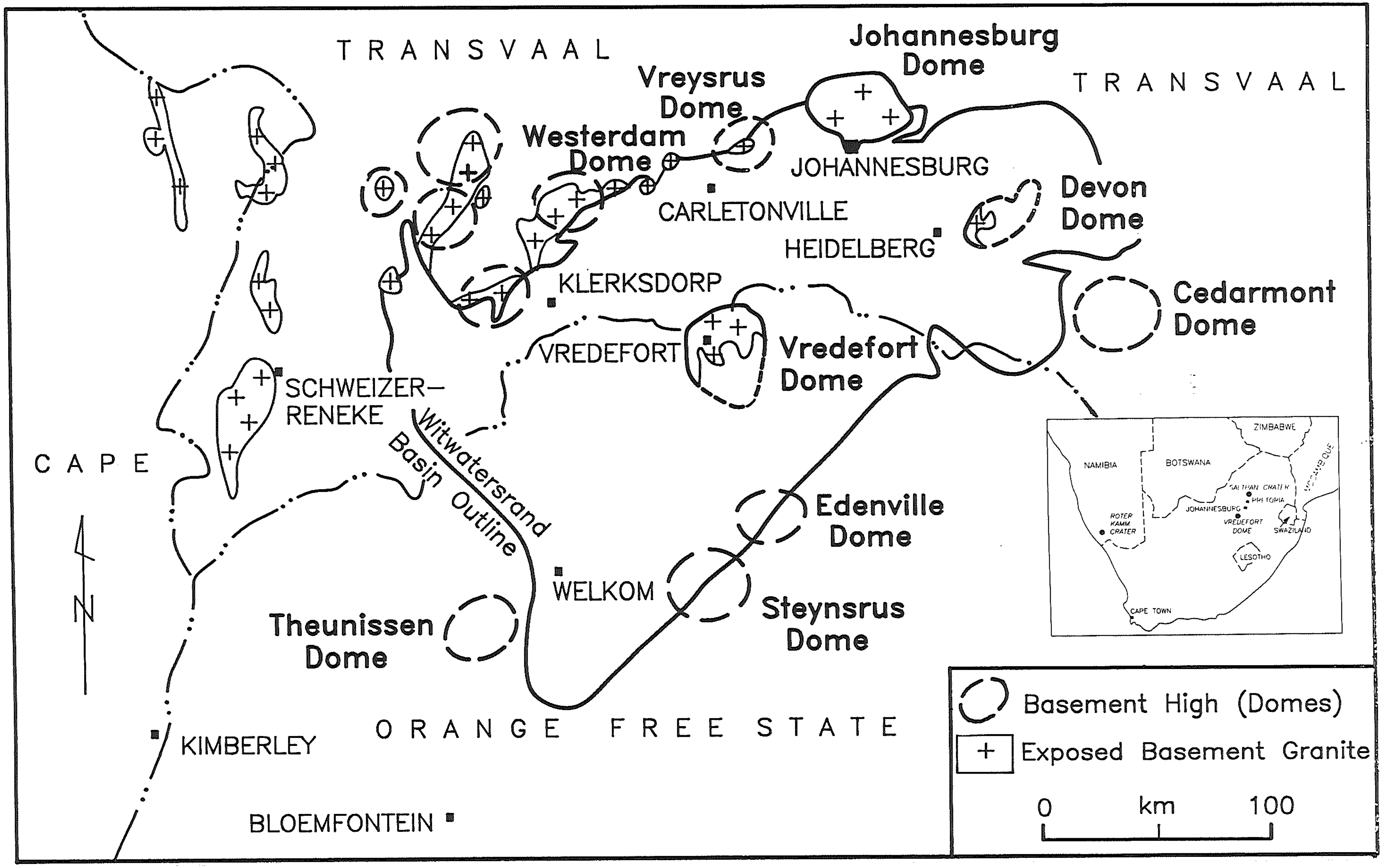


Figure 1: Outline of the Witwatersrand Basin and positions of basement highs around its margins and of the Vredefort Structure in the centre (after Brock and Pretorius, 1964). Inset: Locality map showing the Vredefort Dome and the two confirmed impact structures Roter Kamm in Namibia and the Pretoria Saltpan in the Transvaal, South Africa.

The Vredefort Structure consists of a semi-circular (some authors prefer a polygonal geometry - Antoine et al., 1990) collar of up- or overturned supracrustal sequences around the central core of Archaean granitoids. Corner and Wilsher (1989) concluded that "a gravity low, extending roughly from Vredefort to Edenville in the southeast, indicates relatively shallow basement and an opening of the dome to the southeast" (from Corner et al., 1990; cf. also Roering et al., 1990). The Archaean core is subdivided into the inner Inlandsee Leucogranofels (ILG) terrane and an outer annulus of Outer Granite Gneiss (OGG) (Stepto, 1990). The ILG and OGG are separated by the so-called Transition Zone (Hart et al., 1991), comprising an area of charnockitic rocks and abundant pseudotachylite along the Vredefort Discontinuity, a northeast-southwest trending (Fletcher and Reimold, 1989) or horseshoe-shaped (Hart et al., 1990b) mid-crustal discontinuity of still uncertain lithological or structural character. This zone is also characterised by a strong negative magnetic anomaly that Corner et al. (1990) equated with a similarly anomalous zone at the western margin of the Witwatersrand Basin (the so-called Colesberg Trend). These authors hold the view that this particular mid-crustal layer was brought to the surface in the upturned crust of the Vredefort basement, regarded as a deep cross-section through the crust of the Kaapvaal Craton (Slawson, 1976 - crust-on-edge model; Hart et al., 1990b). It has been suggested (Corner et al., 1990) that the magnetic anomaly could be attributed to a magnetite-rich zone along the contact between OGG and ILG. However, to date the presence of such a magnetite-enriched layer has not been confirmed.

SPATIAL DISTRIBUTION OF PSEUDOTACHYLITE

A major zone of pseudotachylite occurrences tangential to the northern margin of the Vredefort Dome was identified by Fletcher and Reimold (1989). Borehole intersections of pseudotachylite-rich breccia zones up to several tens of metres wide (Figure 2) were described from a series of fault zones in the northern part of the Witwatersrand Basin. In contrast, no pseudotachylite, and only limited (cm-scale) occurrences of other fault breccias have been reported from the East Rand Basin, the southern part of the Witwatersrand Basin and the Orange Free State gold fields (Figure 2). The main occurrences of pseudotachylite are linked to a series of bedding-parallel fault zones, such as the Master Bedding Fault (MBF) (Fletcher and Gay, 1971) near the top of the West Rand Group or the Black Reef Décollement Zone (Fletcher and Reimold, 1989) at the base of the Transvaal Sequence (Figure 3). All these bedding-parallel fault zones tend to dip at low angles towards the south/southeast in the direction of the Vredefort Dome. The remaining volumetrically important pseudotachylite occurrences are connected with generally north-south trending normal faults, for example the Bank Fault (BF in Figure 2).

The spatial distribution of pseudotachylite in the Vredefort Dome was assessed by estimating the areal percentages of breccia at more than 600 exposures, most of them located within the core. Figure 4 represents the raw data that were used to generate the schematic distribution pattern of Figure 5. A narrow annular pseudotachylite-enriched zone follows along the core-collar contact, but the major pseudotachylite occurrences are concentrated within a roughly northeast-southwest extending zone in the northern sector of the core. This zone straddles the Transition Zone between ILG and OGG (Figure 5), but does not extend far into the ILG terrane. In addition, several extensive occurrences are roughly aligned along a parallel trend in the southern part of the core, the Mara Décollement Zone (Reimold et al.,

