Chapter 5

Deformation in the outer parts of the Vredefort impact structure

5.1 Introduction

The Vredefort impact structure has an estimated diameter of ~300 km and is situated in the heart of the Witwatersrand Basin (Gibson and Reimold 2001; see Fig. 1.6). The central parts of this impact structure, the Vredefort Dome, is surrounded by the ~50 km wide Potchesftroom Syncline (see Fig. 1.6c). In the previous chapters, a range of deformation features related to the impact event was described from the collar of the Vredefort Dome. It is also necessary to evaluate structures further from the dome, from the wider impact structure in order to test current hypotheses that these structures are related to specific stages of the cratering process. This investigation is complicated by the long and complex tectonic history of the Witwatersrand Basin that was introduced in detail in section 1.7 (compare e.g., Roering et al. 1990; Robb et al. 1997). Several studies (e.g., Simpson 1977, 1978; Brink et al. 1997, 1999, 2000a,b) suggested a link of certain structures in the wider environs of the Vredefort Dome to the impact event. As a result, a regional overview and a summary of previous studies in the area are given in the following sections with special emphasis on the structures that were identified by Simpson (1997) and Brink et al. (1997, 1999, 2000a,b), before the results of this study are presented.

In order to contribute to the debate about possible relationships to the deformation features in the outer parts of the Vredefort Dome and the impact event, geological structures were analysed by surface mapping in the area between the towns of Ventersdorp, Potchefstroom and the Losberg Complex (Fig. 5.1). The 1: 250 000 (2626 West Rand) geological map was used to assist the surface mapping.

5.2 Regional Overview

The gold rush in the late 19th Century (e.g., Pretorius, 1994) led to extensive exploration of the Witwatersrand Basin, especially since the availability of geophysical methods since the 1930s. However, the main focus was on the discovery of new mineral resources, and the tectonic setting of the region remained obscure. It was only in the 1980s that structural studies in the Witwatersrand Basin aimed at

Fig. 5.1: Schematic map of the northern parts of the Vredefort impact structure that was studied by surface mapping, showing the relevant towns and roads. Numbers represent the locations investigated by surface mapping. The collar rocks around Parys are shown in dark grey and the exposed rocks of the Witwatersrand Supergroup between Ventersdorp and Potchefstroom that were studied are indicated in light grey.

establishing a regional tectonic history were carried out in detail. In recent years, the Witwatersrand Basin has been considered to have evolved in the context of various plate tectonic models (e.g., Burke et al. 1986; Stanistreet et al.1986; Clendenin et al. 1988 – see section 1.7). However, the temporal relationships between deformation features in the rocks in the central parts of the basin around the Vredefort Dome and those formed during the impact event are still largely unknown (see section 1.9).

The impact event must have had a major influence on the structures in the wider environs of the Witwatersrand Basin: 1) Simpson (1977) reported structures from the rim synclinorium (Potchefstroom Syncline) with a concentric pattern with respect to the Vredefort Dome, including some radial strike-slip and normal faults, and fold axes and axial planes (see sections 1.9.4 and 5.3). 2) McCarthy et al. (1986) postulated that the structural control of the Vredefort event reached far beyond the rim syncline and suggested that cleavages and fold trends in the northern part of the Witwatersrand Basin also have tangential orientations with respect to the dome and should, therefore, be Vredefort-related. This was supported by more recent studies (Courtnage et al. 1995; Courtnage 1996; Robb et al. 1997) that suggested that the impact-related structures are more pervasive than previously thought. Courtnage (1996) mapped the area between the Johannesburg Dome and the Bushveld Complex and identified four different deformation events in the Transvaal Supergroup strata. The first deformation event (D_1) produced a heterogeneously developed, southerly-verging, S_1 cleavage, probably of pre- to syn- Bushveld Complex age. The most intense deformation (D_2) post-dates the intrusion of the Bushveld Complex and is represented by northward-verging folds and shear fabrics (S-C fabrics and lineations) displaying a top-to-the north displacement. This deformation event also produced folds, cleavage and faults in the rest of the Witwatersrand Basin and was attributed to the Vredefort event (McCarthy et al. 1986; Gibson et al. 1999). D_3 produced southerly-verging structures, such as folds and steep thrusts, supposedly in post-Vredefort times (Courtnage 1996). Finally, Courtnage (1996) attributed northerly and east-northeasterly trending, subvertical, brittle faults to D_4 that might have been linked to the rise of the Johannesburg Dome. Further ductile structures were identified by Courtnage (1996), such as east-verging folds and west-verging thrust duplexes, which seem to postdate the Vredefort event, although the absolute ages could not be determined. However, east-verging structures are known from the western margin of the Transvaal Basin, where they have been related to the Kheis orogeny (2.1-1.8 Ga, Stowe 1986; Duane and Kruger 1991; Thomas et al. 1994; Robb et al. 1997).

Friese et al. (1995) proposed that the ca. 1.1 Ga Namaqua-Natal accretion event along the western and southern margins of the Kaapvaal craton produced NW-verging thin-skinned thrusting that has affected the rocks in the Vredefort Dome. Henkel and Reimold (1998) suggested that post-impact SE-directed thrusting could also have affected the northwestern part of the structure (see section 2.2).

5.3 Previous structural work in the wider environs of the Vredefort Dome

Prior to the acceptance of an impact origin for the Vredefort Dome, structures arranged concentrically with respect to the present centre were identified around the dome (e.g., Truter 1936; Fletcher and Gay 1972; Simpson 1977, 1978). These structures were initially related to tectonic thrusting from the southeast by some authors (e.g., Du Toit 1954) or to a diapiric doming event (e.g., Brock and Pretorius 1964; Ramberg 1967, 1981) – see section 1.9. Most recently, the formation of these structures (Fig. 5.2) has been attributed to the outward movement of material during crater evolution and subsequent gravitational adjustment during the modification phase (Brink et al. 1997, 2000a,b).

The work of Brink et al. (1997, 2000a,b) was based on some field observations and unpublished geophysical and borehole data from mining activities. These authors proposed that the impact event triggered outward-directed movement of material. This movement took place over thrust zones that were arranged concentrically around the Vredefort Dome. The movement of the concentric thrust zones followed a pre-existing (pre-impact), subhorizontal surface, the so-called Black Reef Décollement Zone (BRDZ), which was first described by Fletcher and Reimold (1989) (Fig. 5.3). During this outward-directed movement, concentric folds were produced, such as the Potchefstroom Syncline; further thrust fault zones developed along the crater-inward-facing limbs of this syncline (Brink et al. 1997, 1999, 2000a).

The postulated traces of these alleged thrust fault zones on the surface represent the ring structures identified by Brink et al. (1997, 1999, 2000a). These authors postulated that the original positions of these "circles" were consistent with the so-called "square root of 2" spacing law by Melosh (1989) for the inner rings of a multi-ring basin. According to Brink et al. (1997, 1999, 2000a), the presently exposed "circles", however, are not consistent with these original impact-related rings but represent the positions of the exposed concentric fault zones that developed over a detachment surface. These authors claimed to have identified at least two „circles" around the crater centre, with a possible third one present at a distance from the second circle (see also McCarthy et al. 1986; Van der Merwe 1994) (see Fig. 1.14).

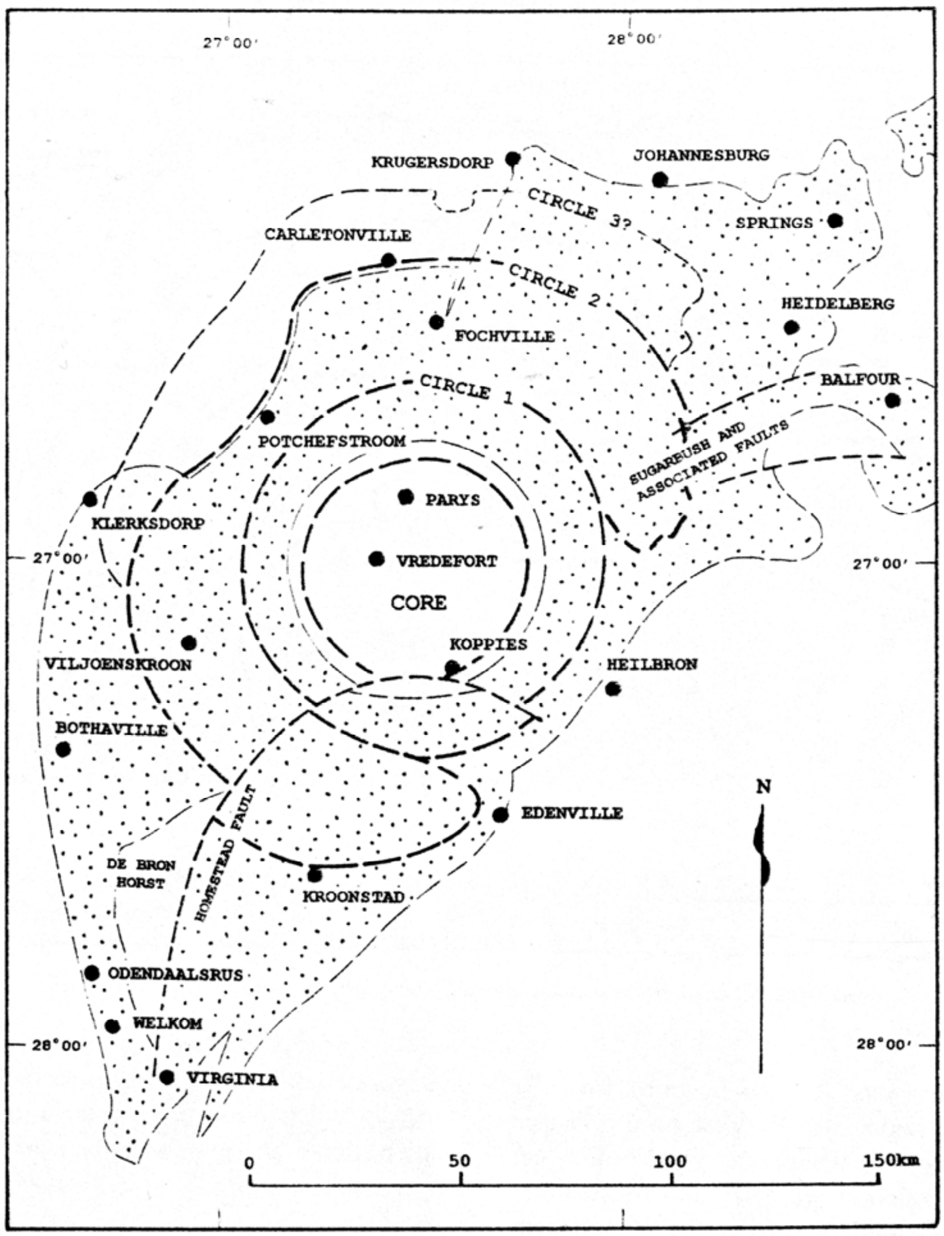

Fig. 5.2: Illustration of major concentric structures around the Vredefort Dome (from Brink et al. 1997). According to these authors, the structures do correspond to the possible "rings" of a multi-ring basin but not to the present positions of the fault zones (see text for further discussion).