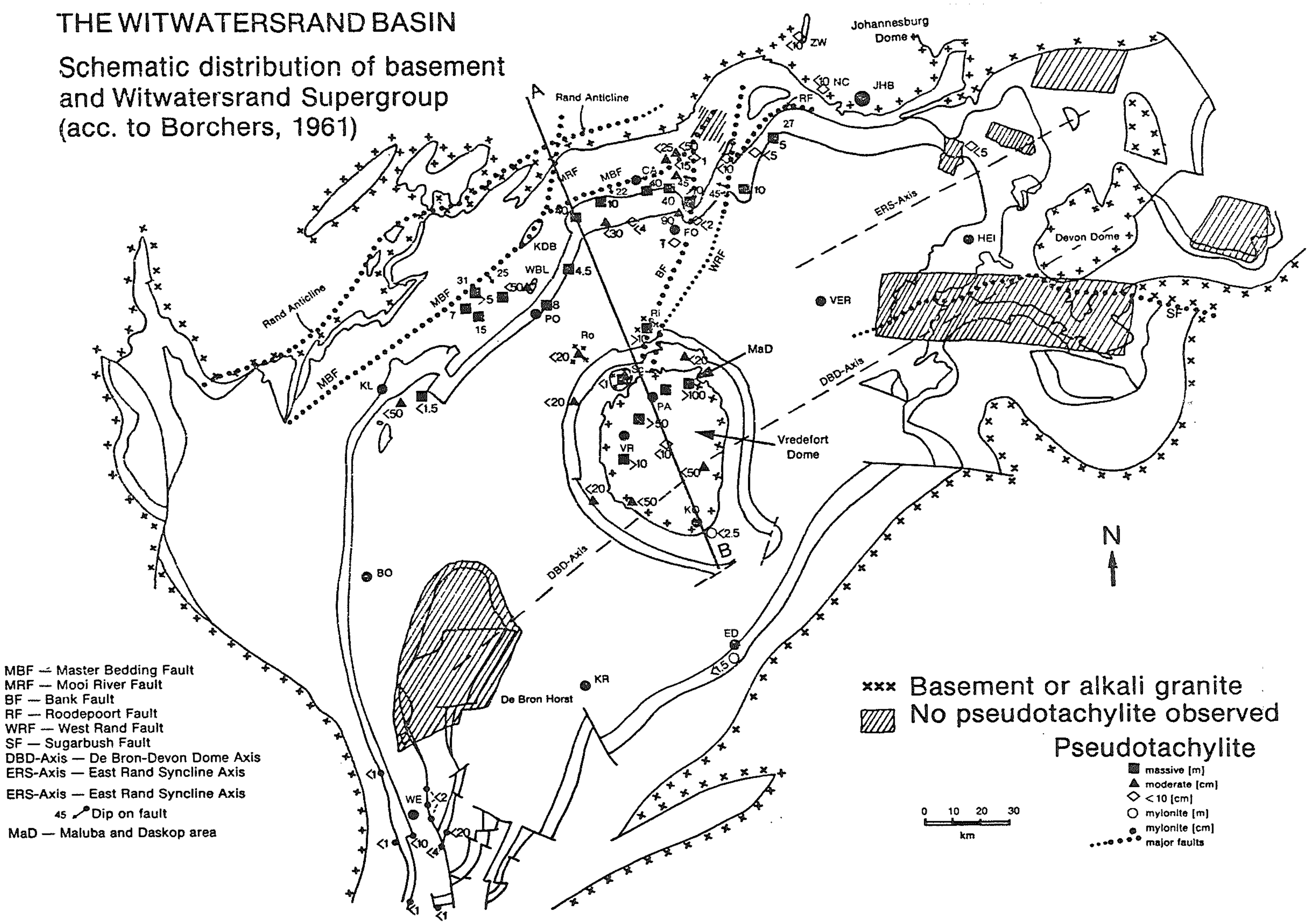


Figure 2: Occurrence and abundances of pseudotachylite and mylonite within the confines of the Witwatersrand Basin (after Fletcher and Reimold, 1989).

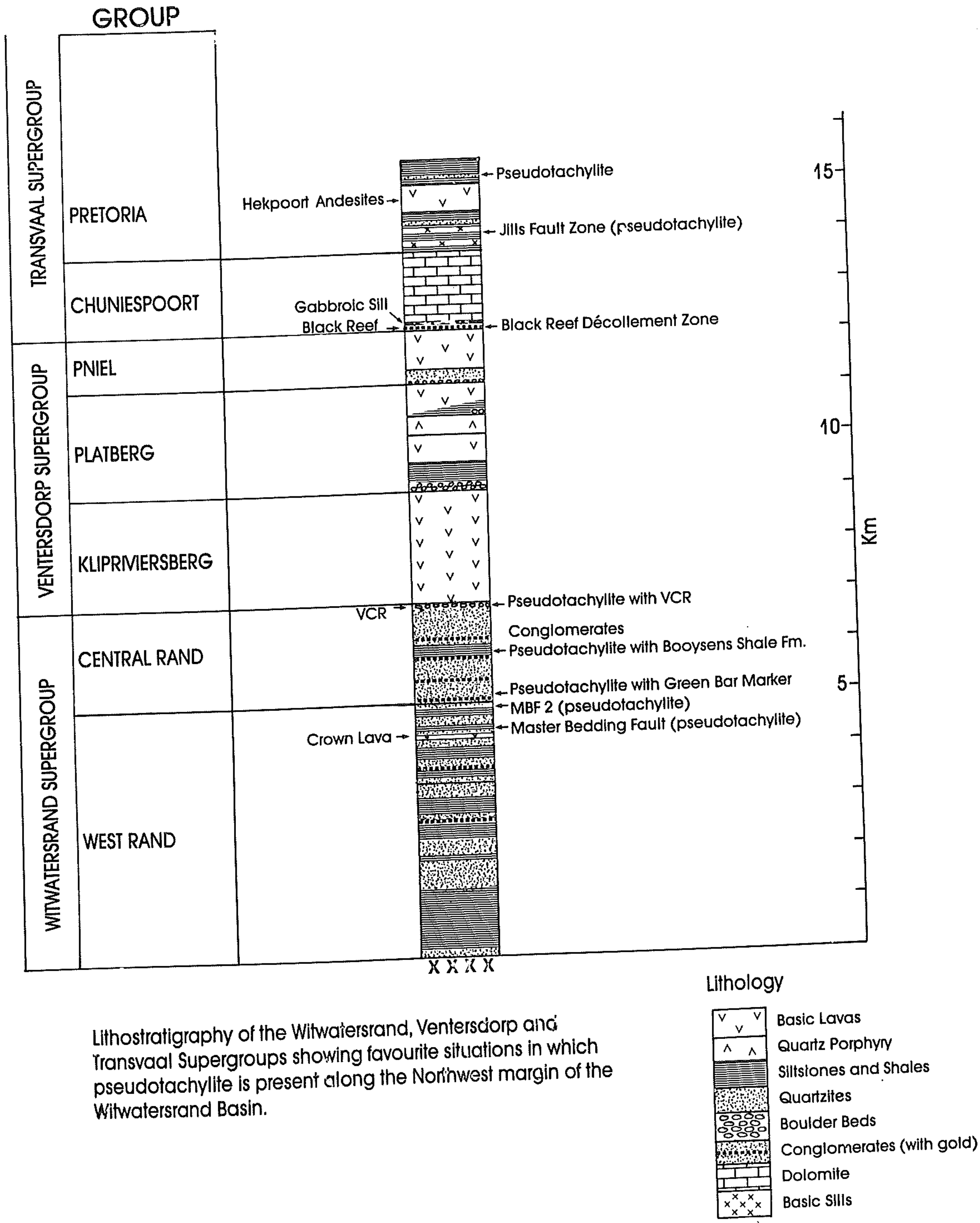


Figure 3: Stratigraphic column for the Witwatersrand and Ventersdorp Supergroups and parts of the Transvaal Sequence, indicating the positions where pseudotachylite has been recorded (after Fletcher and Reimold, 1989).

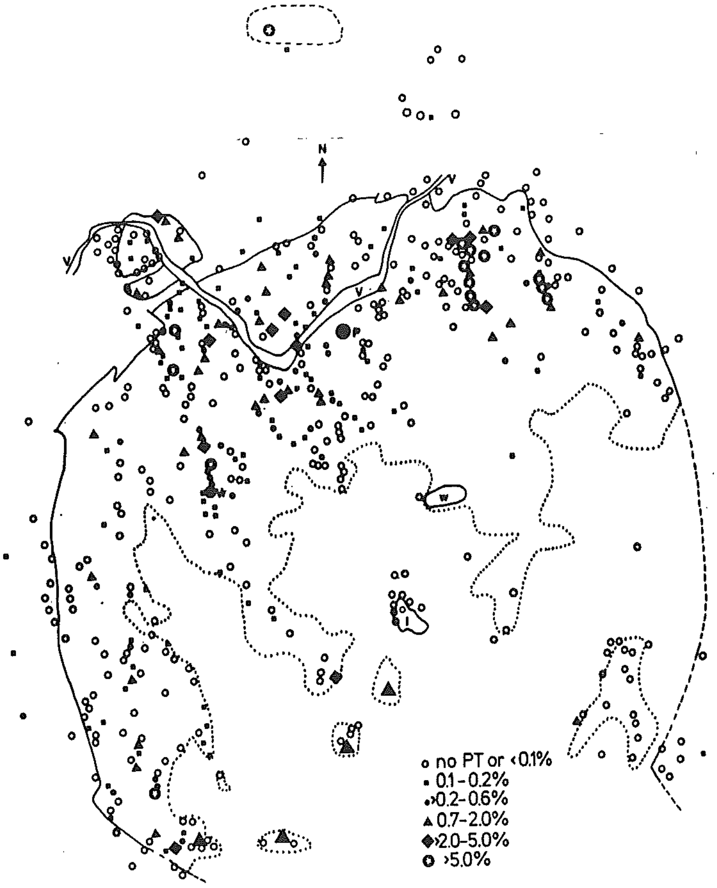


Figure 4: Estimated abundances (in area%) of pseudotachylite at about 570 measurement stations in the core and collar of the Vredefort Dome. P = Parys, Vr = Vredefort, I = Inlandsee, w = wherlite intrusion, PT = pseudotachylite. The dotted line separates outcrop-rich gneiss terrane and Karoo-covered (in the south) terrane.