These concentric structures developed along a detachment zone triggered by the outward-directed movement of material immediately after the impact. These

Fig. 5.3: Schematic diagrams illustrating the alleged formation and movement of the concentric thrust zones over the pre-existing Black Reef Décollement Zone (BRDZ) (after Brink et al. 1997). Stratigraphic distribution before the impact (stage 1). After the impact (point of impact labeled I), material is accelerated outward (stage 2), forming the Ensels (e) and Foch (f) faults along a detachment zone. At the same time the Potchefstroom Syncline is formed (p) and strata above the Ensels Fault are overturned. During the modification stage (stage 3) material moves inward again due to the collapse of the crater rim. This movement occurs along inward-verging, extensional faults (lf) – i.e., along inverted Ensels and Foch faults – thus, forming two “rings”. During the rise of the central uplift (h), gravitational adjustment takes place in the outer parts of the impact structure (stage 4). At the present level of erosion, the remnants of the two rings (named circles 1 and 2) are theoretically exposed on surface.

structures allegedly represented thrust faults during the excavation phase, but were inverted into listric extensional faults during the modification phase, when material slumped inwards again due to the collapse of the crater rim (Brink et al. 1997, 1999, 2000).

The first ring (see Fig. 5.2) was represented by the sole of the so-called Ensels Thrust (Brink et al. (1997, 2000a), about 50 km from the centre of the dome. This thrust comprised the collar strata of the Witwatersrand Supergroup, as well as parts of the Ventersdorp and Transvaal supergroups (Brink et al. 1997, 2000a). According to these authors, this thrust zone detached along the inward-facing limb of an anticline, which is encircled by a syncline – the Potchefstroom Syncline (see Fig. 1.13). Beyond the Potchefstroom Syncline, at a distance of ~80 km from the centre of the dome (Fig. 5.2), a second ring developed over another anticline which was termed the Foch Thrust Zone by Brink et al. (1997, 2000a). This ring exposed Pretoria Group strata below the Hekpoort Formation, and portions of the Chuniespoort Group (Brink et al. 1997, 1999, 2000a) (see Fig. 1.8). Thrust faults further away from the second "circle" that showed a similar structural pattern (i.e., listric geometry, inward-directed fault surfaces) were proposed to belong to a third "circle" (McCarthy et al. 1986; Van der Merwe 1994), called the Wuma Fault (see Fig. 1.13) by Brink et al. (2000a,b). The only deviation from the circular pattern of these thrust zones was observed directly west of Potchefstroom, where the north-south striking pre-impact Blaauwbank Anticline allegedly formed a barrier to the centrifugal movement (see Figs. 1.13, 5.4). The evolution of the Blaauwbank Anticline and the Foch Thrust Zone, as proposed by Brink et al. (2000b), is illustrated in Figs 5.4a-c. Other pre-impact structures (such as faults) that transect the entire Witwatersrand Basin apparently had no major influence on the development of these thrust zones, according to Brink et al. (1997, 2000a,b).

Extensional faults within the first "circle" and beyond the second one were attributed by Brink et al. (1999, 2000a,b) to inward slumping of material in the final stages of the modification phase; however, such inward-verging faults appear to be absent between the first and second "circles". Other studies from the goldfields in the Witwatersrand Basin reported pseudotachylitic breccia occurrences associated with extensional faults and postulated that the south-verging normal faults, which are documented from underground studies (e.g., Killick 1990; Killick and Reimold 1990; Killick and Roering 1995), should also be exposed on the surface.

Fig. 5.4: Next pages: Illustration of the alleged structural evolution of the Blaauwbank Anticline and the Foch Thrust Zone according to Brink et al. (2000b). (a) Stage 1-3, (b) stage 4-6 and (c) stage 7-9.

The Foch Thrust ("second circle") joins one of these extensional faults, termed the Potchefstroom Fault (Truter 1936; Van der Merwe 1986; Fletcher and Reimold 1989), north of Potchefstroom. This fault was first described by Truter (1936) based only on stratigraphic displacements, developed along the eastern limb of the Blaauwbank Anticline. The Potchefstroom Fault merges with the Master Bedding Fault (MBF) northeast of Potchefstroom (Fig. 1.13; Van der Merwe 1986). The MBF was first identified by Fletcher and Gay (1972) in the Carletonville area. Engelbrecht et al. (1986) were able to trace the fault near Carletonville from a number of boreholes but found no evidence on surface. Van der Merwe (1986) showed that this fault had a complex history, with extensional eastward-directed movement in post-Transvaal times followed by left-lateral movement. This movement pattern is consistent with the motion along pre-impact N-S and E-W trending fault systems that were documented throughout the Witwatersrand Basin (e.g., Roering et al. 1990; Myers et al. 1990, 1992; see Figs. 1.10, 1.13 and section 1.7). Brink et al. (2000b) postulated that it was possible to combine both faults and termed this new fault, extending from Carletonville to the southeast of Potchefstroom, the "Potchefstroom-Master Bedding Plane Fault". Brink et al. (2000a,b) alleged an extension of this fault from Potchefstroom to Carletonville by following fault breccias in chert horizons, which they associated with this fault (see section 5.4.2). Brink et al. (2000b) based their conclusion of a syn-impact formation of these thrust faults on the duplication and repetition of stratigraphic sequences as well as on the concentric arrangements of these structures around the Vredefort Dome (see section 6.2.2.3).

Further concentrically arranged extensional faults with domeward dips were reported by Simpson (1977, 1978) from the areas west and southwest of Potchefstroom and in the Potchefstroom Syncline. Detailed work was done by Simpson (1977, 1978) in these areas demonstrating that a set of normal faults showed a domeside-down movement with displacements ranging from 100 to1500 m. However, in contrast to the work of Brink et al. (1997, 2000a,b), she did not observe any outward-directed, concentric thrust faults. Simpson (1977) also stated that the concentric normal faults were better developed closer to the collar, whereas farther away from the collar, faults with radial strike orientations with respect to the centre of the dome were dominant. She also found that folding of the strata occurred around almost vertical axial planes with concentrically arranged axial traces with respect to the dome. As a result of these observations and the fact that the fold hinges are usually disrupted by strike-slip faults with radial strike orientation with respect to the dome, Simpson (1977) concluded that all these structures were formed during a single deformation event, and - based on geometric relationships between these structures - simultaneously with the "updoming" and overturning of bedding. She proposed a flexural slip mechanism for the concentric folds with the movement occurring along lithological boundaries and interfaces of layers of different competency (see Ramsay 1967, p. 392).

5.4 This study

Outcrops in the study area are generally sparse and of poor quality due to limited relief and weathering, as well as the inaccessibility of certain areas where no access was granted by the landowners. Suitable exposures of strata belonging to the Witwatersrand and Transvaal supergroups were found around the town of Potchefstroom – which includes the Spitskop Syncline (Simpson 1977, 1978) west of this town (section 5.4.1), and limited outcrop along the R 53 between the towns of Potchefstroom and Ventersdorp (see Figs. 5.1 and 5.8, section 5.4.3). A well-exposed section of shale units belonging to the Platberg Group (Ventersdorp Supergroup) was found south of the town of Ventersdorp (Fig. 5.9, see section 5.4.3). This outcrop provided an excellent opportunity to study brittle and ductile deformation features at a macroscopic scale (centimetres to metres) and also closely-spaced, penetrative cleavage (millimetre to centimetre scale, see section 5.4.3).

Particular attention was paid to the so-called "circles" or thrust faults proposed by Brink et al. (1997, 1999, 2000a,b). Exposures between the towns of Ventersdorp and Potchefstroom and Potchefstroom and Carletonville, and along a traverse along the road R500 from south of Carletonville to the collar rocks north of Parys, were investigated (Fig. 5.1, sections 5.4.5). However, continuous outcrops of strata are lacking in this area and only a single exposure of one major fault was found on surface – the Potchefstroom Fault northeast of Potchefstroom (see section 5.4.5). Although some minor faults and folds (at a metre-scale) were identified south of Carletonville, map-scale features (such as the faults and folds in the collar rocks of the Vredefort Dome) were not found on surface. Further to the south, towards the collar rocks, the Losberg Complex forms prominent hills in the generally flat landscape and

Fig. 5.5: Schematic map of the area northwest of Potchefstroom showing the main lithologies and structural features as well as the towns mentioned in the text (modified after Brink et al. 2000a). (B) Katdoornbosch Fault, (D) Spitskop Syncline, (E) Potchefstroom Synclinorium, (J) Potchefstroom Master Bedding Plane Fault. The Witwatersrand and Ventersdorp supergroups are shown in the same colour because the relevant structures are only exposed in the Transvaal Supergroup (Pretoria Group and Malmani Subgroup). A chert horizon mentioned by Brink et al. (2000a) was also identified west of Potchefstroom (dashed black line).

provides excellent exposures of quartzite units of the Transvaal Supergroup (see section 5.5).

5.4.1 Spitskop Syncline

The area directly west of Potchefstroom was mapped in detail by Truter (1936), who produced a geological map of this area, including the main structural features, such as faults and folds. Further work was done by Simpson (1977, 1978) and Brink et al. (1997, 2000a,b). Simpson (1977, 1978) presented detailed data of the Spitskop Syncline, and Brink et al. (1997, 2000a,b) postulated the existence of two thrust faults flanking the Spitskop Syncline – the Potchefstroom Fault closer towards the dome and the Katdoornbosch Fault northwest of the Syncline. An overview of the discussion of the structures in this area by these authors is illustrated in Fig. 5.5. However, large parts of this area are currently in use by the military and, thus, inaccessible. Furthermore, the townships west of Potchefstroom have expanded enormously to the northeast and east since the study by Simpson (1977,1978), which made it impossible to investigate her findings in such areas.