1990).

Three boreholes sunk to depths of up to 300 m near the centre of the Dome (Hart et al., 1990a; Reimold, 1990) have revealed only a single, about 45 cm-wide intersection of pseudotachylite. This is consistent with the limited surface exposures of pseudotachylite in the central part of the Dome. It also coincides with the observations by Reimold (1990) and Hart et al. (1991) that the density of Vredefort-type (sub)planar microdeformation features in quartz appears to be directly linked to pseudotachylite abundance seen in outcrops along traverses shown in Figure 5. Maximum microdeformation density is attained in samples from the Transition Zone, whereas further into the ILG the values decrease.

Pseudotachylite in collar strata is mainly confined to bedding-parallel faults. Vein thicknesses rarely exceed a few centimetres, but some mafic intrusives contain up to 1 m-wide pseudotachylite zones. These generally occur near contacts between the mafic intrusive and a rock type of different physical characteristics (e.g. quartzite or shale).

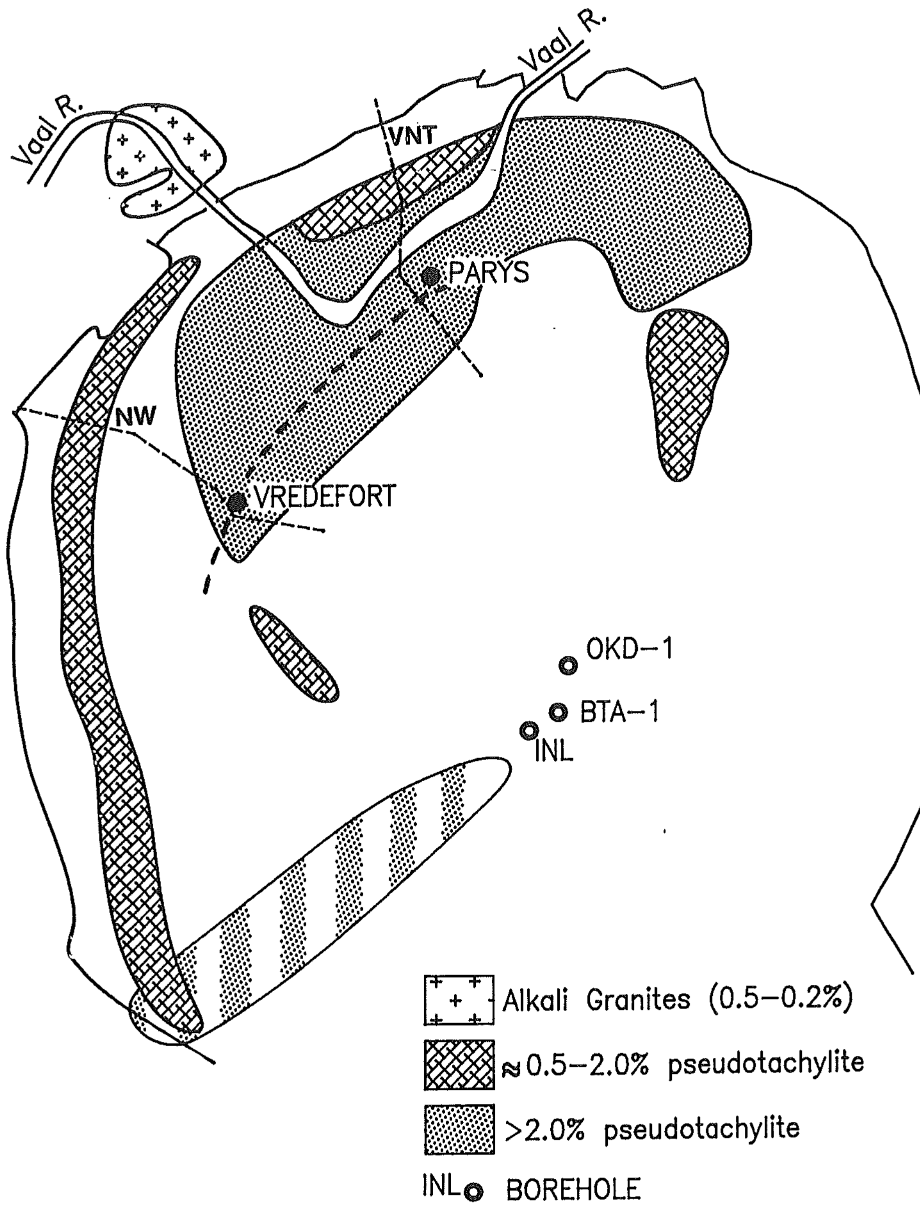


Figure 5: Schematic representation of pseudotachylite distribution in the basement of the Vredefort Dome, generated from the data shown in Figure 4. Heavy dashed line: approximate position of the Transition Zone along the contact between OGG and ILG. Thin dashed lines: sampling traverses for detailed micro-deformation analysis. The partially dotted zone in the southwestern sector corresponds with the so-called Mara Décollement Zone.

PSEUDOTACHYLITE ORIENTATION

Outcrop in the Vredefort Structure is normally two-dimensional with only a few quarries providing three-dimensional exposures. Between 1984 and 1987 more than two thousand strike orientations of pseudotachylite veins were recorded. These data are presented

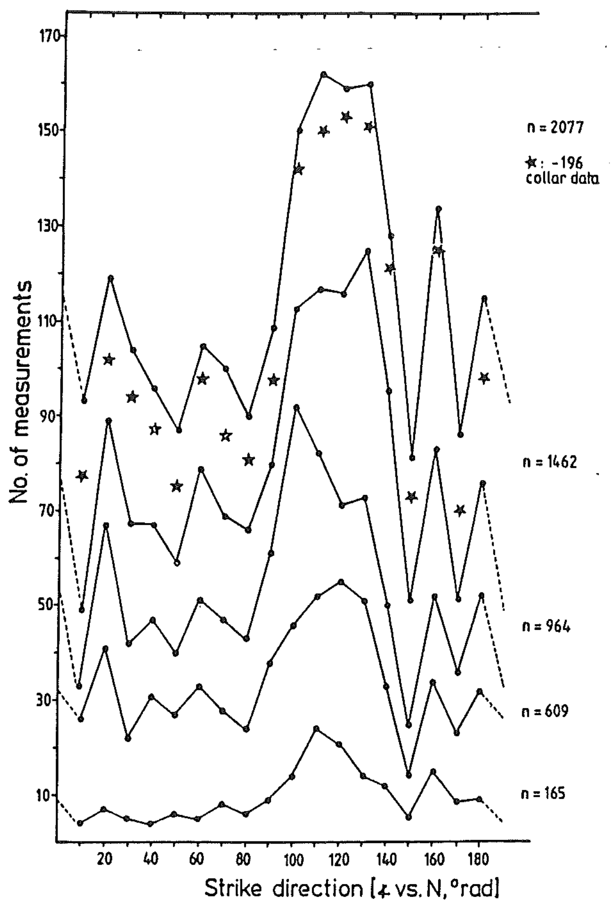


Figure 6: Orientation statistics for pseudotachylite veins and 'dykes'. Statistics were plotted at various intervals during the study period of 1984-1987 showing that the same variation profiles were obtained for data from different parts of the Dome.

in Figures 6 and 7 and compared with orientation histograms for other structural elements of the basement (e.g. gneiss foliation, prominent multiple joint sets, and quartz extension veins. The most important orientation of the veins is the northwesterly trend, followed by the conjugate northeasterly orientation. Structural studies in the core gneisses and greenstones (Colliston and Reimold, 1992; Minnitt et al., 1992) have shown that these directions have represented the principal stress orientations in this region ever since Archaean times. Figure 7 shows that pseudotachylite orientations measured in the alkali granite of the northwestern collar (Figure 2d) are much more varied than those determined in the basement gneiss. Although the volume of data is much less, this can be explained by the isotropic fabric of these granite bodies relative to the strong foliation of the core gneisses.

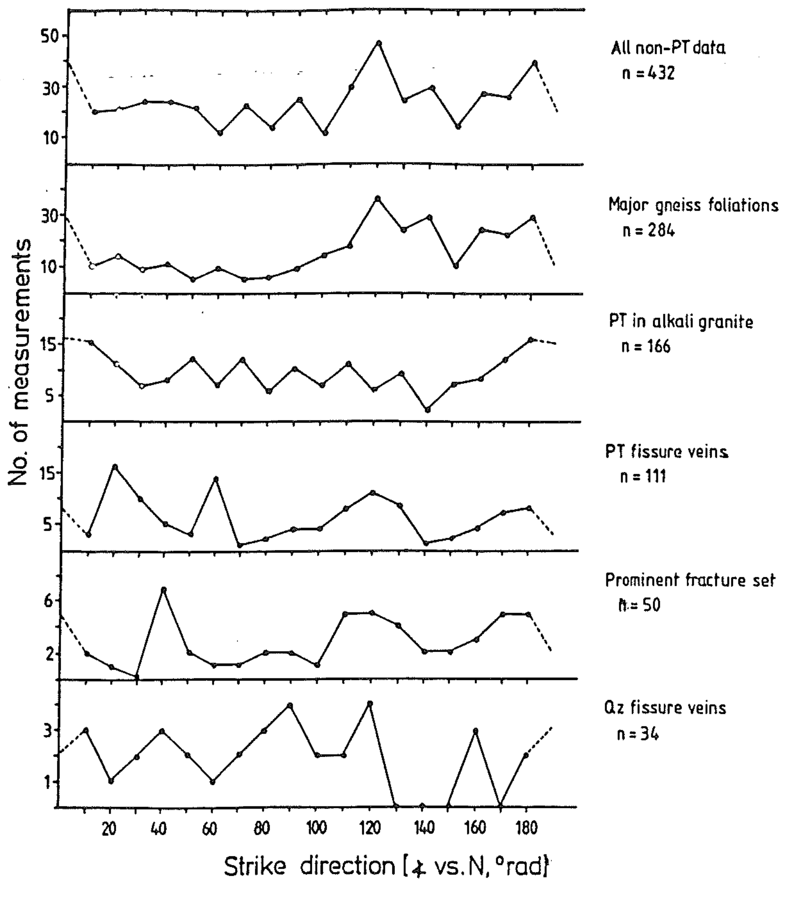


Figure 7: Strike orientation of pseudotachylite veins measured in the alkali granite intrusions into the NW collar (Figure 5), compared with orientation data for other structural elements in the core gneiss (PT = pseudotachylite, Qz = granite.

MODES OF OCCURRENCE AND PSEUDOTACHYLITE GEOMETRIES

Pseudotachylite in the collar generally occurs in the form of bedding-parallel fault veins, with or without narrow injection veins rarely extending for more than a few decimetres into the country rock. Pseudotachylite zones in mafic, sill-like intrusions appear as networks of mm- to cm-wide veinlets surrounding angular to subrounded clasts of generally < 20 cm diameter.

Contacts between rock types of contrasting physical properties are also preferred sites of breccia development in the Witwatersrand Basin. Besides the extensive pseudotachylite-rich breccia zones along the Master Bedding Fault and the Black Reef Décollement Zone, where strata over tens of metres have been brecciated with pseudotachylite comprising up to 60% of the breccia (Fletcher and Reimold (1989), pseudotachylite generally occurs as narrow fault-bounded bands, rarely thicker than a few centimeters. Injection veins are typical (Figures 8B and C, 9F and 10H). Evidence for multiple development of fault rock has been repeatedly observed (Killick and Reimold, 1990; Figures 10B and C). The fault zone along the Ventersdorp Contact Reef (Figure 3) has for example been reactivated several times, each time locally producing fault breccia including pseudotachylites. Further evidence for repeated pseudotachylite formation was discussed by Berlenbach and Roering (1992). These authors presented evidence for three distinct tectonic events manifested on bedding planes in the Kloof Gold Mine north of the Vredefort Dome. The first of these events involved bedding plane-related formation of listric faults, along which gravity sliding took place in southeasterly direction (cf. also Fletcher and Reimold, 1989). The age of this faulting is assumed to be Middle Ventersdorp (ca. 2.7 Ga, Roering et al., 1990), but these faults also truncate older strike-slip faults, some of which are associated with pseudotachylite. The second tectonic phase is a compressional event of NW-directed thrusting, again associated with fault breccia development and hydrothermal activity. No age constraints were given for this event, but the authors refer to out-of-the-basin thrusting at approximately 2.5 Ga noted along the northern margin of the Witwatersrand Basin. A final compressional event, with NE-verging thrust faults, was also recorded.

Several modes of pseudotachylite development have been described from the core of the Vredefort Dome (Bisschoff, 1962; Killick and Reimold, 1990). 'Dykes' and veins, ranging from a few metres to a kilometre in length, and from less than a centimeter to more than 50 m in width, are regularly encountered. Many veins are relatively straight, others are of a more ramifying nature; many are subvertical, others change their attitude from subvertical to subhorizontal over distances of a few centimeters in a manner that was noted for tectonic pseudotachylites as well. In addition to vein systems, large network breccias, commonly extending over tens of metres, are found at many exposures (Figure 8A). Their shapes are generally irregular, but where three-dimensional control is available, major generation planes or shear boundaries can be identified along one or more margins. Network breccia has also formed at intersections of major generation planes (normally both >10 cm wide). Pseudotachylite occurs in a variety of different forms that are often similar to those described from tectonic pseudotachylite settings (Sibson, 1975; Grocott, 1981; Swanson, 1992). Besides network breccia, individual fault veins (Figure 8B) with or without injection veins, paired shears (Figures 8D, 9A, 9B and C), and rip-out structures (Figure 9F) are typical. In places conjugate pairs of fault veins or shears (Figure 9D) are present, and their orientations generally follow the principal stress directions (NE-SW, NW-SE) in the basement.

Contacts with host rocks are usually straight, but rip-out structures are observed in places. Extension and shear fractures are commonly observed within several centimetre wide zones adjacent to pseudotachylite veins. Commonly this zone has been subjected to extensive hydrothermal alteration (Reimold et al., 1992b). In pseudotachylite-bearing Witwatersrand fault zones (for example breccia development in the Ventersdorp Contact Reef fault zone) hydrothermal alteration can be pervasive throughout a much wider (several metres) zone, affecting both the hanging- and footwall.

Figure 8:

(A). Pseudotachylite network breccia with gneiss clasts on farm Samaria south of the town of Vredefort. Pen for scale = 15 cm.

(B). Fault vein with obliquely cut (and apparently wide), irregularly shaped injection vein in a dimension stone block of OGG-type gneiss of the Rietpoort quarry north of Parys. Length of fault vein approximately 2 m.

(C). Sketch of a simple fault vein with perpendicular injection veins (OGG block from Leeukop Hill quarry, northwest of Parys); vein length = ca. 1.5 m.

(D). Two paired shears with pseudotachylite development; the main feature is a ca. 1 m long shear zone exposed in the airport concourse at Jan Smuts Airport Johannesburg. Inset shows a sketch of a ca. 1.5 m long, NW-SE-trending pseudotachylite zone intersected in a quarry northwest of Parys.

(E). A verticle (up to 25 cm-wide), east-west-trending pseudotachylite fault vein from the Rietpoort Quarry. Note the concentration of clasts along the northern (right) margin of the vein.

(F). Another exposure at Jan Smuts Airport: a ca. 80 cm long, irregularly shaped pseudotachylite vein representing a subhorizontal injection vein branching off a diagonal vein or shear zone.