Although there is only limited outcrop west of Potchefstroom, the orientation of the Spitskop Syncline, as demonstrated by previous workers (e.g., Truter 1936; Simpson 1977; Brink et al. 1997, 2000a,b), is confirmed by this study. The fold axial plane of the syncline strikes NE-SW (Fig. 5.6), tangential to the Vredefort Dome.

Only quartzites of the Daspoort Formation of the Pretoria Group crop out in the Spitskop Syncline. These quartzites are strongly fractured, and, in places, cataclastic breccias are present. A chert horizon mentioned by Brink et al. (2000a) that follows the general strike of the strata directly west of Potchefstroom could also be identified (Fig. 5.5, see section 5.4.2). The bedding on the eastern limb of the syncline dips with moderate angles to the north-northwest (Fig. 5.6). The few data available from the western limb show a shallow dip of the bedding towards the south-southeast (Fig. 5.6). The fold axial plane dips 70° towards the southeast, thus verging away from the dome. The bedding is slightly folded at a decametre spacing. Besides the most prominent sets of joints, which are subvertical and perpendicular to the bedding (NE-SW, labelled I in Fig. 5.6b), oblique joints (WNE-ESE, labelled II in Fig. 5.6b) are also present and display almost vertical dip angles. They occur with a decimetre spacing and do not exceed lengths of a few tens of centimetres.

Crosscutting relationships between all joint sets are observed, in places, but no displacements along these surfaces were found. A relationship between these joints and the syncline (e.g., increasing joint intensity towards the fold hinge) could not be established, due to the limited exposure and the fact that the fold hinge is not exposed at all (see also Simpson 1977). Similarly, no relationship between the fold and the

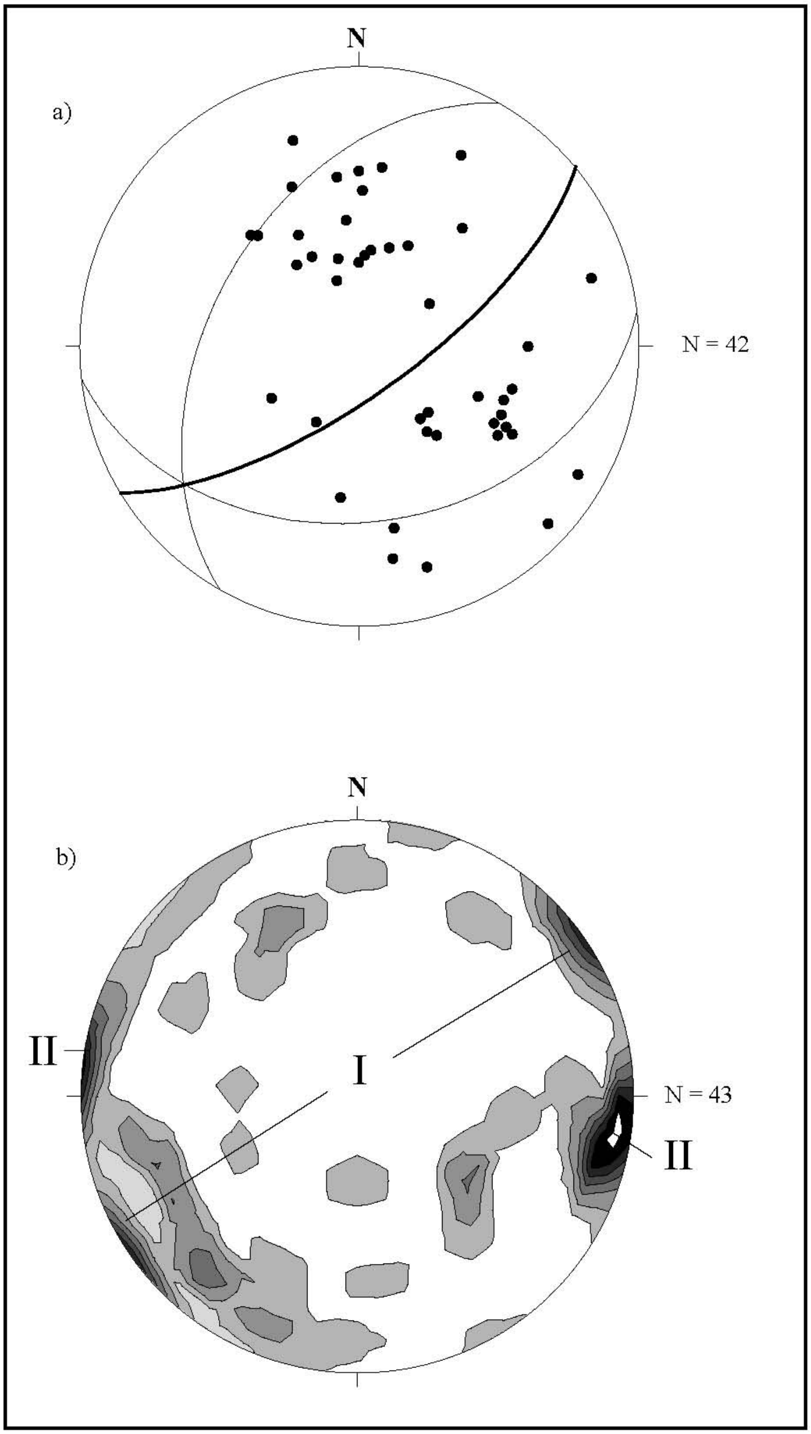

Fig. 5.6: Lower hemisphere equal area stereographic projection (Schmidt net) of the poles to (a) bedding and to (b) joints measured in the area of the Spitskop Syncline. The data show a NE-SW trend of the fold hinge, which plunges shallowly to the southwest. The fold axial plane dips 70° towards the southeast (bold great circle). Joints with normal orientations to bedding are labelled (I), which would correspond to the radial joints (labelled I in section 2.7) in the collar rocks. Joints with oblique orientations to the bedding are labelled II. Contours in (b) range from 1 to 7% (darkest colour).

cataclastic breccias was found. As a consequence, the association of intense fracturing and the increase of fracture density in the hinge zone of folds and along traces of large-scale faults, as demonstrated in the collar rocks (see section 2.7), cannot be evaluated at the Spitskop Syncline. In contrast to the fold structures in the collar rocks (see section 2.5), no major faults disrupt or displace the strata.

5.4.2 Brecciation

Several authors (e.g., Engelbrecht et al. 1986; Van der Merwe 1986; Brink et al. 2000a,b) reported an allegedly unusual type of brecciation occurring in the chert horizons of the Pretoria Group in the wider environs of the Vredefort Dome. Brink et al. (2000a,b) associated the brecciation with their alleged thrust zones linked to the Vredefort event (see section 5.2). They suggested that brecciation occurs where the chert horizons intersect the ramp zones of these thrust faults. The brecciation appears to be restricted to the chert horizons. These authors compared this deformation style with “chocolate-tablet-type boudinage” (as described by Wegmann 1932 and Sylvester and Christie 1968) and related this brecciation to the release of three-dimensional hydrostatic compression during the outward movement of material along these thrusts during the impact, resulting in an “explosion” of the cherts.

Surface mapping during this study identified such a chert horizon directly west of Potchefstroom. There, a chert horizon in the Malmani Subgroup (Fig. 5.5) displays this type of brecciation (Fig. 5.7). This horizon is parallel to the adjacent strata and commonly has an exposed thickness of not more than a few metres, although Brink et al. (2000a) reported a thickness of 180 m of “chocolate-tablet-type breccia” from a borehole near Fochville. These brecciated layers contain clasts but do not show any layering or preferred orientation of clasts (this work).

According to Brink et al. (2000b), the matrix of these breccias showed similarities with pseudotachylitic breccias observed in the Vredefort Dome (see Chapter 5), as they consist of a fine-grained and dark grey matrix, which comprises homogeneous cherty material, and clasts. No microscopic work was ever reported by these authors. These clasts, however, are somewhat different to the clasts in pseudotachylitic breccias from the core of the Vredefort Dome in that they are typically angular and much smaller, and because these breccias are restricted to chert horizons, they are monomineralic (Brink et al. 2000b). The clast-matrix ratio is also

Fig. 5.7: Photograph of the chert horizon in the Malmani Subgroup northwest of Potchefstroom (location 769, see Fig. 5.4 and Appendix No. 6). It consists of a fine-grained matrix and randomly oriented clasts. Brink et al. (2000a) related this type of brecciation to Vredefort-age thrust systems and termed it "chocolate-tablet boudinage". Pen for scale ca. 10cm.

distinctly higher than in the pseudotachylitic breccias in the Vredefort Dome, thus, suggesting a different origin. Furthermore, these authors stated that, in places, clasts showed the same spatial and orientational relationships to the beds from which they were derived. This observation and the monomineralic assemblage of these breccias make them different from the pseudotachylitic breccias found in the core and collar of the Vredefort Dome and in the Witwatersrand Basin. The latter can contain clasts of different composition, such as exotic clasts derived from some distance away (Reimold and Colliston 1994).

The postulated association of the chert horizon with the ramp thrust zones (Brink et al. 2000b) could not be confirmed during this study, as no such thrust zone was found on surface in proximity of these horizons. The chert horizons are restricted to certain stratigraphic units and are consistently bedding-parallel. Also, in contrast to Brink et al. (2000b), it was found during this investigation that the clasts do not show any layering or preferred orientation with respect to bedding. The randomly oriented clasts strongly contradict the terminology of a "chocolate-tablet boudinage" as proposed by Brink et al. (2000b). Lineations or shear surfaces, which could indicate movement along these surfaces and which could be associated to the thrust faults proposed by Brink et al. (1997, 2000a,b), were also not observed during this study, due to the poor outcrop conditions. Furthermore, no continuous exposure of these brecciated chert horizons was observed. Thus, Brink et al.'s (2000a) interpretations of these breccias are not supported and must be considered speculative.

A cataclastic breccia was observed in granitic rocks and quartz pegmatite at DePan, north of Carletonville (Figs. 5.8 and 5.9, locations 668 and 669, see Appendix

Fig. 5.8: Photograph of cataclastic breccia in the wider environs of the Vredefort Dome at DePan, north of Carletonville (location 668, see Appendix No. 6). The centimetre-sized clasts are usually well-rounded and consist of the surrounding granitic rocks.

No. 6 and Fig. 5.1). The breccia contains centimetre-sized, commonly well-rounded clasts of the surrounding lithology (Fig. 5.8) and although variable orientations with regard to the Vredefort Dome (radial, tangential, oblique) were observed, the dykes are usually straight and oriented predominantly N-S, which is radial with regard to the Vredefort Dome.

This breccia type is similar in occurrence to the pseudotachylitic breccias found in the collar and the core of the Vredefort Dome. This breccia occurs as several dykes up to 0.5 m in width and up to several tens of metres in length (Figs. 5.8 and

Fig. 5.9: Photograph of breccia occurrence in quartz pegmaite in the outer parts of the Vredefort Structure, at DePan, north of Carletonville (see Fig. 5.1, location 669, see Appendix No. 6). The dykes are oriented mainly N-S and can reach lengths of up to several tens of metres and widths of commonly 0.5 m. They are easy to identify from the surrounding rocks owing to their darker colour.

5.9). The fillings of these dykes contain a very fine-grained matrix that resembles the host rock lithology (granite/quartz pegmatite) (Figs. 5.8 and 5.9). The dykes contain a few centimetre-sized, commonly well-rounded clasts only locally. Further occurrences of both types of breccia were not observed in the wider environs of the Vredefort Dome in the course of this study. Thus, a spatial or geometric relationship with impact-related pseudotachylitic breccias in the Witwatersrand Basin and the Vredefort Dome could not be established.

5.4.3 Thrust faults

No evidence for concentric thrust faults, as proposed by Brink et al. (1997, 2000a,b), was found in the area around Potchefstroom on surface during this study. Although some good exposure of quartzite of the Hospital Hill Subgroup of the

Witwatersrand Supergroup was found about 20 km southeast of Ventersdorp (locations 763-767, see Fig. 5.1), no movement indicators, such as slickensides or major shear surfaces, were observed. The bedding dips consistently, with commonly shallow to moderate angles, towards the southeast. It is, in places, slightly warped and shows small-scale displacement of marker horizons by not more than 10 cm (Fig. 5.10).

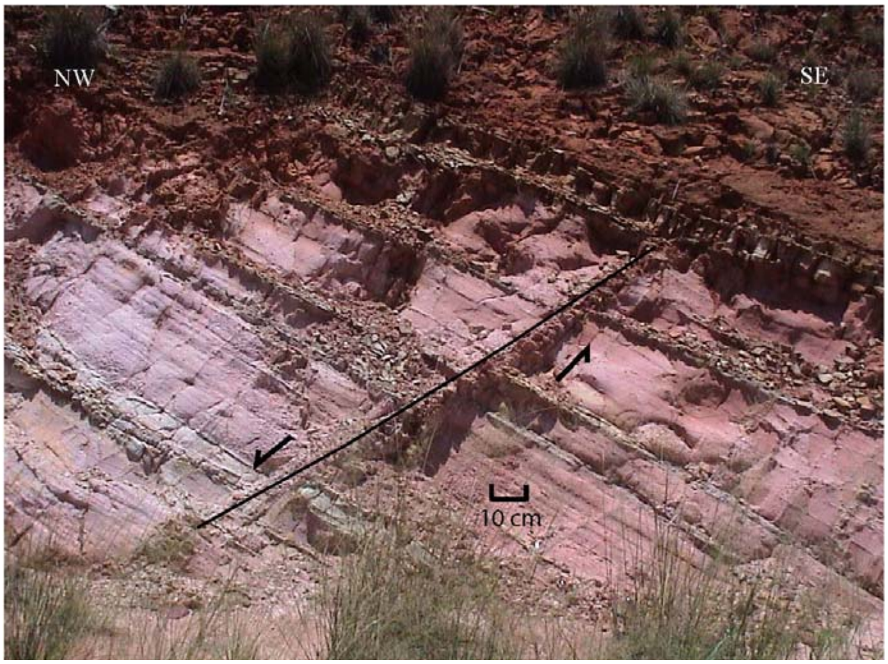

Fig. 5.10: Photograph of a road-cut of strongly weathered shales along the road Ventersdorp – Potchefstroom, ca. 20 km southeast of Ventersdorp (location 763, see Fig. 5.1 and Appendix No. 6). The bedding is slightly warped and steepens towards the SE. Displacement by ~10 cm took place along a normal fault, perpendicular to the bedding (hangingwall towards the NW, i.e., away from the centre of the dome).

The displacement occurs almost perpendicular to the bedding, indicating a normal fault movement towards the northwest (i.e., away from the centre of the dome). No major extensional fault was observed in this area on surface that could be associated with this small-scale fault.

A road-cut directly south of the town of Ventersdorp, at the junction of the N14 (Ventersdorp-Krugersdorp) and the R53 (Ventersdorp – Potchefstroom) (Fig. 5.11), exposes on both sides of the road shales of the Platberg Group (Ventersdorp Supergroup) over a distance of ca. 200 m (location 762, see Fig. 5.1 and Appendix No. 6). The strata show a southward-dipping set of northeast-verging thrust faults. In the light of the alleged concentric thrust faults in the outer parts of the Vredefort impact structure (see section 5.3, Brink et al. 1997, 2000a,b) and the fact that no discussion of this outcrop was published previously, a detailed discussion is presented. The outcrop was divided into four sections, numbered from 1 to 4 (Fig. 5.11, Figs 5.13-5.16).

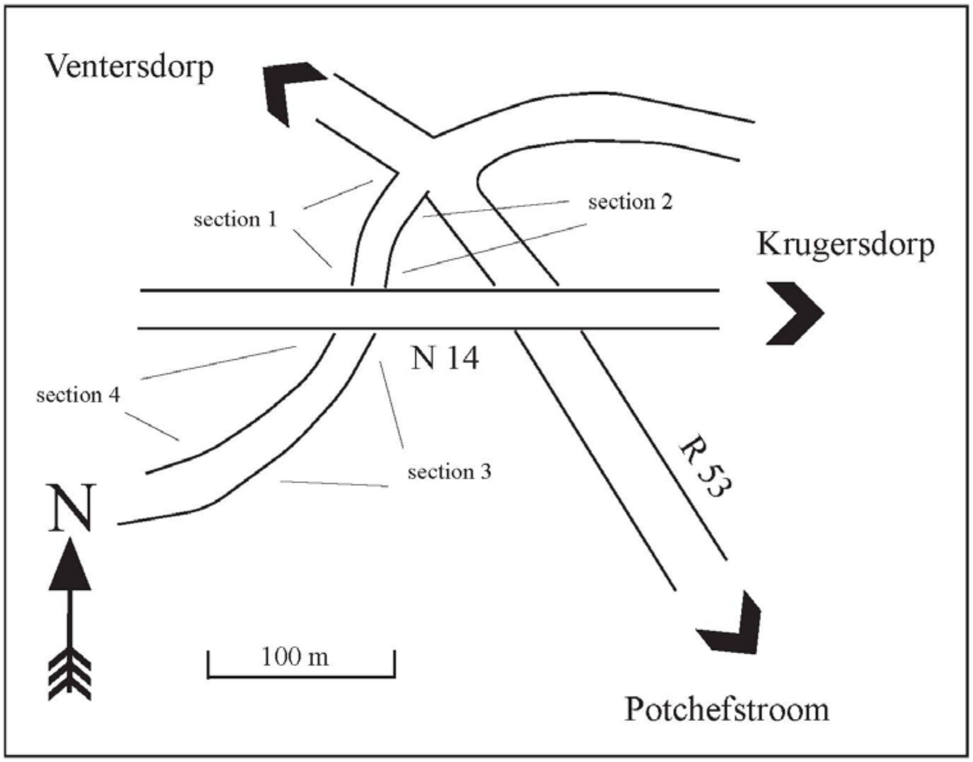

Fig. 5.11: Schematic map of the road-cut near Ventersdorp. The outcrop of shales of the Platberg Group was divided into four sections, each of which is described in detail in the following text.

The shales are intensely fractured and weathered, and display a cleavage and several sets of reverse faults. The bedding dips at shallow to moderate angles to the northeast (Fig. 5.12a). The strike of the bedding is fairly consistent; however, the dip angles increase in the vicinity of the thrust faults. The cleavage (Fig. 5.12b) is narrow-spaced (mm-spacing) and displays a consistent angle of about 15° to the bedding plane (Fig. 5.12a), but is steeper than the dip of the bedding (Figs. 5.12a and b). The cleavage maintains this consistent orientation in the vicinity of the thrusts, and even where the bedding is folded. The majority of thrust planes shows a similar strike orientation as the bedding. However, they dip to the NNE at steeper angles than the bedding. Some thrust faults deviate from this pattern and dip towards the NNW (Fig. 5.12c).