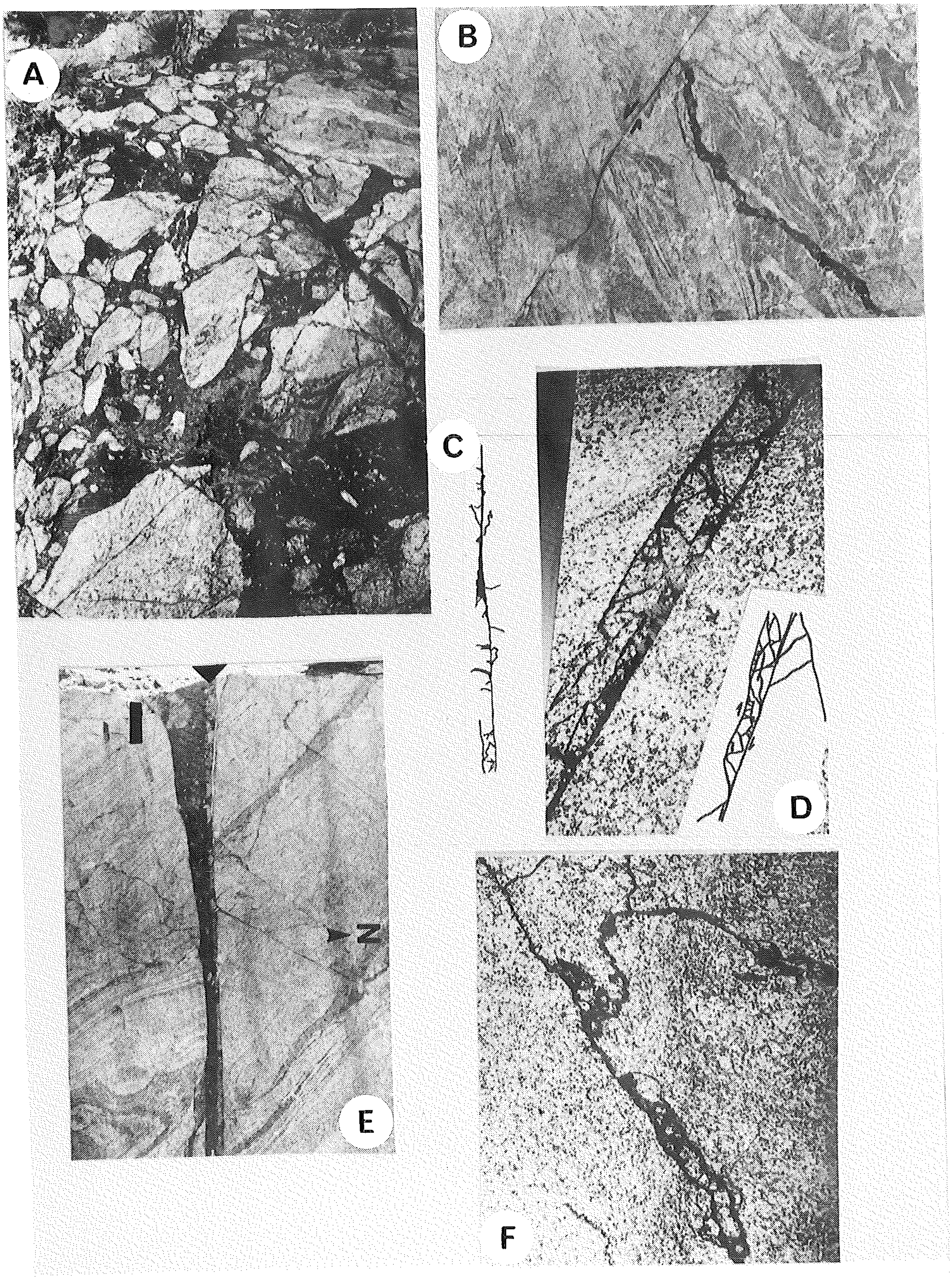

A
B
C
D
E
F

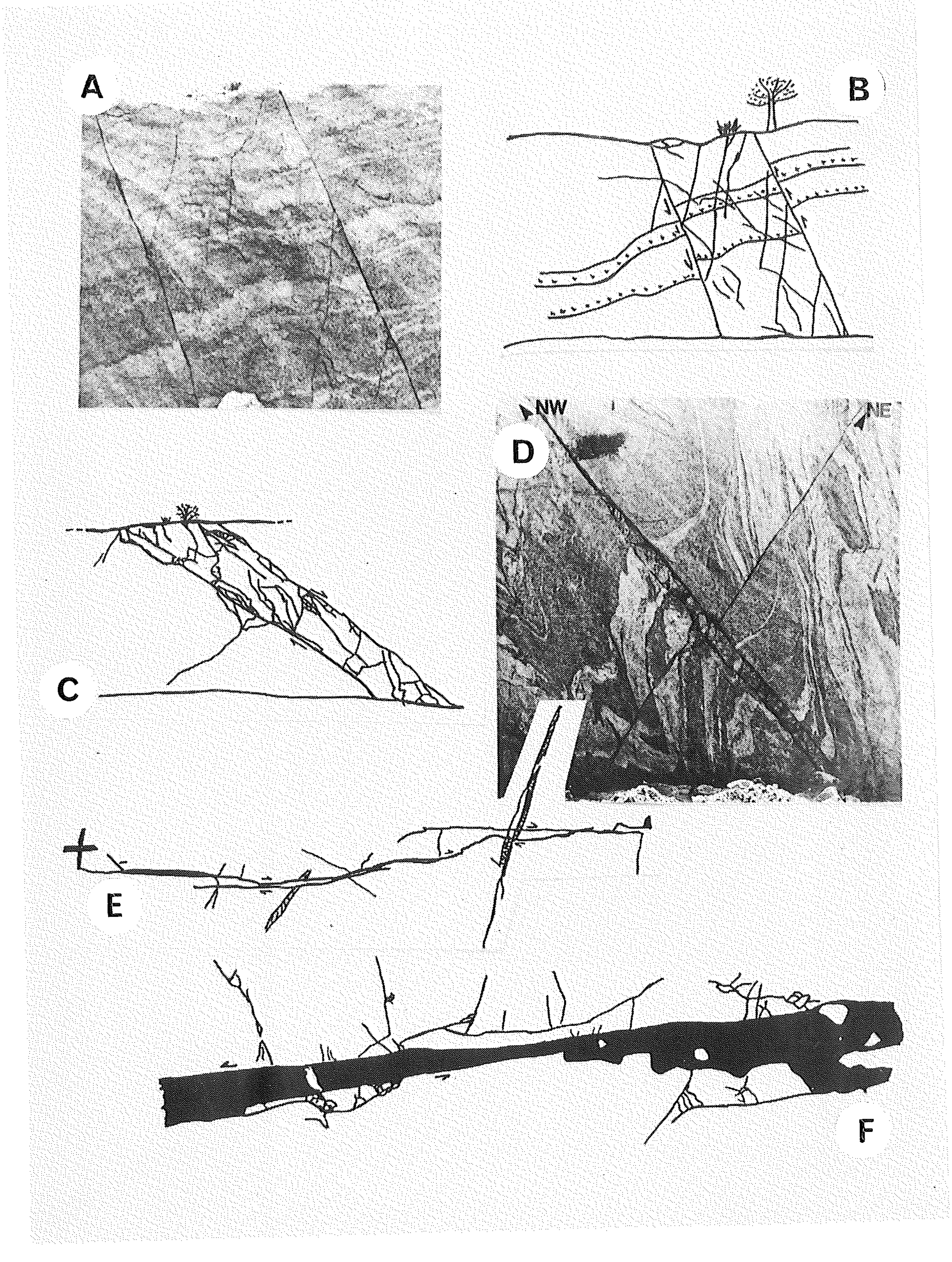
Figure 9:

(A). Ca 3 m high shear zone in OGG of the National Sun Granite quarry north of Parys. A sketch of this zone is shown in Figure 9B.

(C). A paired shear with several systems of Riedel shears (ca. 2 m high, same locality as Figure 9A). Shears strike in NW-SE direction.

(D). A conjugate pair of NW- and NE-trending pseudotachylite veins/shears, one with a rip-out zone along part of its extension. Height of this exposure ca. 3.5 m.

(E). and (F). Sketches showing two horizontal pseudotachylite vein systems (3 and 4 wide) respectively) from Leeukop Hill. The horizontal shear zone in Figure 9E (extending in east-west direction) cuts across two older shear zones with cataclasite (hatched). Figure 9F shows injection veins, rip-out zones and extension veins (parallel to strike) exposed on a north-south oriented quarry face.


A
B
NW
NE
D
C
E
F

Displacements along pseudotachylite generation planes can vary from < < 1 mm to approximately 1 m. No relationship could be established between vein thickness and displacement distances, as proposed by Sibson (1975) for tectonic pseudotachylites. Thin veins developed in well-banded gneiss generally mark contacts between mafic and felsic bands and are preferably located on the mafic side of such contacts. Where three-dimensional exposure is available, clasts are notably concentrated along one vein margin (Figures 8E and 12B). In the example shown in Figure 8E, the vein trends in east-west direction. If the concentration of clasts along the northern margin was due to gravitational settling, the vein must have been subsequently upturned from the horizontal position in a southerly direction. This is in direct contrast to the crust-on-edge model which assumes up- or overturning from the horizontal towards the north. Provided the crust-on-edge model is correct it follows that this vein was formed after the upturning of the basement. A similar concentration of clasts can be observed within a 50 cm-wide zone along the eastern margin of an approximately northwest-southeast trending, 5 m-wide granophyre dyke northeast of the town of Vredefort (Reimold et al., 1990c).