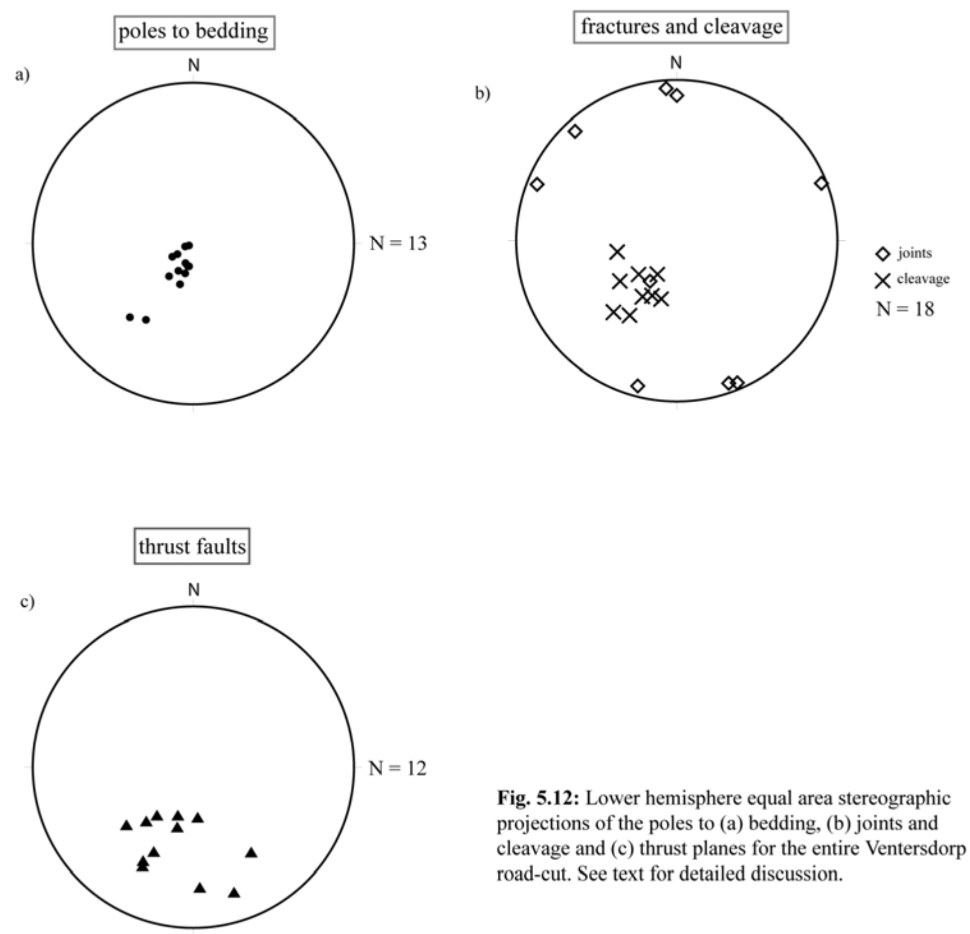

Fig. 5.12: Lower hemisphere equal area stereographic projections of the poles to (a) bedding, (b) joints and cleavage and (c) thrust planes for the entire Ventersdorp road-cut. See text for detailed discussion.

5.4.3.1 Section 1

This section (Fig. 5.13) is situated in the northwestern corner of the road-cut (Fig. 5.11) and is about 70 m long. Bedding dips at shallow angles towards the northeast (Fig. 5.13b), but seems to shallow somewhat towards the northeastern side of each thrust segment, which is in contrast to the general pattern of bedding orientation close to the thrust planes. The cleavage displays similar shallow dip angles to the bedding, but occurs at an angle of ~11° to the strike of the bedding (Fig. 5.13b).

Four reverse (thrust) faults were identified. The dip angles vary from 54° to 71° NNW, but seem to decrease gradually towards the north-northeast (Fig. 5.13a). The individual thrusts displace the bedding by a maximum of about 1 metre. The bedding is, in places, folded on a decimetre-scale (Fig. 5.13c). This tight folding is only observed in close proximity to the thrust planes and extends about 30-40 cm into

Fig. 5.13: (a) Photograph of section 1 near Ventersdorp. Four reverse faults (dashed lines) and several extensional fractures (solid white lines) were identified. (b) The measurements of structures are plotted into a lower hemisphere equal area stereographic projection (Schmidt net, bedding, cleavage and thrusts planes are shown as poles to the orientations, joint orientations are shown by great circles). Note that the bedding (bold great circle) and cleavage orientations are given as averages (for 4 and 3 measurements, respectively). (c) A small-scale (tens of centimetre) upright fold (white line) is developed close to a thrust plane (white dashed line) (length of pen, ca. 10 cm).

the southeastern side (footwall) of the thrust planes. On the northwestern side (hangingwall) of these thrust planes the bedding is only slightly warped. Steeply-dipping, pervasive joints with variable orientations cut through the bedding. They are predominantly straight but show, in places, an anastomosing appearance (Figs. 5.13a and b).

5.4.3.2 Section 2

This section (Fig. 5.14) is located in the northeastern corner of this road intersection (see Fig. 5.11) and is about 30 m long. The bedding dips towards the north-northeast at angles around 21° (Figs 5.14a and b). The cleavage displays an angle of ~13° to the strike of the bedding and dips slightly steeper than the bedding planes (Fig. 5.14b). In
this section, only one thrust fault is present that displaces the bedding by ~1 m. A second, normal fault is present within ~50 cm from the thrust (reverse) fault (Fig. 5.14a). The bedding is again slightly warped, especially between the two faults. These two faults may merge at the top of the outcrop, but the poor quality of exposure at the top of this outcrop and the partial talus/soil cover prohibit confirmation of this. No major, pervasive joints were observed in this section, in contrast to the other sections, where large-scale (metre-scale) joints are common.

It has to be pointed out that this exposed section is smaller than the other sections. Small joints at a cm- to dm-spacing are common. They anastomose and have a general east-west strike and steep dip angles (~80°). These joints are not penetrative and are usually not more than a few centimetres in length.

Given the close distance between the two faults, it seems plausible that the normal fault may be associated with the reverse fault and represents a failed thrust ramp. This is supported by the parallel orientation of the normal fault and the reverse fault, and the lack of such normal faults in the remainder of the entire outcrop.

5.4.3.3 Section 3

This section (Fig. 5.15) is situated in the southeastern corner of the locality (see Fig. 5.11) and is about 100 m wide. The bedding dips shallowly to the northeast (Fig. 5.15a,b), but is warped on a metre-scale and steepens close to the thrust planes

Fig. 5.14: (a) Photograph of section 2 of the road-cut near Ventersdorp (see Fig. 5.9). This section exposes a reverse and a normal fault (dashed lines) at a distance of a few tens of centimetres to each other, and that disrupt the bedding twice. The white dashed lines illustrate the warped bedding in the vicinity of the faults. (b) Poles to bedding, joints and shear planes are given in a lower hemisphere equal area stereographic projection (Schmidt net).

Fig. 5.15: (a) Section 3 displays three thrust planes (dashed lines). The main thrust is situated roughly in the centre of the outcrop and produced folding and a m-scale displacement of the bedding. (b) Lower hemisphere equal area stereographic projection (Schmidt net) of poles to bedding (filled circles and great circles), cleavage, and thrust planes. Note that only the average orientation for the bedding is given (for 4 measurements). The axial plane is given by a bold great circle. (c) Close-up of the fold in section 3. The cleavage turns into an axial planar cleavage (white line) in the fold hinge. The upper limb of the fold is thinned out, indicating drag along the thrust plane.

observed in this section (Fig. 5.15a), dipping to the northeast at angles between 31° and 56°. The two minor thrusts show displacements of a few tens of centimetres and of ~0.5 m, respectively. The main thrust, however, has displaced the bedding by 1.5-2 m and produced a tight fold beneath the thrust plane. The upper limb of this fold is truncated by the thrust plane (Fig. 5.15c). The fold axial plane dips at 38° to the northeast (046°). The cleavage displays an average angle of ~19° to the bedding orientation (Fig. 5.15a,b), but becomes parallel to the bedding on the upper limb of the fold, i.e., in close proximity to the thrust plane, where it turns into an axial planar cleavage in the fold hinge. To the NE of the thrust plane the cleavage again displays a consistent angle of ~10° to the bedding. The consistently parallel orientation of the cleavage to the faults in the entire outcrop suggests an early- to syn- faulting formation of the cleavage. Small-scale joints with almost vertical but variable strike orientations are present. They are open and anastomosing, but not pervasive and only a few tens of centimetres in length.

5.4.3.4 Section 4

This section (Fig. 5.16) is located in the southwestern corner of the study site (Fig. 5.11). The bedding dips, as in sections 2 and 3, more to the north-northeast than at section 1, and the dip angles increase slightly towards the northeast. They range between 26° and 32°. Two thrust faults are apparent in this section (Fig. 5.16a). The northeastern thrust plane displaces the bedding by at least 1 m. The thrust to the southwest terminates below the top of the outcrop. The layers above this termination are folded into a tight, SW-verging fold, consistent with a blind thrust (Ramsay and Huber 1987). The thrust shows a displacement of ~0.5 to 1 m (Fig. 5.16c). The cleavage shows a consistent pattern with regard to the bedding orientation, but the strike angle between this cleavage and the bedding decreases in the folded zone. Almost vertically inclined extensional joints are also present in this section (Fig. 5.16a), but generally show a wide spacing (m-spacing), with a locally pervasive character. Their strike is almost parallel to the strike of the thrusts.

Further mapping in the wider environs of this location failed to find similar structures. Although the bedding is commonly warped, it does not show any evidence

Fig. 5.16: (a) Section 4 exposes two reverse faults (black dashed lines), including a blind thrust (left black dashed line, for further details, see text). Joints are represented by solid white lines. (b) Poles to bedding, cleavage, thrust planes and joints are shown in a lower hemisphere equal area stereographic projection (Schmidt net). Note that only the average bedding orientation is shown (great circle). (c) Close-up of the blind fault. The different behaviour of individual units to the thrusting can clearly be seen.

of thrusting or of a pervasive cleavage. The northeasterly dip directions of bedding along the exposed section near Ventersdorp is a deviation from the generally southeasterly dip directions found to the south of this area (see Fig. 5.10). This may be explained by local tilting of strata due to map-scale faulting or folding (Courtnage 1996, see section 5.5) or by the vicinity to the Rand Anticline (see Figs. 1.13 and 1.14).

Minor thrust faults were identified south of Carletonville, about 2 km north of the N12 (location 515, see Appendix No. 6, Fig. 5.1) at a road-cut along the R500. Two folds are present in strongly weathered shales of the Timeball Hill Formation, but only one is disrupted by a minor thrust fault (Fig. 5.17). However, these shales are, in places, highly magnetic and, therefore, exact measurements could not be taken. The shales are intensely fractured on a centimetre-scale but folded on a metre-scale (Fig. 5.17). A metre-scale asymmetric fold is present with an almost vertical fold axial plane (Fig. 5.17). The fold is disrupted by a northeasterly-dipping fault, which has sheared off the northern limb of the fold structure (Fig. 5.17). This fault has displaced the shale layers by at least 1 m; however, intense weathering and soil cover on the top of the outcrop made it impossible to establish the exact slip sense and magnitude. The fault verges to the south, i.e., towards the Vredefort Dome. The disruption of the fold by the fault indicates that faulting occurred after the formation of the fold (see section 5.6). Some 200 m further northwest, in the same outcrop, another open metre-scale fold is exposed (Fig. 5.18). The orientation of the fold axial plane (subvertical) is very similar to the abovementioned fold and suggests that these two structures may be related. The second fold structure is not disrupted by any faults.

A fracture cleavage is also present that is pervasive and shows a consistent orientation with regard to bedding. Due to the highly magnetic character of the shales, an axial planar orientation of the cleavage in the fold hinges could not be confirmed.