Field evidence demonstrating the multiple generation of pseudotachylite (Figures 10A and F) in the Vredefort Structure was first presented by Reimold et al. (1986). Macroscopically and microscopically inclusions of older pseudotachylite in a younger generation and cross-cutting relationships between older and younger pseudotachylite were repeatedly observed. Re-exploitation of older fault zones (such as the mylonitic vein shown in Figure 10D) by pseudotachylite veins can also be found. Breccia clasts in pseudotachylite are also known from the Sudbury Breccia (Dressler, 1984). However, the temporal relationships between shatter cones and pseudotachylite are different for the Vredefort and Sudbury occurrences. Clasts with shatter cones occur in Sudbury pseudotachylite, but have not been recorded from the Vredefort Dome. The Sudbury relationship is consistent with the view that shatter cones form early in the impact cratering process (during the compressional phase - cf. Martini, 1991), whereas pseudotachylites are thought to be mainly generated during the decompression phase. In contrast to Sudbury, the Vredefort pseudotachylite veins have been partially superposed by shatter cones (Figure 10E) or by multipli-striated joint sets (MSJS, Nicolaysen and Reimold, 1987).

In addition, shatter cones have been found in the Vredefort Dome that are transected by pseudotachylite veins. And Manton (1962) observed "shattering" in mafic intrusives of the collar that was, in turn, crosscut by pseudotachylite. Thin glassy films on shatter cone surfaces indicate that pseudotachylite was also formed at the time of shatter cone formation (Gay et al., 1978; Nicolaysen and Reimold, 1987; Martini, 1991).

A unique pseudotachylite occurrence has recently been exposed in a dimension stone quarry in OGG on Leeukop Hill (Farm Koppieskraal, north of Parys - Figure 11). Two cuttings, the one trending east-west and the other north-south, provide sections through this pseudotachylite-rich hill (Figures 11 and 12A). The major breccia zones have been highlighted in Figure 11 which shows a few fault veins in addition to a number of subhorizontal and subvertical breccia zones. Some of the subhorizontal breccia zones dip gently towards the north (Figure 12A), while those from the main cutting can be identified as being part of a subvertical zone. Clasts in these breccia zones appear to have settled against the bottom contacts of the breccia zones (Figures 11 and 12B). With regard to the

Figure 10:

(A). Ovoid clast of older, mafic pseudotachylite in light grey, younger pseudotachylite vein from Broodkop Hill, southeast Dome (after Killick and Reimold, 1990). Knife for scale = 9 cm.

(B). Three generations of fault breccia from the Ventersdorp Contact Reef fault zone on Elandsrand Gold Mine (ca. 50 km north of the Vredefort Dome) (after Killick and Reimold, 1990). Light-grey mylonite clasts are incorporated in pseudotachylite II. Specimen ca. 12 cm long.

(C). Drillcore, ca. 15 cm long, through part of the breccia associated with the Bank Fault (cf. Figure 2), showing two generations of light and dark pseudotachylite.

(D). Photograph and sketch of a 2 m high section of a pseudotachylite fault vein, trending in northwesterly direction in the Rietpoort Quarry. The pseudotachylite is emplaced into an older mylonite zone shown in stipple.

(E). A narrow pseudotachylite vein on farm Gatoma in the collar west of the town of Vredefort. The vein is superposed by a perfectly developed shatter cone segment. Scale in cm.

(F) An older, folded pseudotachylite vein (dotted) cut by a younger (dark = fresher) vein. (Farm Gansvlei, SW core). Coin diameter for scale is 2.5 cm (after Killick and Reimold, 1990).

(G). Pseutotachylite (smooth, medium grey) cross-cutting coarse-grained cordierite-andalusite hornfels on the farm Rendsburgdrift (at the NW collar-core contact). The pseudotachylite is, in turn, cut by multipli-striated joint sets (MSJS, Nicolaysen and Reimold, 1987) thought to be related to the shatter cone phenomenon.

(H). East-west trending fault-related pseudotachylite in the Ventersdorp Contact Reef fault zone, Elandsrand Gold Mine. Pen (length ca. 15 cm) indicating an injection vein branching off the main generation plane at the reef-footwall quartzite contact.


A
A
B
C
E
CM
IN
mm
F
G

Figure 11: Massive pseudotachylite developments in the ca. 100 m wide, E-W trending Leeukop Quarry, north of Parys. B - area shown in Figure 12B.

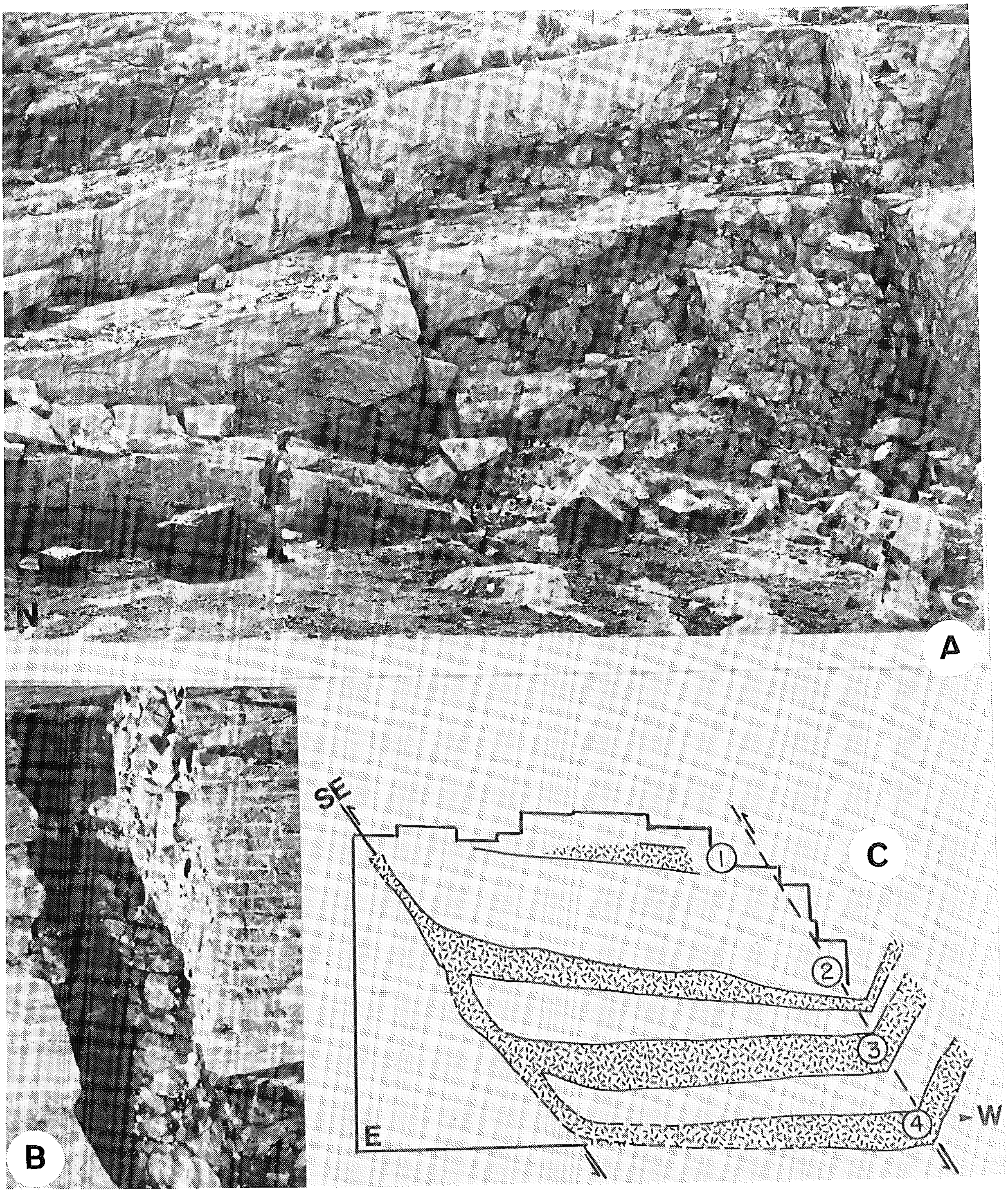


Figure 12: (A) North-south cutting through the western end of Leeukop Hill, perpendicular to the main quarry of Figure 11.

(B) Well-rounded OGG clasts concentrated at the bottom contact of an apparently subhorizontal breccia zone (width ca. 4 m) from the main quarry (Figure 11, lower right). These apparently subhorizontal exposures can all be linked to a subvertical breccia zone (compare Figure 12C).

(C) Schematic cross-section (not to scale) through Leeukop Hill illustrating the relationships between steep shears and internal structure in the breccia zone (for further explanation cf. text).

crust-on-edge model, this could only be explained by basement overturning towards the north, in stark contrast to the observations relating to Figure 8E, discussed above. A schematic interpretation of the geology of Leeukop Hill is shown in Figure 12C: subvertical shears trending in southeasterly direction delimit a pseudotachylite-rich zone that comprises subhorizontal and subvertical breccia zones in Riedel shear-type fashion.

Fletcher and Reimold (1989) suggested that the shallowly northwards-dipping pseudotachylite sheets occasionally observed in quarry exposures (for example the Otavi quarry northeast of Parys) could indicate that the major bedding-faults identified in the northern part of the Witwatersrand Basin might reappear as shallow thrust faults on the Vredefort Dome. The recent findings on Leeukop Hill certainly question the validity of this hypothesis. The Otavi situation (Figure 10 of Killick and Reimold, 1990 - after Bisschoff, 1962) could be the result of a geometry similar to the Leeukop shear zone. Otavi is situated on strike of a major at least 1 km long and up to 50 m wide pseudotachylite zone termed the 'Great Dyke', trending in a NW-SE direction. It is possible that the Otavi quarry intersects the internal structure of an extended shear zone. Mapping of pseudotachylite zones in the northeastern segment of the exposed basement revealed a series of subparallel, NW-SE trending pseudotachylite zones (tens of metres wide and up to several kilometres in strike length) parallel to the Otavi-related zone. However, Fletcher and Reimold's observation that pseudotachylite on the Dome is concentrated in several subparallel, NE-SW trending zones remains valid and requires explanation.

MINERALOGY

Petrographic observations on Vredefort pseudotachylite have been recorded by Shand (1916), Hall and Molengraaff (1925), Nel (1927), Willemse (1937), Speers (1957), Bisschoff (1962), Killick and Reimold (1990), Reimold (1991) and Reimold et al. (1990b, 1992b). With the exception of some descriptions by Killick et al. (1988), no detailed petrographic data on Witwatersrand pseudotachylite are available.

Matrices of Vredefort pseudotachylite generally fall into two categories: 1. they are either aphanitic, and then generally loaded with tiny magnetite crystallites and locally show other devitrification features such as incipient crystallisation of feldspar, pyroxene or hornblende; or 2. they are microcrystalline with mainly fine-grained subophitic, intersertal, or spherulitic textures. Only samples from the so-called 'Great Dyke' yielded matrix grain sizes up to 300 μm. Main microlite phases are plagioclase, pyroxene, amphibole, biotite and magnetite. The most important alteration products are chlorite and sericite.

Quantitative mineralogical data on Vredefort and Witwatersrand pseudotachylites are scarce. Reimold (1991) presented some defocussed beam microprobe analyses, and Reimold et al. (1986b) were able to show that the characteristics of clasts and matrices of pseudotachylite samples from Vredefort, Sudbury, the Witwatersrand Basin, and the Sand River Gneisses are very similar with regard to textural parameters such as grain size and grain form statistics, matrix content, and degree of clast recrystallisation. Clast populations can generally be related to the composition of the host rock, but in some of the larger network breccias exotic fragments may also be found. Sometimes precursor rocks of such clasts could be found less than 100 meters from the breccia exposure (cf. also Bisschoff, 1962). Clasts, from millimetre- to metre-sizes, are normally sub- to well-rounded, and commonly at least partially annealed. Where annealing of granitic clasts is advanced, only refractory quartz clasts are still recognisable. Deformation features observed in clasts comprise partial to complete cataclasis, buckling and displacement of plagioclase twin lamellae, besides the Vredefort-type (sub)planar microdeformation features, the nature and origin of which is still controversial (Carter, 1965, 1968; Lilly, 1981; Grieve et al., 1990; Reimold, 1990; White, 1992). These microdeformations in quartz are occasionally observed in clasts in Witwatersrand pseudotachylites as well. Fricke et al. (1990) describe a thin veinlet of fine-grained recrystallised quartz and K-feldspar, strongly enriched in CO_2 fluid inclusions, from a sample of ILG. They concluded that this veinlet could have consisted of "glassy, diaplectic" material, and that "the concentration of CO_2 fluid in the quartz parts of the veinlet might be caused by a preferential solution of CO_2 in the transient, diaplectic, glassy state formed by the shock". (Diaplectic mineral glasses, such as the SiO_2 phase lechatelierite or the feldspar glass maskelynite, are believed to form only under elevated shock pressures, in excess of about 25 GPa, and to be diagnostic of impact processes). The writers, by contrast, have not recognised any clear evidence for the existence or pre-existence of diaplectic mineral phases in Vredefort samples. Dressler (1984) interpreted an observation by Speers (1957) of a partially isotropic plagioclase clast in Sudbury Breccia as possible evidence for diaplectic glass, but similar isotropisation has never been described from Vredefort.

Martini (1978, 1991) identified the high-pressure SiO_2 polymorphs coesite and stishovite in some pseudotachylite veinlets from the outer collar - evidence that is widely regarded as diagnostic for impact processes. Martini (1991) declared that his field and petrographic observations justified the conclusion that two generations of pseudotachylite could be recognised at Vredefort. Firstly a 'Type A' variety with coesite and stishovite that was formed during early compression, and secondly 'Type B' pseudotachylite, without high-pressure phases and comprising the bulk of Vredefort pseudotachylite, allegedly formed towards the end of the cratering process during decompression. Reimold et al. (1992a) disputed the evidence for the existence of these two types in a discussion with Martini (1992). It was argued that to date identification of high-pressure SiO_2 phases had only been attempted in samples from certain deep-crustal settings and impact structures, and that it should be tested whether the high-strain-rate conditions at pseudotachylite formation during seismic slip could lead to coesite and stishovite formation.

It may be significant that, besides the microdeformations in quartz, no other shock(impact)-characteristic deformation phenomenon has been described from other minerals in Vredefort rocks.

Brandl and Reimold (1990) showed that the orientation statistics for microdeformation features in clasts from Vredefort, Sudbury, the Witwatersrand, and various tectonic pseudotachylites compare rather well. Recently several attempts to characterise planar deformation features (PDFs) by application of TEM methods have been reported (Gratz, 1992; White, 1992). Gratz suggested that a range of microdeformation types could be recognised in shocked specimens, and White reported planar deformation features in Vredefort quartz from within a pseudotachylite veinlet, but not from quartz in its immediate environs. Reimold (1990) pointed out that PDF-like microdeformations in quartz from tectonic pseudotachylite do exist and that PDFs from high-strain environments need to be critically and micro-analytically compared with PDFs of unambiguous shock(impact) origin. Recognition of Witwatersrand pseudotachylite (i.e., discrimination from fine-grained cataclastic breccia) is often very difficult, especially when the material is altered. Scanning electron microscopy is generally needed to resolve the nature of breccia matrices. The following identification criteria for pseudotachylite have been applied successfully in recent years: (1) the identification of crystallisation products in matrix (microlites of feldspar or mafic minerals, euhedral magnetite or pyrite crystallites, dendritic crystals in pockets of mesostasis); (2) the presence of vesicles; (3) corrosion textures at clast margins, interpreted as the result of marginal fusion, and partial or complete annealing of clasts; (4) partial or complete assimilation of clasts into matrix leaving "ghost" clasts; (5) reaction and/or fusion rims around clasts; and (6) porous "sinter"-textures within clasts (compare the recognition criteria for tectonic pseudotachylites given by Maglaughlin and Spray, 1992b). It was repeatedly noted that melt formation along Witwatersrand faults took place on a local scale, in pockets or schlieren between clastic zones. These observations are in agreement with those of Killick et al. (1988) who also described coexisting pseudotachylite and other breccia types.

GEOCHEMISTRY

Major and trace element compositions for a large number of Vredefort pseudotachylites, sampled in felsic, intermediate and mafic host rocks, were reported by Reimold (1991). Other analyses were provided by Willemse (1937), Wilshire (1971), and Schwarzman et al. (1983).

In the case of large network breccias studied, mixing between several precursor rock types could be demonstrated. In narrow vein occurrences, the chemical composition of the breccia generally closely resembles that of the host rock. If any mixing took place, it was usually restricted to $<$ 1 cm distances.