The pattern of structures in this outcrop could not be correlated conclusively to the observed structures near Ventersdorp owing to the lack of exact measurements. Besides these structures, no evidence of thrusting, as proposed by Brink et al. (1997, 2000a,b), was found in the outer parts of the Vredefort structure on surface. An interpretation of these data is given in section 5.5.

Fig. 5.17: (a) Shale of the Timeball Hill Formation exposed along a road-cut (location 515, see Appendix No. 6). The layers are folded on a metre-scale (white solid line). A fault has disrupted the fold along its northern limb (dashed line). Owing to strong weathering and soil cover, the slip magnitude for the fault could not be determined exactly. Hammer for scale, ca. 30cm. See text for further details.

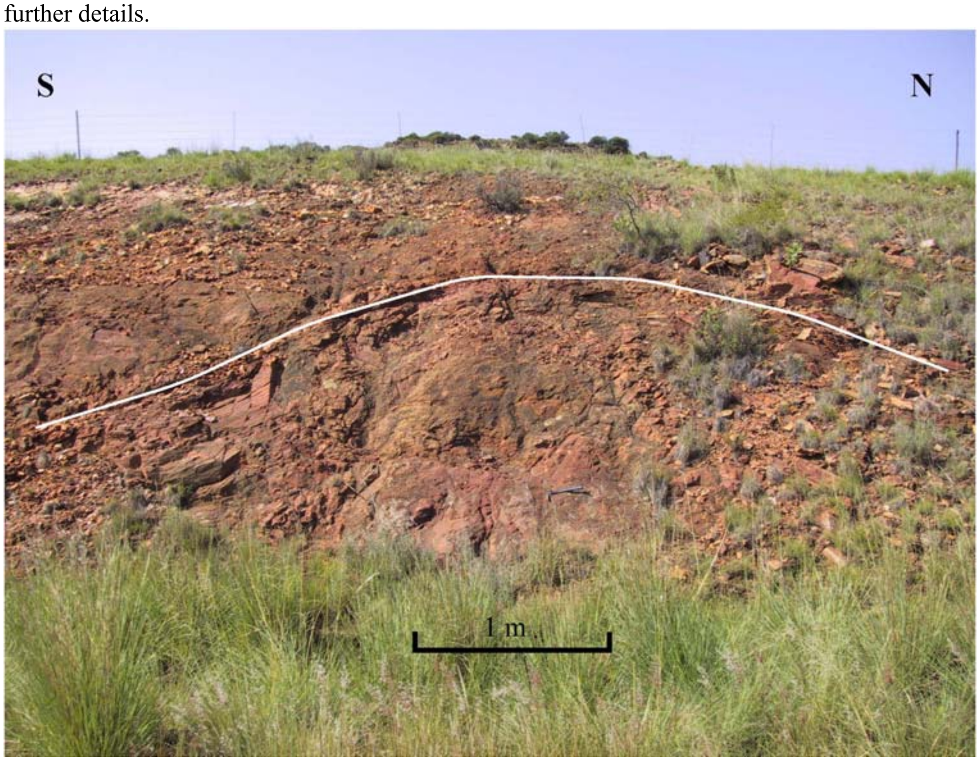

Fig. 5.18: Open fold structure (white solid line) in shale unit of the Timeball Hill Formation about 200 m to the northeast of the location in Figure 5.17. The fold axial plane is almost vertical, similar to the one in Fig. 5.17, but this one is not disrupted by a fault.

5.4.4 Extensional faults

Some minor extensional faults were identified south and southwest of Potchefstroom, consistent with the results of previous studies (e.g., Simpson 1977; Engelbrecht et al. 1986; Brink et al. 1997, 2000a,b). However, surface mapping during this study failed to find continuous exposures of the faults. They can usually only be identified by evaluation of aerial photographs. One rare exception is a road-cut near Boskop (see Figs 5.1 and 5.5), about 20 km northeast of Potchefstroom, where the Potchefstroom Fault is exposed. At this road-cut a range of lithologies is evident including dolomites and quartzite with intercalated chert layers and shales (location 808, see Appendix No. 6). Depending on their specific rock properties, the lithologies show different types of deformation.

The usually massive quartzites and dolomites do not show any movement indicators; instead, the bedding is disrupted by intense fracturing and the rocks have locally a brecciated appearance (Fig. 5.19). However, this brecciation is different from the so-called "chocolate-tablet boudinage"-type breccia observed in the chert layers (see section 5.4.2) in that the matrix is coarser-grained and usually contains small clasts. The fragments are subangular to well-rounded and do not exceed sizes of a few centimetres. The bigger clasts are typically rounded and comprise a polymict assemblage of clasts from the surrounding lithologies, in contrast to the monomict "chocolate-tablet boudinage" brecciation described by Brink et al. (2000a,b). The lateral extent of mixing is in the order of a few metres.

Planar structures are best developed in the shale layers. The bedding is slightly warped. The dip of the fault is ~51° towards 083° (Fig. 5.20a,c). Only one possible boudin was observed. Its asymmetry (Fig. 5.20b) suggests a movement of the hangingwall down to the east, as proposed by e.g., Van der Merwe (1986), and Brink et al. (2000a,b). However, due to the fact that this structure is not well exposed at the bottom of this outcrop, it may also represent a rootless, isoclinal fold.

The rocks are strongly weathered and under the microscope show strong recrystallization of minerals and growth of alteration minerals. The very fine-grained clasts (tens of µm) are aligned parallel to a shear fabric observed under the microscope (see Fig. 5.21b). In places, clasts are also recrystallized and show sub-grain formation (Figs 5.21a and b). The clast shown in Fig. 5.21a has

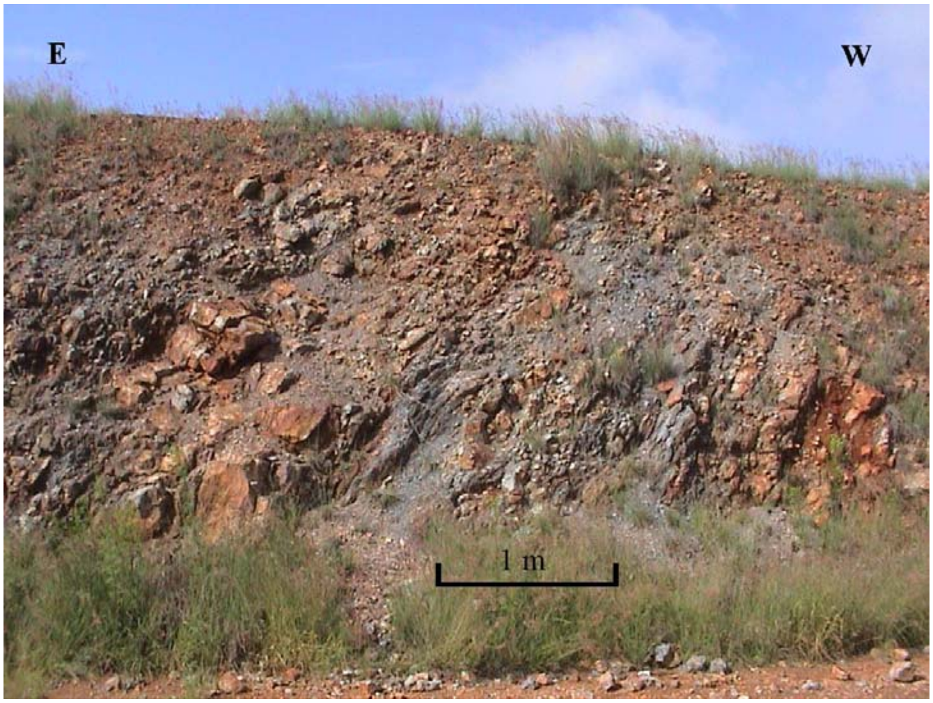

Fig. 5.19: The only outcrop of the "Potchefstroom-Master Bedding Plane Fault" (term according to Brink et al. 2000b) at a road-cut near Boskop. The rocks show evidence of intense brittle deformation, but no evidence of faulting is seen in most of the individual stratigraphic units, except in the shales (location 808, see Appendix. No. 6).

tails on both sides. The pressure shadows indicate a σ-clast geometry with a dextral shear sense (i.e., at an outcrop-scale, hangingwall to the east). Strong recrystallization and weathering has obliterated any further kinematic indicators. Most other clasts that are recrystallized do not show evidence of shearing, but are clearly elongated parallel to the fault plane (Fig. 5.21b).

A thin section derived from close to the possible boudin shows evidence of shearing of minerals with a sinistral displacement of up to 0.5 mm. At a microscopic-scale, the hangingwall was seen to have moved to the east (Fig. 5.22a). The shearing followed extensional fractures, which are oriented obliquely to bedding (Fig. 5.22b). The shear pattern can be reconciled with a S-C fabric; however, the displacement is less than 1 mm and the shearing and fracturing could only be observed in this thin section. The microscopic observations suggest predominantly pure shear conditions rather than simple shear. Shearing appears to have been generally minor along this fault, and the elongated and flattened clasts may also resemble the original orientation of a slaty cleavage.

Fig. 5.20: (a) Photograph of a shale unit exposed at the road-cut near Boskop (see Fig. 5.5), which displays an eastward-dipping fault plane and a possible asymmetric boudin. The boudin indicates a movement of the hangingwall down to the east, but could also be interpreted as a rootless isoclinal fold (see text for discussion). (b) Close-up of the possible asymmetric boudin. A tail is only developed at the eastern end (bottom left). The bedding is slightly warped. (c) Lower hemisphere equal area stereographic projection (Schmidt net) of the average bedding orientation (bold great circle), joint orientations (great circles), fault planes (triangles), and lineations (open triangles) at the road-cut near Boskop.

Linear grooves on fracture surfaces elsewhere in the outcrop indicate bedding-parallel right-lateral movement of the strata. However, due to the highly fragmented and weathered nature of this outcrop it could not be determined whether these features indeed represent striae formed by tectonic processes or by the excavation of the road. In case of tectonic movement along the joint surfaces, the grooves would indicate lateral movement, as proposed by several authors (e.g., Van der Merwe 1986; Roering et al. 1990). These authors concluded that this fault movement postdated the eastward-directed dip-slip extensional movement and related it to the latest movement along this fault. A temporal relationship between these two movements, dip-slip and strike-slip, however, could not be observed during this study. Given the small amount of movement by shearing observed in thin sections, and the lack of any discernable movement at the outcrop-scale, an impact-related formation of this fault – with inward-directed movement during the modification phase of the Vredefort impact event – is highly questionable. For further discussion see section 5.5.