Reimold and Koeberl (1991) discussed initial chemical results from profiles across pseudotachylite-rich Witwatersrand fault zones. They concluded (in agreement with Vredefort results of Reimold, 1991, and earlier data by Killick et al., 1988) that evidence for mixing of several host rock types, namely those in the vicinity of the sampling site, can be found wherever large volumes of pseudotachylite were formed. It was further suggested that during pseudotachylite formation considerable hydrothermal activity could take place, possibly leading to large-scale remobilisation of base metals, including gold.
Often systematic differences were noted between the compositions of Vredefort pseudotachylites and their respective host rocks. However, for different host rock types (felsic, intermediate or mafic) different effects were recorded. Reimold (1991) observed that for pseudotachylites in granitic host rock depletion of SiO_2 and enrichment of TiO_2, Fe_2O_3, CaO, and, to a lesser extent, of MgO are noted. Pseudotachylites in mafic environments display less consistent chemical deviations from their host rock compositions, although enrichment in K_2O and depletion in CaO could often be observed. While the trace element data do not allow general trends to be defined, they do indicate that elements associated with feldspars, as well as Sc, are frequently enriched in pseudotachylite. Reimold concluded on

the basis of this study that Vredefort pseudotachylite probably formed from selective (preferential - not partial) melting of ferromagnesian and hydrous ferromagnesian minerals, followed by melting of feldspar minerals and some quartz. Reimold et al. (1987) had suggested this process for pseudotachylite formation in the Rochechouart impact crater (France), and it was also favored for the generation of tectonically produced pseudotachylite (Maddock, 1988, 1992). Spray (1992) provided an explanation for this process by comparing the relative shear yield strengths, fracture toughnesses, and thermal conductivities of the major rock-forming minerals. Spray's data also indicate that plagioclase and pyroxenes have very similar properties, which could explain the inconsistent enrichment/depletion trends observed for many elements when comparing pseudotachylite-mafic host rock pairs.

CHRONOLOGY

Following the recognition of multiple pseudotachylite formation and of the complex temporal relationships with shatter cones, the need arose for absolute age determinations of Vredefort pseudotachylites. It was also timely to test the applicability of the ^{40}Ar-^{39}Ar stepheating technique as a tool for absolute dating of fault rocks (Reimold et al., 1990b). Earlier, only one attempt had been made to date Vredefort pseudotachylite from the Otavi locality using the U-Pb technique (L.O.Nicolaysen, pers. comm.). This resulted in an age similar to that of the 3.08 Ga old OGG country rock (Hart et al., 1981).

Reimold et al. (1990b) presented the first ^{40}Ar-^{39}Ar stepheating data for six pseudotachylite samples from widely spaced localities on the Vredefort Dome. The results ranged from 2.25 (K-Ar age) over 2.1 Ga to 1.44, 1.39, 1.33, and 1.09 Ga (^{40}Ar-^{39}Ar) ages, leaving doubts as to whether these ages represented pseudotachylite formation ages or times of post-Bushveld/post-Vredefort thermal overprint (Walraven et al., 1990 recommended ages of 2.065 and 2.002 Ga for these events). Reimold et al. (1990b) pointed out further that, while local volcanic activity between 1.1 and 1.3 Ga ago is known from the central part of the Kaapvaal Craton, no regional overprint at that time has been proven yet. Subsequently the ^{40}Ar-^{39}Ar results of Allsopp et al. (1991) on whole rock and mineral separates from different lithologies, again from widely spaced locations on the Dome, cast further doubt on the suggestion that the relatively recent pseudotachylite ages could represent only resetting events.

Recently, Reimold et al. (1992b) reported ^{40}Ar-^{39}Ar stepheating results obtained for various mineral separates from host rocks of apparently young pseudotachylite. Biotite and hornblende from the host rock to a 1.44 Ga pseudotachylite yielded well-defined plateau ages of 2.07 +- 0.01 and 3.01 +- 0.03 Ga, respectively - suggesting that no thermal resetting occurred later than ~ 2 Ga ago. Four different mineral separates of the host rock to a pseudotachylite previously dated at 1.39 Ga provided rather complex age spectra with average ages between 1.39 and 1.76 Ga. However, petrographic analysis of the host rock sample showed that these mineral phases, collected from the narrow zone immediately adjacent to the completely unaltered pseudotachylite veinlet, had been subjected to hydrothermal overprinting. The unaltered part of the host rock sample yielded a Rb-Sr mineral isochron corresponding to an age of 2008 +- 46 (2σ) Ma (Reimold et al., 1990b). Consequently, the alteration event probably took place at the time of pseudotachylite formation, namely at 1.39 Ga ago.

The first age determinations for Witwatersrand pseudotachylite were carried out by Trieloff et al. (1992). ^{40}Ar-^{39}Ar stepheating experiments on 7 samples from two localities about 90 km apart at the Ventersdorp Contact Reef fault zone yielded plateau ages close to 2 Ga. This invariably raises the questions whether the breccia-forming event can be related to the Vredefort event, and whether it is possible, on the basis of the existing chronological knowledge, to separate the Vredefort and Bushveld events in time. A further result is that obviously no regional overprint affected the northern region of the Witwatersrand Basin since Bushveld times. This also provides additional support for the young pseudotachylite ages from Vredefort being formation ages. While direct geological evidence exists for multiple breccia generation along the Ventersdorp Contact Reef fault zone, only one event has been dated to date. Berlenbach and Roering (1992) also indicated that pre-Bushveld pseudotachylite could have existed, that might have been thermally reset at 2 Ga. Further chronological studies on Witwatersrand pseudotachylite are clearly warranted.

DISCUSSION

The following points need to be considered in attempting to derive a satisfactory hypothesis for the origin of the Vredefort Structure:

1. limited pseudotachylite and brecciation in the central region of the Vredefort Structure;

2. major pseudotachylite occurrences along NE-SW-trending lineaments (in the Vredefort Dome and the Witwatersrand Basin);

3. pseudotachylite in the Witwatersrand Basin being fault-related, and pseudotachylite geometries, also in Vredefort, being similar to those known from tectonic settings;

4. pseudotachylite having formed at several stages during the evolution of the Vredefort Structure and the Witwatersrand Basin;

5. temporal relationships between pseudotachylite and shatter cones/MSJS being multiple and complex;

6. chemical pseudotachylite-host rock relationships being the same as noted for tectonic settings;

7. pseudotachylite-related mineral deformation appearing similar to that associated with tectonic pseudotachylite;

8. no microdeformation, and no shock-diagnostic deformation features in minerals other than quartz having been observed; and

9. confirmation of the presence of coesite and stishovite in Vredefort pseudotachylite.

Most workers have accepted, on the basis of this last argument, in conjunction with the presence of shatter cones and planar deformation features in quartz, that the Vredefort

Structure is of certain impact origin. It is also true that the Witwatersrand Basin and the Vredefort Structure have experienced a long and complex geological evolution, which has to be considered when interpreting the analytical data. Nevertheless, the structural pseudotachylite-related observations, as well as the chemical and chronological observations summarised in this paper are not readily explained solely by impact processes. On the other hand, one could apply Dressler's (1984) Sudbury-related reasoning to Vredefort, whereby the absence of significant displacements and limited evidence for shear movement associated with Sudbury Breccia favoured explosive brecciation rather than brecciation caused by a directional force. Thus, the Vredefort debate remains unresolved and controversial. Most of the arguments raised above need to be reconciled with either impact or tectonic hypotheses. It is evident from this compilation that only limited structural and mineralogical data exists on Vredefort and Witwatersrand pseudotachylites. The metamorphic evolution of the Dome area, compared with the regional metamorphic record, as well as the temporal relationships between metamorphic and deformation events need to be resolved. Further application of chronological methods to pseudotachylites and their host rocks, not only from the Vredefort Structure, but also from its environs is required. Furthermore, metamorphic minerals need to be dated in order to establish a timeframe for thermal events. Dating of pseudotachylites and metamorphic minerals from different stratigraphic horizons in the Witwatersrand Basin could resolve problems relating to the thermal effects of Bushveld metamorphism at ca. 2 Ga ago. Also, the existing pseudotachylite distribution map for the Witwatersrand Basin needs to be augmented, and tectonic information, especially from the southern part of the Basin, needs to be synthesised and discussed in the light of existing hypotheses (such as the impact hypothesis). Another inviting aspect of considerable consequence for the understanding of the ore-related processes that took place in the Basin is the question of the effectiveness of the Vredefort event on remobilisation of base metals in the Witwatersrand strata, the nature and origin of the fluids involved, and the possibility that these effects could still be identified in outlying parts of the Witwatersrand Basin.

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