During further field mapping along the road R500 towards the south (i.e., towards the collar of the Vredefort Dome), no major structures (faults, folds) were found. The landscape is relatively flat and only some road-cuttings provide some exposure of inferior quality.

Evidence of major thrust zones is, at least on surface, absent. Only small-scale structures are locally present, such as decimetre-scale folds and striations on bedding and joint surfaces. North of Fochville, a road-cut exposes andesites of the Hekpoort Formation of the Transvaal Supergroup (location 516, see Fig. 5.1). Joints usually do not extend over more than a few tens of centimetres in length; they occur at spacings of tens of centimetres. Further indication of small-scale shearing is evident on some subvertical joint surfaces that display slickensides indicating a sinistral strike-slip movement (labelled I in Fig. 5.23). The slip magnitude, however, is unknown. Given the development on small-scale (decimetre-scale) joint surfaces, it is most likely in the order of <1 cm. A second cluster of striations (labelled II in Fig. 5.23) that is present on shallowly southward-dipping joint surfaces do not show any evidence of shearing. However, the poor quality of the striations in outcrop does not allow a conclusive interpretation of such features.

Fig. 5.21: Microphotographs of strongly weathered and altered shale from Boskop (location 808, see Appendix No. 6). (a) Fine-grained recrystallized quartz and other alteration minerals are evident. The elongated tails on both sides of the clast indicate a σ-clast geometry and its pressure shadows suggest a dextral shear sense, i.e. at an outcrop-scale, east-side-down movement (crossed polarizers). (b) Example of a flattened clast, which is the dominant occurrence of clasts in thin sections. This indicates predominantly pure shear conditions during formation (crossed polarizers).

Fig. 5.22: Microphotographs of the shear zone in a shale unit at Boskop (location 808, see Appendix No. 6). (a) Evidence of shearing is found in a few thin sections of the shale unit close to the possible boudin in Fig. 5.18, indicating a sinistral displacement of up to 0.5 mm, with a quartz layer as the marker horizon (bedding is subhorizontal). (b) Extensional fractures with oblique orientations to the bedding (arrows) that are filled with an opaque phase.

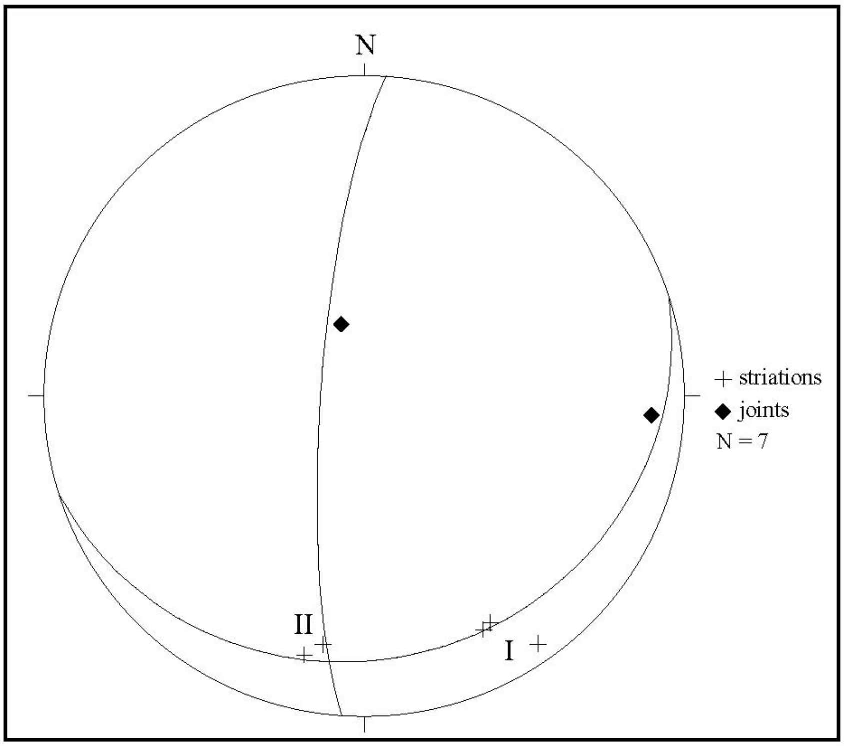

Fig. 5.23: Lower hemisphere equal area stereographic projection (Schmidt net) showing the main joint orientations (filled diamonds and great circles) and striations (lineations) observed in a road-cut north of Fochville (location 516, see Fig. 5.1 and Appendix No. 6). One set of striations resembles slickensides with a sinistral strike-slip movement (labelled I) on subvertical joint surfaces. The second set of striations (labelled II) on shallowly southward-dipping joint surfaces cannot comfortably be confirmed as slickensides due to the poor quality of exposure.

The only remarkable elevation in this area is represented by several hills belonging to the so-called Losberg Complex, a few kilometres south of the town of Fochville (see Fig. 5.1).

5.4.5 The Losberg Complex

The Losberg Complex (Fig. 5.1) represents one of several intrusive complexes around the Vredefort Dome (see detailed discussion in section 1.7). However, it is the only non-alkaline intrusion around the dome with a complete differentiation sequence (Jansen 1953). It is located about 5 km southeast of Fochville and forms isolated hills in the generally flat landscape around that town (Fig. 5.24). The complex is divided into several hills - the Groot Losberg, Klein Losberg and Leeuwkop (Jansen 1953) (Fig. 5.24).

The intrusive rocks comprise a complex range of lithologies of ultrabasic to acidic composition and are overlain by mostly fine-grained white quartzites of the Magaliesberg Formation of the Transvaal Supergroup (Jansen 1953).

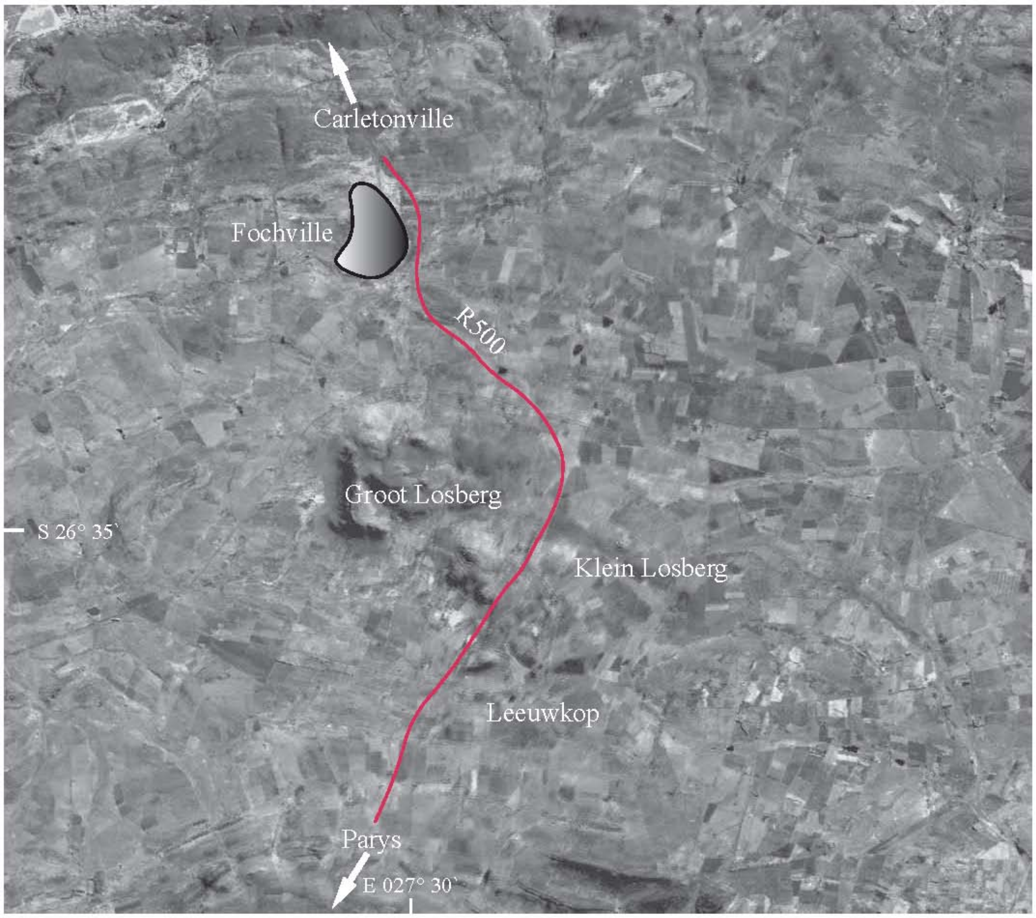

Fig. 5.24: Close-up of 1:25 000 aerial photograph of the Losberg Complex, south of Fochville. The Complex is divided into the Groot Losberg, Klein Losberg and Leeuwkop. For the location of the Losberg Complex in a regional context see Figs. 1.12 and 5.1.

The mapping was largely carried out on the Groot Losberg (locations 809 to 815, see Appendix No. 6). Although most of the Groot Losberg was mapped and not a single likely impact-related macroscopic deformation feature was found, it has to be pointed out that some areas could not be mapped due to inaccessibility, e.g,. the southwestern part of the Groot Losberg that is part of a game farm.

The quartzite is fine-grained and pure and does not show any macroscopic impact-related deformation features, such as pseudotachylitic breccias or shatter cones. The bedding orientation of the quartzites of the Magaliesberg Formation is not uniform and shows two clusters on the stereonet (Fig. 5.25a). The clusters demonstrate that some quartzite units in the northern part of the Groot Losberg dip with moderate angles towards the south-southwest, whereas some in the southern part of the study area mostly dip moderately towards the north (Fig. 5.25a). Although there is a certain spread of some measurements for both clusters, the general trend of the bedding orientation indicates the presence of a major, upright, east-plunging syncline. This trend and the distance from the centre of the dome suggest that this syncline is part of the Potchefstroom Syncline (Simpson 1977, 1978); however, the scale and variable dips of this syncline (hundreds of metre-scale) occur on a smaller-scale and are not consistent with that of the Potchefstroom Syncline observed in the area near Potchefstroom (Simpson 1977, 1978; this study). Although the scale and dips conform more to those observed in the Spitskop Syncline (ses section 5.4.1), the orientation is definitely not the same as in the Spitskop Syncline, which trends NE-SW. Furthermore, it is unknown whether the intrusive rocks underlying the quartzite show a similar deformation pattern, due to their poor exposure. The spread of bedding orientation in quartzite rocks on both parts (northern and southern) of the Groot Losberg occurs at a scale of tens to hundreds of metres and may be explained by macroscopic rotation and folding of the quartzites, although, as pointed out above, no discernable large-scale structures were found. Evidence of folding and faulting within quartzite units around the Potchefstroom Syncline was presented, however, in detail by Simpson (1977, 1978) and this study (see sections 5.4.1 and 5.4.2). Alternatively, the different bedding orientations may indicate fragmentation and differential rotation of the sedimentary rocks by the intrusion. Jansen (1953) suggested that no consistent bedding orientation for the northern and southern parts could be observed, owing to the fragmentation and folding of the sedimentary strata overlying the intrusion. Given the lack of discernable macroscopic brittle structures that could be accounted for by a rotation of strata, and the spread of measurements on the northern and southern parts of the Groot Losberg (Fig. 5.25a), folding of strata on a smaller-scale seems to be the mostlikely explanation for the variable bedding orientation.

The fracture orientations in the intrusive rocks and the quartzites are similar (Fig. 5.25b), but fractures in the quartzites show a closer spacing than those in the intrusive rocks. In the intrusive rocks, fractures are generally straight and pervasive displaying a regular dm- to m-spacing, but no associated parallel small-scale (cm-spaced) fractures are present as in the quartzites. In general, the fracture pattern is comparable with the fracture geometry observed in the collar rocks (labelled I to IV,

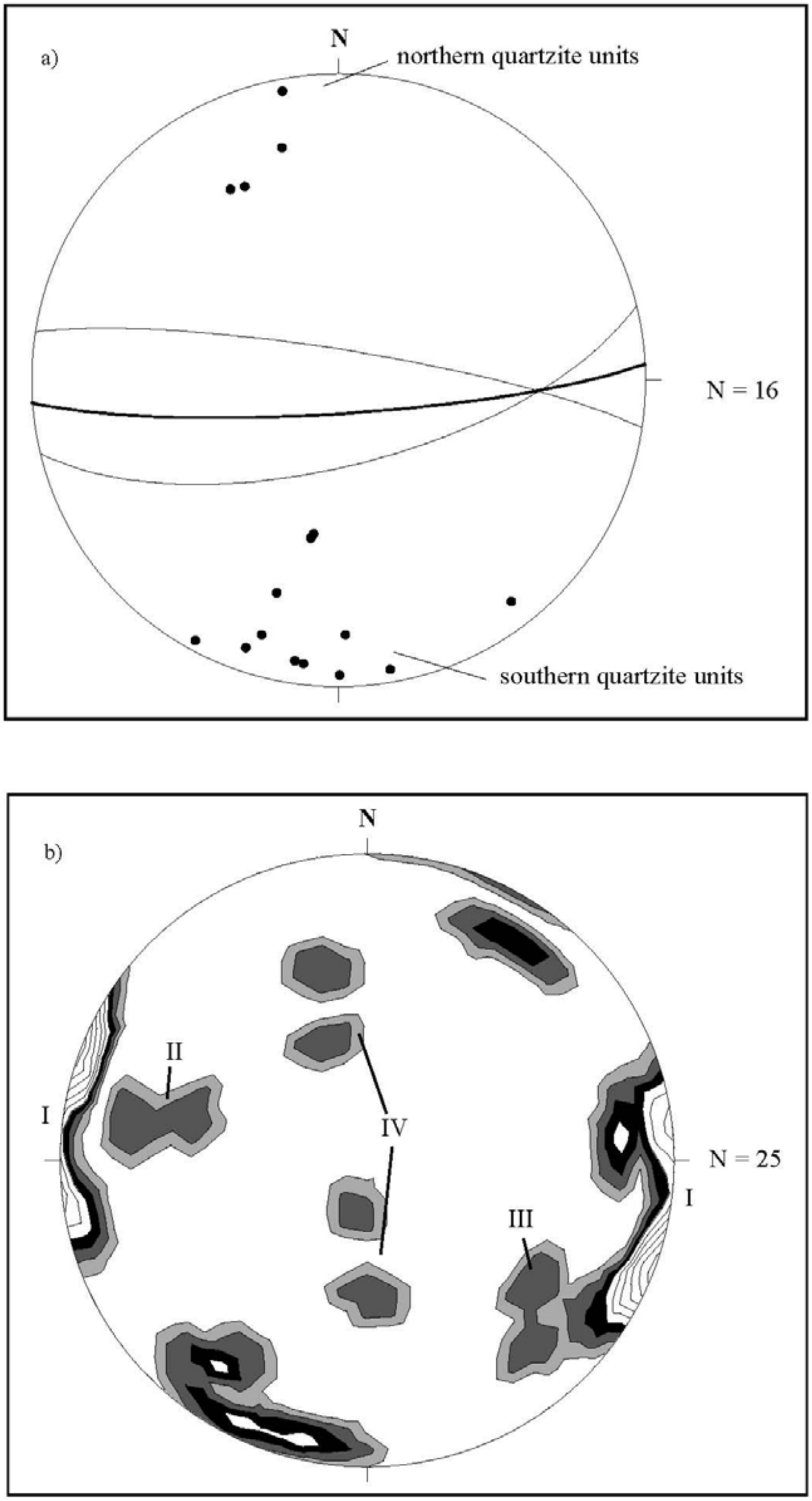

Fig. 5.25: Lower hemisphere equal area stereographic projection (Schmidt net) of the poles to bedding (a) and fractures (b) of the Groot Losberg. The bedding orientations can be divided into two clusters with southerly and northerly dips, respectively. Although the bedding is not consistent in both clusters, the general trend of the bedding shows a synclinal form. The axial plane is shown by a bold great circle. Contours in (b) range from 0.00 to 7.00 and max. dens. = 7.35 (at 99/ 6), min. dens. = 0.00.

see section 2.7). The consistent fracture pattern in both the intrusive rocks and the overlying quartzites indicates a similar time of formation of fractures, and given the observations from other studies on fractures in different parts of the Vredefort Dome (e.g., Simpson 1977, 1978; Lilly 1981; this study, see section 2.7), it can be attributed to the impact event or to post-impact fracturing. For a detailed discussion on the fracture pattern in the collar rocks see sections 2.7 and 6.3.4.

5.5 Synthesis of data

Although surface mapping was in general hampered by sparse exposures of structures, some small-scale (cleavages, fractures) and macroscopic (folds, faults) structures were identified in the outer parts of the Vredefort impact structure. The main questions concerning the structures presented above are whether they can be linked without doubt to one of the deformation phases that affected the Witwatersrand Basin (e.g., McCarthy et al. 1986, 1990; Myers et al. 1992; Courtnage et al. al. 1995; Courtnage 1996) prior to the Vredefort impact event, or whether they are impact-related. In particular, it is of interest whether certain observed structures can be attributed to the alleged thrust zones around the collar of the Vredefort Dome, as proposed by Brink et al. (1997, 2000a,b).

Thrust planes that were found during this study show a close relationship with metre-scale folds in that they disrupt and displace the fold hinges (Fig. 5.17) or, in some cases, produced drag folding and thickening of fold hinges (Fig. 5.15). This geometric relationship indicates that thrusting probably occurred post-folding.

The single normal fault that was observed at section 2 of the road-cut exposure near Ventersdorp (section 5.4.3.2) (see Fig. 5.14) is believed to have formed coevally with the thrust fault in this outcrop. Although the poor outcrop conditions (weathering, soil cover) hinder further investigation of the normal fault, it might resemble a failed thrust ramp related to the thrusting.

The structures that were solely found in shale units are associated with a well-developed cleavage. The cm-spaced fracture cleavage maintains a consistent orientation and angle to the bedding in both outcrops (see Figs. 5.12b,c and 5.18), with the exception of areas where strata are folded on a larger-scale (metres). In these cases, the cleavage orientation becomes bedding-parallel, and in the fold hinge turns into an axial planar cleavage (see section 5.4.3.3). This consistent orientation of the cleavage corresponds to the orientation of the thrust faults (Fig. 5.12b and c) and suggests that the cleavage formed either before or simultaneously with the thrusting, which is consistent with previous studies (e.g., Courtnage 1996) that reported such thrust faults in Transvaal Supergroups rocks.

Similar structures involving a strong cleavage, thrust faults and folds were reported from elsewhere in the Witwatersrand Basin (e.g., McCarthy et al. 1986; Courtnage 1996), but with northerly-directed thrust movement. A strong pre-Vredefort, south-verging, cleavage in Transvaal Supergroup rocks was identified by Courtnage (1996) and attributed to pre- or syn-Bushveld times. However, McCarthy et al. (1986) claimed to have identified impact-related thrust planes with northerly-directed movement as far north as in the area of the Johannesburg Dome, and Courtnage (1996) also mentioned that certain structures are only found locally and some shear planes were affected by later (post-impact) folding events. In the context of tilting of strata and the fact that the observed structures are not continuously exposed, the structures presented in this chapter (with southward-directed thrusting and NNE-dipping surfaces) may originally have had a different orientation. In the case of a tilting of bedding to a horizontal orientation, the steep thrust faults would become shallow thrust faults with displacement of the hangingwall still towards the NNE. This would mean that the movement along the faults would still be tangentially to the dome and could, thus, not be reconciled with a small-scale manifestation of the larger, inward-facing, concentric faults that were related to the impact-event (see below). As a consequence, the structures that were observed at an outcrop-scale, such as thrust faults, folds and cleavages, e.g., at the road-cut near Ventersdorp (section 5.4.3), cannot comfortably be linked to the Vredefort event. In addition, an intense cleavage pattern is also known from the very fine-grained shale units of the Witwatersrand Supergroup exposed in the collar of the Vredefort Dome. The relationship with impact-related structures revealed a pre-impact origin for these cleavages (e.g., Lilly, 1978, McCarthy et al. 1986; Gibson 1993). Given the strong relationship between thrust faults and cleavage in both outcrops, a pre-impact origin of the metre-scale faults, as well as the folds, is suggested.